CARBON CAPTURING
AND
SEQUESTRATION

AN OPTION TO BUY TIME?

BY

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Preliminaries

Before the thesis starts, please read the following technical preliminaries.

The thesis is written in British english. Titles of references might deviate from this.

The thesis makes use of mathematical symbols and abbreviations. Mathematical symbols are emphasised by the use of italics (e.g. x), while the abbreviations are written in capital letters. Usually, if an abbreviation appears for the first time in the flowing text it is parenthesised; alternatively the relation is emphasised by a word like denoted or for short. Moreover, some chemical notes are used that are treated like abbreviations. Reading is facilitated by repeating the long version of an abbreviation, if has not appeared over some pages. Moreover, common abbreviations are used like e.g., i.e. etc.

The thesis is structured in levels of chapters, sections, etc. The internal cross references are abbreviated with Ch. regardless of the level. Moreover, several equations (Eq.), figures (Fig.) and tables (Tab.) are used. Cross reference to Eq. , Fig. and Tab. are indicated by two numbers: the first indicates the chapter and the second the number of the item in the order of appearance of the corresponding type.

The thesis comprises a table of content as well as lists of figures, tables and abbreviations. Note that the captions of tables and figures can deviate from the entries in the lists, which is due to a lack of space. The list of abbreviations contains a column, which indicates the page of first appearance, except from those introduced here.

The thesis makes extensive use of units to describe particular entities. Some notes have are necessary on this:

1. Energy units used in this thesis are either in Joule (J) or Watt hours (Wh); note that one Wh equals 3600J. If a particular form of energy is considered this is indicated by a subscript: electricity (e), thermal (t) and hydrogen (H_2).

2. The magnitudes used in this thesis are quite large so that appropriate scaling units are required. Physical units are scaled by the use of kilo (k$\hat{=}10^{3}$), mega (M$\hat{=}10^{6}$), giga (G$\hat{=}10^{9}$), tera (T$\hat{=}10^{1}2$), peta (T$\hat{=}10^{1}2$), exa (E$\hat{=}10^{1}8$) and zeta (Z$\hat{=}10^{2}1$). Monetary units are in \$US. They are scaled by the use of the Chuquet system: million (mil. $\hat{=}10^{6}$), billion (bil. $\hat{=}10^{9}$) and trillion (tril. $\hat{=}10^{1}2$). Moreover, sometimes the use of small monetary units is required: mills\$US equal 0.001·\$US. If \$US is extended by a subscript this indicates the base year for deflation.

3. Weight and length units are given in the metric system. Tons denote metric tons; i.e. 1000kg. The use of barrels (bbl) is the only exception from the metric weight system.

In mathematical formulas the use of $\dot{x}$ denotes the derivative od x with respect to time.

Foreword

This thesis is the outcome of four and half years joining Potsdam-Institute for Climate Impact Research (PIK). It evolves from my interests in economics as well as engineering sciences that are prominent in the climate change research arena.

In some sense this work is the further development of my Diploma on Extreme Climate Events and the Carbon Cycle. Here the focus has been on the level of emission mitigation using a Ramsey-type model integrating the climate system developed by William D. Nordhaus. In the end it becomes clear that preventing such events requires a detailed look at technologies.

Admittedly, my theoretical foundation on Ramsey-type models has been limited at that time. In the last few years this has changed to some extent. It became clear to me that Ramsey's quest for the optimal consumption and saving decision is fundamental in economics. It becomes an highly important question, if environmental problems shall be solved by using several technologies. This is not only a matter of technology choice, but also a matter of economic growth and income distribution, which in turn are essential in economics.

My attention was attracted to carbon capture and sequestration at the International Energy Workshop 2001 in Laxenburg. James Edmonds gave a presentation on that issue in which he emphasised the huge amount of carbon that has to be treated in technical facilities instead of emitting it into the atmosphere. My first impression from that idea has been a mixture of laughter, mock and denial, which lead me to investigate it further. Now I learned a lot of interesting things about the technology and geology and issues surrounding these sciences. From an economic point of view this technology can make a contribution to climate protection, but I still have my doubts.

Integrating the carbon capture and sequestration technology into the Ramsey-type *MIND* model revealed the relationship between technologies, growth and income distribution in a carbon constraint world. This has been combined with the development of *SimEnv*, an environment that allows the computation of extensive sensitivity analysis developed at the Data & Computation Department at PIK. This and the power of a parallel computing machine allowed the computations presented in this thesis, which provide deeper insights into the quantitative and qualitative behaviour of the *MIND* model.

It can be said that this thesis is the outcome of an interesting and policy relevant scientific question that is answered by combining economic theory, climate science, engineering, geology and computation. This thesis gained a lot from people to who I want to address some thankful acknowledgments.

First of all I want to thank Ottmar Edenhofer for patience, ideas, discussion and support in various ways. I also thank Carlo Jaeger for the freedom to do all that work and for some very interesting thoughts and hints.

Next, I want to thank Michael Pahle, Christian Flachsland, Elmar Kriegler and Hermann Held for corrective actions, discussion and problem solving capacity. For helpful discussions and problem solving capacity I thank Marian Leimbach, Katrin Gerlinger, Kai Lessmann, Gerhard Petschel-Held, Matthias Lüdeke, Jürgen Scheffran, Jürgen Kropp, Klaus Eisenack and Thomas Kleinen. I want to thank Claus Rachimow and Michael Flechsig for *SimEnv* support.

I want to thank some friends for being patient, supporting and let me know the other things in life; the list is too long and I'm afraid of forgetting somebody, who would become angry. Then I want to thank all those people, who made the very good music I listened to, while I wrote this thesis; this list is very long too and I leave it with the advise to listen to Alice Donut and On the Might of Princes while writing text and Kyuss while writing code.

Lastly, I want to thank my family for patience and support.

Contents

List of Figures

List of Tables

List of Abbreviations

Abbreviation	***Explanation***	***First Appearance***
AG	Aktiengesellschaft	p. 209
AIM	Asian Integrated Model	p. 111
ALL	Scenario Name	p. 142
AOGF	Abandoned Oil and Gas Fields	p. 241
ASF	Name of IAM	p. 111
ASU	Air Separation Unit	p. 177
AUS	Australia	p. 115
BAU	Business as Usual	p. 33
BOF	Blast Open Furnace	p. 157
CCS	Carbon Capture and Sequestartion	p. 3
CDIAC	Carbion Dioxide Information Analysis Center	p. 23
CES	Constant Elasticity of Substitution (Production Functions)	p. 54
CGE	Computable General Equilibrium Model	p. 39
CH_4	Methane	p. 10
CO	Carbon Monoxide	p. 183
CO_2	Carbon Dioxide	p. 1
CO2DB	CO_2 Double Database	p. 114
COE	Cost of Electricity	p. 170
CPP	Climate Protection Path	p. 128
DC	Developing Countries	p. 115
DCF	Damage Cost Function	p. 34
DEA	Di-ethanol Amine	p. 161
DIAM	Dynamics of Inertia and Adaptability Model	p. 35
DIC	Direct Internal Combustion	p. 186
DKK	Danish Krone	p. 121
DM	Deutsche Mark	p. 76
EAF	Electric Arc Furnace	p. 205
E&D	Exploration and Development	p. 2

EE	Scenario Name	p. 142
EKC	Environmental Kuznets Curve	p. 18
EOR	Enhanced Oil Recovery	p. 232
EP	End-of-the-Pipe	p. 155
EPRI	Electric Power Resource Institute	p. 170
ESM	Energy System Model	p. 36
ETH	Eidgenössische Technische Hochschule	p. 191
EU	European Union	p. 20
EURO	European Currency	p. 121
FFC	Fossil Fuel Combustion	p. 10
FG	product specific abbreviation	p. 167
FGD	Flue Gas Desulphurisation	p. 2
FT	Fischer-Tropsch Synthesis	p. 205
GAM	Gas Absorption Membrane	p. 168
GAMS	General Algebraic Modelling System	p. 168
GDP	Gross Domestic Product	p. 105
GHG	Greenhouse Gas	p. 8
GMT	Global Mean Temperature	p. 8
GQ	Guiding Question	p. 4
GSM	Gas Separation Membrane	p. 168
GT	Gas Turbine	p. 170
GWP	Gross World Product	p. 15
H_2	Hydrogen	p. 183
HEV	Hicks Equivalent Variation	p. 145
HFC	Hydrofluorocarbons	p. 11
HHV	Higher Heating Value	p. 211
HSM	Hydrogen Separation Membrane	p. 194
HSMR	Hydrogen Separation Membrane Reactor	p. 195
IAM	Integrated Assessment Model	p. 31
IEH	Indirect External Heat	p. 187
IES	Intertemporal Elasticity of Substitution (Utility Function)	p. 49
IGCC	Integrate Gasification Combined Cycle	p. 157
IIASA	International Institute for Applied System Analysis	p. 114
IMAGE	Name of IAM	p. 111
IGT	Institute of Gas Technology	p. 188
IPCC	Intergovernmental Panel on Climate Change	p. 24
KP	Kypto Protocol	p. 10
KRW	Kellogg-Rust-Westinghouse	p. 188
LA	Latin America	p. 115
LBD	Learning by Doing	p. 37

LHV	Lower Heating Value	p. 173
LM	Leakage Mechanism	p. 230
LNG	Liquified Natural Gas	p. 179
LP	Linear Programming	p. 36
LUC	Land Use Change	p. 10
MARKAL	Market Allocation	p. 36
MBEL	Mitsui Babcock Energy Ltd.	p. 188
MCA	Monte-Carlo Analysis	p. 270
MCF	Marginal Cost Function	p. 33
MDEA	Methyl Di-ethanol Amine	p. 161
MEA	Mono-ethanol Amine	p. 161
MERGE	Model for Evaluating Regional and Global Effects of GHG Reduction Policies	p. 41
MESSAGE	Name of IAM	p. 36
MIND	Model of Investment and Technological Development	p. 6
MOVE	Model Validation Environment	p. 29
MP	Montreal Protocol	p. 10
MRTS	Marginal Rate of Technical Substitution	p. 70
N_2O	Nitrious oxide	p. 11
NA	North America	p. 115
NC	New Combinations	p. 155
ND	New Design	p. 155
NGCC	Natural Gas Combined Cycle	p. 170
NO_x	Nitrogen Oxide	p. 2
NONE	Scenario Name	p. 2
O_2	Oxygen	p. 167
O&M	Operation and Maintenance	p. 29
OECD	Organisation for Economic Cooperation and Development	p. 17
OGHG	Other Greenhouse Gas	p. 85
OP	Organisation of Petroleum (Exporting Countries)	p. 115
PC	Pulverised Coal (Power Plant)	p. 157
PE	Primary Energy	p. 15
PFC	Perfluorocarbons	p. 11
PIK	Potsdam-Institute for Climate Impact Research	p. iii
PIM	Perpetual Inventory Method	p. 105
PRENFLO	Name of Gasifier	p. 188
PSA	Pressure-Swing Adsorption	p. 185
PSI	Paul-Scherrer Institute	p. 191
PV	Photo-Voltaic	p. 118
RAG	Ruhrkohle AG	p. 209

R&D	Research and Development	p. 40
RD&D	Research, Development and Deployment	p. 73
REN	Scenario Name	p. 142
RHD	Reboiler Heat Duty	p. 162
ROE	Return on Equity	p. 207
SA	Sequestration Alternative	p. 230
SC	Sequestration Capacity	p. 230
SF_6	Sulphur Hexafloride	p. 11
SimEnv	Simulation Environment	p. 75
SM	Sequestration Mechanism	p. 230
SMR	Steam Methane Reforming	p. 185
SO_2	Sulphate Oxide	p. 2
SOFC	Solid Oxide Fuel Cell	p. 196
SRES	Special Report on Emissions Scenarios	p. 16
SS	Sequestration Site	p. 230
ST	Steam Turbine	p. 170
TAR	Third Assessment Report (of IPCC)	p. 123
TCF	Total Cost Function	p. 34
TWA	Tolerable Windows Approach	p. 25
UGS	Underground Gas Storage	p. 231
UK	United Kingdom	p. 12
UNFCCC	United Framework Convention on Climate Change	p. 8
US	United States (of America)	p. 20
USA	United States of America	p. 34
WBGU	Wissenschaftlicher Beirat Globale Umweltveränderungen	p. 97
WE	Western Europe	p. 115
WWII	World War II	p. 107
ZECA	Zero Emission Coal Alliance	p. 159

Chapter 1

Carbon Capturing and Sequestration

1.1 Economy, Energy and Climate Change

Sustainable economic growth is lively discussed in economic sciences. The discussion *inter alia* aims at identifying factors that could reduce economic growth and even lead to negative growth rates. Scarcity of fossil fuels delivering energy to the economy and the limited potential of the natural system to absorb the by-product of the use of fossil fuels – namely carbon dioxide (CO_2) – are considered as such factors. To reconcile the discussion assume for a moment that fossil fuels are the only energy source.

Suppose that fossil fuels are plentiful. If the natural system is able to absorb large amounts of CO_2, then there is simply no problem to sustainable development regarding fossil energy use. If the natural system is assessed to have a low absorbing capacity of CO_2, then the problem is that the use of fossil fuels is limited in order to avoid negative environmental effects. Limitations on the emissions of CO_2 lead to negative economic impacts depending on the flexibility of the economy to substitute fossil fuels. This frames a fossil fuel rich, atmosphere scarce economy.

If fossil fuels are assessed to be scarce, then the problem of climate change is solved automatically because there are not enough fossil fuels to pollute the atmosphere. In that case the problem of sustainable development is one of fossil fuel scarcity. This economy is framed as a fossil fuel poor economy.

In fossil fuel poor as well as fossil fuel rich, atmosphere scarce economies the relationship of energy and economy is crucial. In these settings sustainable growth is achievable, if the economy is able to substitute energy by capital and labour or to develop a production structure that allows to direct technological change towards fossil fuel saving technologies. If sustainable growth is not achievable the distribution of less growing economic output would be directed to fossil fuel suppliers at the expense of labour and capital.

The energy problem could also be framed as one in which economic acteurs are additionally able to increase the amount of fossil fuels through exploration and development (E&D), improvements of mining technologies and the deployment of new energy technologies. The solution of fossil fuel scarcity during the 1970ies has been mainly one of E&D, substitution and saving. Although considerable efforts have been undertaken to develop renewable and nuclear energy sources, the global energy system still depends heavily on fossil fuels. Moreover, the nuclear fission strategy failed *inter alia* to develop reliable breeding technologies to overcome the problem of uranium scarcity; nuclear fusion is unlikely to become available before 2050. Saving and substitution have made a contribution towards an increasing energy productivity, but growth of population and economic activity exceeded that, which leads to increasing fossil energy use and CO_2 emissions.

The historical evidence suggests that fossil fuels will remain the back-bone of the global energy system, although renewable energy technologies exhibit steady cost reductions and growth rates of deployment. Fossil fuels are easy to use, the reserve estimates promise huge amounts and the energy system related infrastructure is locked-in in fossil fuels. These are not good *news* for the climate system because it indicates increasing CO_2 emissions.

During the discussion of fossil fuel scarcity another problem became evident: local and regional air pollution mainly due to sulphur dioxide (SO_2) and nitrogen oxides (NO_x) emissions from fossil fuel use. This problem has mainly been solved by cleaning the emissions of fossil fuels using flue gas de-sulphurisation (FGD), catalysts etc. This has been economically meaningful because cleaning fossil fuels has been less costly than doing without.

Some scientists of energy, environment and economy see this as one step of a deep-lying process: as the economy grows the energy demand increases, which leads to environmental problems that act on ever larger scales of space and time. Since fossil fuels remain the energy of choice that lead to these environmental problems, the task is to reduce the corresponding emissions by cleaning fossil fuels. From this point of view de-carbonisation of fossil fuel emissions is a natural step that has been preceded by FGD. The main differences are technical and are related to the physical properties of the pollutant and the amount of removed pollutants that have to be treated.

Removing CO_2 instead of emitting it into the atmosphere is called carbon capture. Sequestration means that the captured CO_2 has to be removed by a process to some place, from where it does not leak into the atmosphere. This leads to the term carbon capture and sequestration (CCS). Carbon capture is a technical process that requires considerable amounts of capital and energy. Several approaches are already discussed. Sequestration of CO_2 in deep-lying geological formations or the deep ocean are discussed alternatives. Ocean sequestration is considered to be a leaky alternative and itself could lead to environmental damages. Sequestration in geological formations – considered in this thesis – seems to be less risky and easier to handel from an administrative point of view, since avoided CO_2 emissions have to be accounted in some way.

Although the historical evidence is in favour of fossil energy carriers, scenarios on future development of energy and economy see the peak of fossil energy use as late as the middle of the 22nd century. Due to fossil fuel scarcity the global energy system has to switch to alternative sources and technologies of energy production to support economic growth. Therefore, the historical experience of using and cleaning fossil fuels is limited – more or less – by the scarcity of fossil energy carriers. At some point in time renewable energy sources are considered mature enough to enter the energy system at rapidly growing market shares.

Although fossil energy carriers are scarce, the corresponding CO_2 emissions without CCS would be a multiple of the CO_2 actually present in the atmosphere. This is considered to possibly lead to catastrophic changes of the world climate.

CCS and renewable energy are two alternatives to address the climate problem from the energy supply side. Aiming at stabilisation of the world climate the major problem of the renewable energy strategy is that their pre-mature introduction would require enormous efforts in order to decrease the costs to the competitive level. The corresponding reduction of energy supply could lead to economic losses that are unbearable, although they are temporary. The use of CCS is considered to enhance the supply of clean energy and therefore to overcome the energy supply shortage. The costs of carbon capture, possible leakage of CO_2 and the deceleration of investment related cost reductions of renewables question this option.

This leads to the main question of this thesis: is CCS an option to buy time in order to shift the climate induced transition to a renewable based energy system? The question assumes that the shift towards renewables is inevitable in the long run, if fossil fuel scarcity induces this transition. The pressure from the climate system leads to a pre-mature transition and CCS could defer this pre-maturity towards its *natural* timing.

1.2 Guiding Questions

The thesis is organised around six guiding questions (GQ) that will be introduced next:

1. ***Is CCS an option to buy time?*** This question aims at the role of CCS in a long-term climate protection strategy whether it is temporary or long-term solution or used at all.
2. ***Is the result robust?*** This question aims at the changes of model outcome 8under varying exogenous model parameters.
3. ***What is the relationship between CCS and other CO_2 emission mitigation options?*** This question asks for an integrated emission mitigation strategy that takes account of several options.
4. ***What are the opportunities and risks of pursuing CCS?*** This question is related to an assessment of the economics and technology. It is addressed by an literature review.
5. ***What is an appropriate way to model CCS?*** This question asks for the modelling and integration of CCS into a given model framework.
6. ***What is an appropriate model framework for the assessment of climate protection strategies in general and CCS in particular?*** This question is related to the scope and level of detail of a model framework. It aims at assessing model frameworks and provides a plan for further research.

Table 1.1: Overview of the thesis by guiding questions and chapters. Crosses × indicate that a chapter deals with a guiding question.

	GQ 1 Option to buy time	GQ 2 Robust result	GQ 3 CCS & other options	GQ 4 Opportunities & risks	GQ 5 Modelling CCS	GQ 6 Frame-work
Ch. 2 Setting			×		×	×
Ch. 3 Ramsey						×
Ch. 4 *MIND1.0*	×		×			×
Ch. 5 CCS details				×		
Ch. 6 CCS module					×	×
Ch. 7 Results	×	×	×			
Ch. 8 Conclusion	×	×	×	×	×	×

1.3 Plan of the Study

The thesis has a considerable scope in terms of the number of pages as well as the variety of issues addressed. Therefore, a guide for reading is given precedence of the main body of the thesis.

The remainder of the thesis is structured in seven chapters. Tab. 1.1 summarises the thesis by combining the guiding questions and the chapters.

- ***Setting the Scene*** Ch. 2 introduces the problem of climate change and options to deal with it. It encloses the overall set of options to CO_2 emission mitigation options. The issue of different data sources and criteria on model behaviour is discussed. Afterwards modelling approaches are introduced that assess CO_2 emission mitigation options with a particular focus on CCS. It is concluded that hybrid models of endogenous economic growth with an integrated climate model and explicit representation of the energy system are the most appropriate framework to assess CO_2 emission mitigation options as well as to integrate and assess CCS. This chapter deals with GQ 3, GQ 5 and GQ 6.

- ***The Ramsey Model*** Ch. 3 introduces the Ramsey model of optimal consumption-saving decisions that is the back-bone of the hybrid model framework. The model, the analytical solution and the interpretation are recapitulated. After a discussion of the suitability of the Ramsey model to assess climate change three extensions of the Ramsey model are developed. These extensions serve as a basis to discuss issues of integration of stock pollution, the integration of the energy system and endogenous growth. This discussion contributes to GQ 6.

- ***MIND1.0*** Ch. 4 introduces the Model of Investment and Technological Development Version 1.0 (*MIND1.0*) model structure and the assumptions of exogenous model parameters. This model integrates the main CO_2 emission mitigation options. Within the model framework an exogenous path of CCS is assumed that peaks in the middle of the 21^{st} century in order to assess the potential to reduce the economic losses of CO_2 emission mitigation (GQ 1) and the relationship of CCS to other options (GQ 3). Several problems of the modelling framework are also discussed (GQ 6).

- ***Techno-economics and Geology of CCS*** Ch. 5 introduces the techno-economic and geological issues of CCS. This chapter provides a detailed introduction and discussion of the CCS option by reviewing the literature. Tt discusses the opportunities and risks of CCS on a broad basis (GQ 4). Moreover, it serves as a basis for the integration of CCS into the *MIND* model.

- ***Modelling CCS*** Ch. 6 introduces the approach for modelling and integration of CCS in order to set up the model *MIND1.1.* It discusses the main advantages and drawbacks of the approach. This chapter contributes to GQ 5 and GQ 6.

- ***Results*** Ch. 7 presents the results of *MIND1.1.* It is found that also as endogenous modelled CCS is an option to buy time, but the robustness of this finding is questionable, if exogenous parameters are varied. Therefore, the model is analysed using sensitivity and Monte-Carlo analysis. The analysis reveals that the result is robust against changes of several parameters over broad ranges. The robustness becomes questionable for variation of parameters that affect the growth of the potential use of renewable energy. This chapter is a main contribution to GQ 1, GQ 2 and GQ 3

- ***Conclusion and Further Research*** Ch. 8 summarises the thesis and draws conclusions considering the model results as well as the discussion related to risks and opportunities of CCS. The CCS option is discussed in relation to other CO_2 emission mitigation options. Moreover, it discusses problems regarding the modelling framework and the integration of CCS, which provides an overview of directions of future research.

Chapter 2

Setting the Scene

2.1 Introduction

This chapter serves to introduce the problem of climate change and alternative approaches to model economy, energy and climate interrelationships that are used to assess climate change mitigation strategies.

In Ch. 2.2 the problem of climate change is introduced along the lines of a cause-effect chain. This allows to identify three fundamentally different options to deal with the climate problem. This thesis deals with one of these options, namely CO_2 emission mitigation.

In Ch. 2.3 the sources and kinds of anthropogenic emissions are introduced of which CO_2 is found to be the most important. Since CO_2 emission mitigation by CCS is the primary focus of this thesis a closer view is taken on CO_2 emissions that are considered to be appropriate for this option.

Ch. 2.4 introduces a portfolio of CO_2 emission mitigation options including CCS. The options are described, discussed and related to past experience.

Ch. 2.5.2 discusses the problem of multiple objectives and strategy selection. Since climate change is one objective among others it is necessary to relate decisions of emission mitigation to broader economic relationships that might be affected.

Ch. 2.6 discusses different sources of data for the assumption of exogenous model parameters and criteria on the qualitative and quantitative behaviour that a model should reproduce.

Ch. 2.7 introduces the four main modelling approaches used in the scientific

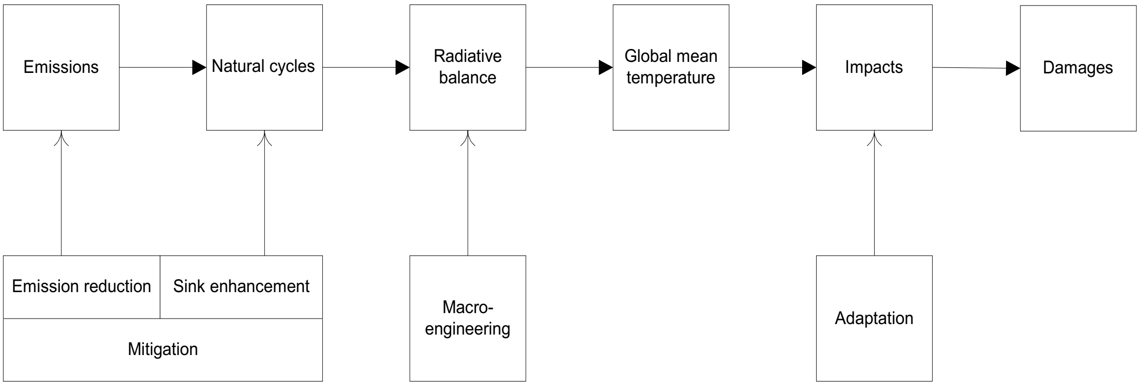

Figure 2.1: Cause-effect chain of climate change and options reducing impacts.

literature to assess CO_2 emission mitigation. It discusses the main advantages and drawbacks of the several approaches.

Ch. 2.8 summarises the section and discusses the most important conclusions.

2.2 Cause-Effect Chain of Climate Change

In the following the essential features of climate change are given as it is of interest for this thesis. The framing focuses on anthropogenic changes of the climate system. It serves as a framework to structure the main options for dealing with climate change.

Anthropogenic climate change can be thought as a cause-effect chain that is illustrated in the top row of Fig. 2.1. The anthropogenic emissions of climate relevant substances from the socio-economic system cumulate in the atmosphere according to natural cycles like the carbon cycle. These substances alter the radiative balance of the earth system, which leads to a delayed change of the global mean temperature (GMT). Increasing GMT might lead to negative impacts on the socio-economic systems. The adaptative capacity of the socio-economic system to deal with climate change impacts implies the damages.

Art. 2 of the United Nations Framework Convention on Climate Change (UNFCCC) aims at stabilising greenhouse gas (GHG) concentrations at a level that prevents dangerous interference with the climate system and therefore aims at the atmospheric composition. A broader approach would target the stabilisation of the GMT or the improvement of the capacity to adapt to climate change.

The main options for addressing climate change can be distinguished into three different groups shown in the lower row of Fig. 2.1. First, mitigation options address the net emissions of climate relevant substances. This includes the gross emissions from anthropogenic sources as well as the enhancement of sinks to remove climate relevant substances from the atmosphere. Second, the direct control of the radiation balance of the earth through macro-engineering. This includes measures like placing reflectors or scatters in the stratosphere or in the orbit between the earth and the sun reducing the solar radiation incident on the earth (Govindasamy and Caldeira (2000) and Teller et al. (1997)) or increasing the albedo by changing the optical properties of the earth's surface; see e.g. Hoffert et al. (2002, p. 986) for an overview. Third, adaptation aims at appropriate reactions to climate change. This includes the building of dams, change of agricultural practises as well as institutions that manage compensation of climate related damages and risks.[1]

This thesis deals with CO_2 emission mitigation options aiming at the stabilisation of the GMT. Other options introduced above are not considered.

2.3 Climate Relevant Atmospheric Substances

The atmosphere is a mixture of gases and particles that influence climatic conditions on earth. Concentrations of some of the gases and particles alter the radiation balance of the atmosphere. There are two different groups of climate relevant emissions that have been identified to be relevant for climate change and originate from anthropogenic source: greenhouse gases GHG and aerosols. These climate relevant substances differ with respect to the sign of influence on the radiative forcing as well as the lifeptime in the atmosphere. This latter feature also implies differences with respect to the regional scale of changes of the radiative forcing; i.e. the shorter the residence time in the atmosphere, the more limited is the spatial impact on radiative forcing around the emission source. Substances with long atmospheric lifetimes are considered to be well mixed at the global scale.

This thesis focuses on emission mitigation of the GHG CO_2 from fossil fuel com-

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[1] An additional option discussed in some studies is called terraforming; see Fogg (1998) for a review of Mars related terraforming. This aims at creating habitable conditions equivalent to earth on planets other than earth through geo-engineering like triggering a run-away greenhouse effect. Since these concepts would need at least tens of thousands of years they are out of the focus of this thesis.

bustion and the corresponding aerosols. Although the model used in this thesis does not allow the mitigation of all types of climate relevant emissions, the corresponding emissions have to be taken into account as boundary conditions.

The sources of CO_2 emissions are of particular interest for this thesis because CCS is considered to be a mitigation option for large scale point sources. Hence, the amount of CO_2 emissions originating from such sources are of particular interest, if the CCS option shall be considered.

In this section the types and sources of all GHG emissions are introduced in Ch. 2.3.1. Then the view is put on CO_2 emissions and focus on the CO_2 emissions of large point sources in detail in Ch. 2.3.2. Ch. 2.3.3 introduces aerosol emissions and the link to fossil fuel combustion.

2.3.1 The Types and Sources of Greenhouse Gases

The role of GHGes for climate change have been understood quite well so far. GHG absorb *outgoing* infrared radiation reflected by the earth's surface, which increase the radiative forcing and this in turn leads to an increase of the GMT. Without any GHG in the atmosphere the GMT would be -19°C; presence of naturally occurring GHGes increase the GMT to 14°C.

There are several GHGes that are considered to be relevant for climate change. Six of these gases are considered within the Kyoto Protocol (KP) to the UNFCCC. Additional GHGes are considered within the Montreal Protocol[2] (MP) that deals with the so called ozone hole. Moreover, there are several gases that control the atmospheric chemistry of GHG, but are no GHG. The following list contains the six GHGes under the KP; see Ehhalt and Prather (2001, p. 248 – 254):

1. ***Carbon dioxide CO_2*** has been identified as the most important GHG because it contributes the largest share to the anthropogenic increase of radiative forcing and grows fastest. Anthropogenic sources of CO_2 emissions are fossil fuel combustion (FFC), cement production, traditional biomass combustion and land use change (LUC).[3]

2. ***Methane*** (CH_4) is the second most important GHG, although the lifetime is only about a decade. The anthropogenic sources are numerous: life stock

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[2] It contains chlorofluorocarbons, hydrochlorofluorocarbons and others.

[3] Modern biomass combustion is not considered as a contribution to the net CO_2 emissions.

in the agricultural sector, rice production, oil and natural gas extraction and transportation, combustion of biomass, landfills, coal mining and sewage; see also Chesnaye et al. (2001).

3. ***Perfluorocarbons*** (PFC) is a group of GHG that does not occur in natural cycles without anthropogenic emissions and have very long lifetimes of more than 10000 years. The sources are semi-conductors, aluminium production etc.; see also Harnisch et al. (2001).

4. ***Sulphur hexafloride*** (SF_6) is characterised by very long atmospheric residence time of about 3000 years. SF_6 stems exclusively from anthropogenic activities and the sources are the production of windows, magnesium and tires, gas insulated switch gears, etc.; see also Harnisch et al. (2001).

5. ***Nitrious oxide*** (N_2O) stems to the largest part from rice production and to a minor share from industrial processes; see also Gale et al. (2001).

6. ***Hydrofluorocarbons*** (HFC) is used in refrigerators and air-conditioners having atmospheric lifetime between decades and centuries. Some HFCs are also controlled by the MP.

Fig. 2.2 gives an overview of the emissions of all GHG in 2000 on the basis of carbon equivalent emissions using the concept of global warming potentials. This concept aggregates the different features of GHGs to allow comparison of the emissions on a common basis; see Ramaswamy (2001, p. 359). The emissions from cement production are contained in the FFC category and traditional biomass combustion is subsumed under LUC.

The emissions of CH_4 and nitrous oxides contribute considerably to the total GHG emissions. Nonetheless, CO_2 emissions is by far the largest single source. In turn FFC is much larger than LUC related CO_2 emissions.

The GHGes lead to an increase of the radiative forcing. Ramaswamy (2001, p. 351) assessed the increase of radiative forcing in 1998 due to the anthropogenic induced increases of GHG concentrations at $2.4\frac{\mathrm{W}}{\mathrm{m}^2}$.

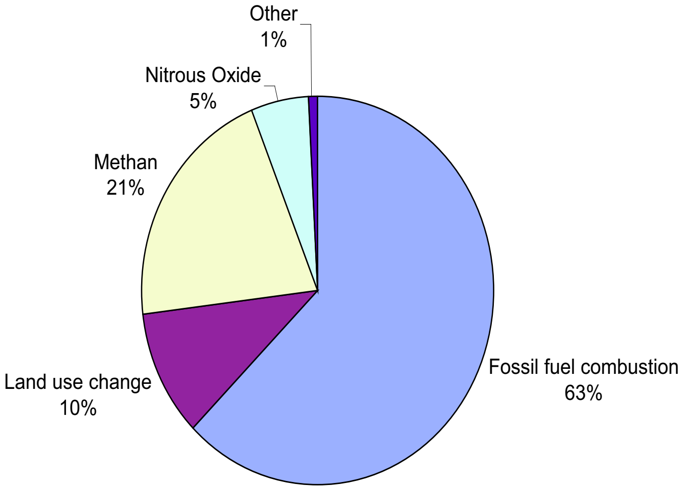

Figure 2.2: Anthropogenic emissions of GHG in 2000 using global warming potentials. The total carbon-equivalent GHG emissions have been 10.6GtC. Source: based on Ehhalt and Prather (2001, p. 244 – 254).

2.3.2 CO_2 Emissions from Fossil Fuel Combustion

In the following the focus on the sources of CO_2 emissions from FFC. They are limited to large point sources that are differentiated by industrial sectors and by region because CCS is an option that is thought to be applied at large scale industrial operations mainly in developed countries.

Gale (2002) focuses on the emissions from 14641 single industrial CO_2 emission sources worldwide. These accounted for 3.67GtC CO_2 emissions in 2000; this is 55% of all FFC. The study distinguishes these emissions by region and type of industrial use. The corresponding figures are given in Fig. 2.3.[4]

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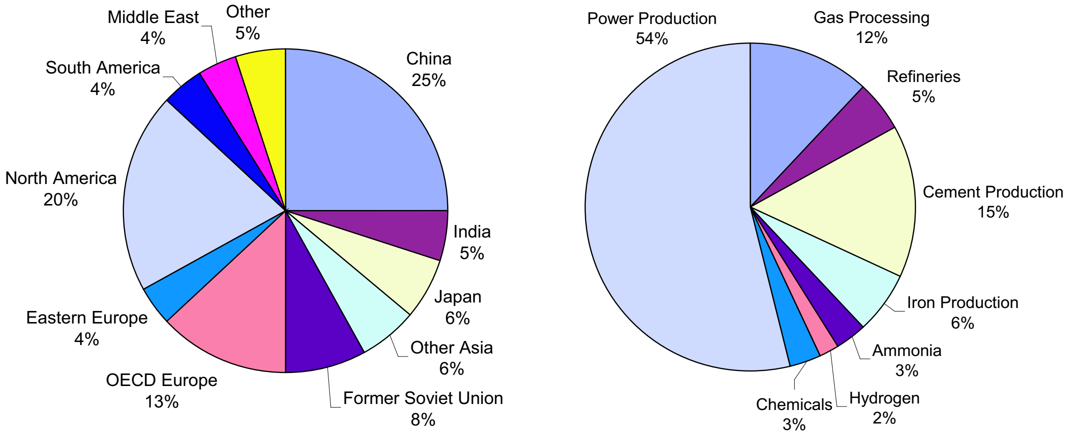
[4] The numbers in that figure are not without problems. The emissions of China from large point sources with 0.92GtC are very high. BMWi (2003, p. 16) reports 0.75GtC for Chinas total emissions in 2000. The Chinese statistics are known to be questionable; e.g. the increase of coal use in the statistics has been 28% from 2001 to 2002; see BP (2003, p. 33), which comes with an increase of CO_2 emissions of 0.17GtC; see BMWi (2003, p. 16). For comparison, the total CO_2 emissions in Germany in 2000 have been 0.25GtC and in the United Kingdom (UK) also 0.17GtC; see BMWi (2003, p. 16). Moreover, the emissions from cement plants also seem high. The figure implies 0.55GtC emissions from cement plants. According to Hendriks et al. (1998) and Thambimuthu et al. (2002, p. 32) the global cement related carbon emissions in 1994 have been 0.3GtC. The numbers include all emissions from cement production; i.e. calcination and fossil fuel use.



(a) By region

(b) By industry

Figure 2.3: CO_2 emissions of large point sources by region and industry. Source: Gale (2002, p. 17).

CO_2 emissions from large scale industrial sources cover a considerable share of the total CO_2 emissions. The major source are power plants, which account for more than half of these emissions. There are some processes that are interesting for carbon capture because they offer low capture costs; see Ch. 5.1. This includes hydrogen production, ammonia synthesis, chemical production and gas processing.

The regional distribution of CO_2 emissions shows that a considerable share is located in industrialised countries. Some 35% of that figure are within the countries that already have ratified the Kyoto protocol.

2.3.3 The Special Role of Aerosol Emissions

The role of aerosols is by far less well understood compared to GHGes. Aerosols are particles like dust or sulphates. They remain in the atmosphere for short time periods of less than a year and are therefore not well mixed. Aerosols have direct and indirect effects on the radiative forcing.

The direct effect is the absorbtion of *incoming* solar radiation, which decreases the radiative forcing and in turn decreases the GMT. This implies that aerosols lead to short-term regional cooling effects. But there are also some aerosols – like black carbon – that are considered to lead to increases of the GMT. The indirect effect of aerosols is related to the formation of clouds, which in turn alter the reflection of incoming solar radiation, which decreases the radiative forcing.

Aerosols from anthropogenic sources considered with respect to the radiative forcing are those related to the combustion of fossil fuels and biomass. Penner (2001, p. 291) assessed the actual reduction of radiative forcing through the direct effect of aerosols from fossil fuel combustion in the range $0.1 - 1.0\frac{\mathrm{W}}{\mathrm{m}^2}$ and from biomass combustion in the range $0.1 - 0.5\frac{\mathrm{W}}{\mathrm{m}^2}$.

West et al. (1997) assessed the effect of aerosols within an integrated climate-economy framework. They found that various aerosol emissions are compatible with a particular energy scenario and that in high aerosol scenarios especially the Northern hemisphere is affected by the cooling effect. The computations indicate that the increase of the mean temperature of the northern hemisphere is 0.7°C higher than in the southern hemisphere in climate protection scenarios.

The cooling effect of anthropogenic aerosol emissions from fuel combustion can not be seen as an option for climate change policies. The aerosols – espec. sulphate emissions and carbon-particulate matter – lead to considerable local and regional health and environmental effects; see WBGU (2003, Ch. 2).

2.3.4 Summary

There are several substances emitted into the atmosphere from various sources with different characteristics. CO_2 emissions from large scale industrial sources represent a considerable share of all anthropogenic GHG. The warming effect of long-living GHGes is partially offset by short-lived aerosols that are a by-product of fossil fuel and biomass combustion.

2.4 The Options of CO_2 Emission Mitigation

2.4.1 Introduction

This thesis focuses on CO_2 emissions mitigation options that could be achieved using various options. These options can be structured using the Kaya-identity; see Kaya (1990). The Kaya-identity is a decomposition of the atmospheric CO_2 emissions ($CO_{2,\mathrm{atmo}}$) during a period from FFC into several basic determinants. For this thesis an extended version of the original Kaya-identity is used:[5]

$$\mathrm{CO}_{2,\mathrm{atmo}} = \frac{\mathrm{CO}_{2,\mathrm{atmo}}}{\mathrm{CO}_2} \cdot \frac{\mathrm{CO}_2}{\mathrm{PE}} \cdot \frac{\mathrm{PE}}{\mathrm{GWP}} \cdot \frac{\mathrm{GWP}}{\mathrm{POP}} \cdot \mathrm{POP}. \tag{2.1}$$

Explanation starts with the most right hand term:

1. ***POP*** is the population that is an indicator for the size of the overall economy; see Ch. 2.4.2.

2. ***GWP/POP*** is the per-capita income, where GWP is the global world product, and describes the level of economic activity; see Ch. 2.4.3.

3. ***PE/GWP*** is the energy intensity that characterises the primary energy (PE) needed to produce a unit of GWP; see Ch. 2.4.4.

4. $\boldsymbol{CO_2/PE}$ is the carbon intensity, which describes the CO_2 emissions per unit of PE used; see Ch. 2.4.5.

5. $\boldsymbol{CO_{2,atmo}/CO_2}$ is the carbon emission intensity and is the fraction of all produced CO_2 that is emitted into the atmosphere. If CCS is applied it is less than one. This factor has not been considered in the original Kaya-identity.

The (extended) Kaya-identity is a heuristic tool that helps to structure CO_2 emission mitigation options because they are related to the determinants of CO_2 emissions into the atmosphere. A problem related to this identity is that the factors are not independent; e.g. carbon capture requires additional PE and therefore lowering the carbon emission intensity leads to increasing energy intensity.

The following discussion relates the determinants of CO_2 emissions to options of CO_2 emission mitigation. The discussion includes a general assessment of the CO_2 mitigation options and past experience as well as the most important interrelationships between the determinants.

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[5] Taking the logarithm of the identity and computing the total derivative with respect to time gives the identity in growth rates. On the left hand side are the growth rates of atmospheric CO_2 emissions and on the right hand side is the sum of the growth rates of the determinants of CO_2 emissions.

2.4.2 Population

Lowering the growth of atmospheric CO_2 emissions through population control aims at reducing the fertility rate. This is related to at least four issues.

The first issue is related to the problem that a normative statement aiming at the best outcome of the individuals of a population should consider the number of individuals as given or as a variable that could be influenced. From my point of view this question cannot be decided on the ground of scientific arguments, because this would require to answer the question whether one can derive an optimal solution of the aggregate welfare of individuals by excluding some individuals.

The second issue is related to the assessment of policies that would be necessary to reduce the fertility rate, if one accepts the use of population control. Without going into details the negative impacts of population control as well as the significance of such policy intervention into the privacy of individuals seem not to be justified by the impacts of climate change and the availability of alternative options.

The third issue is related to the interdependency with other determinants of the Kaya-identity, espec. the per-capita income. This phenomenon discussed as demographic transition, which proposes that economic growth decreases fertility rates and increases life-expectancy, which implies a temporarily growing population; see Nakicenovic and Swart (2000a, p. 192 – 200). This suggests to represent that link in models of long-term economic growth. Nakicenovic and Swart (2000a, p. 112 – 113) propose to deal with this phenomenon in models by combining the exogenous assumptions of population growth, economic development and other parameters based on expert knowledge in order to formulate consistent scenarios.[6] Murota and Ito (1996) assess the option of accelerating economic growth to decelerate population growth endogenously by in order to reduce CO_2 emissions.

Fourth, the link between population growth and economic development is the relationship between population and labour force. Models used to assess CO_2 emission mitigation assume a constant ratio between population and work-force, hence,

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[6] For example, the Special Report on Emission Scenarios (SRES) scenarios of population are related to economic development. The high population A2-scenario is characterised by slow economic growth and low regional income convergence. The low population A1 and B1-scenarios are characterised by high and medium economic growth, respectively, and considerable regional income convergence. This is in accordance with the empirical finding that lower income levels tend to favour higher fertility rates. See Fig. 4.5 on p. 99 for the scenarios.

ignoring important phenomena of demographic development and its implications on the amount of labour and the redistribution of income. There are at least two points to note, which are not yet addressed in studies on model climate change:

1. ***Aging*** The aging society in OECD countries[7] implies a smaller labour force, while the number of retired persons increases. The problem will become most important, when the so-called baby-boomer generation will retire. This will lower the labour force considerably and increase the need for redistribution of income, because these people are entitled with claims on pension funds; see Fougere and Merette (1999) and Stiller (2000) for studies on several OECD countries.[8] This issue is related to energy and climate protection strategies, because income redistribution competes with saving that is need to finance investments in new technologies.

2. ***High fertility countries*** Several low income countries exhibit high fertility rates. Since increased household size at low income levels is in conflict with child education, these economies might decrease schooling in order to increase household income. The short-term behaviour might hamper the process of income convergence in the long run.

In summary, population control is indefensible on scientific grounds, the related instruments are highly questionable and the effect on emissions is unclear. However, it is questionable to ignore the interrelationship between demographic development and per-capita income that shall be addressed in future modelling efforts. Although the structure of demographic development is changing over long time scales, the population number should be assumed exogenously in models that address normative questions. For a broader discussion see e.g. O'Neill et al. (2001, Ch. 2, 4 and 6) and Simon (1996, Ch. 15 – 18 and p. 578 – 616).

2.4.3 Per-Capita Income

The option of controlling the atmospheric CO_2 emissions via per-capita income aims at decreasing growth of production factor use or the growth of labour productivity.

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[7] OECD is Organisation of Economic Cooperation and Development.

[8] Up to my knowledge there are no studies on aging in China. This is worth to note since population control policies lead to an aging China at a considerably lower income level than OECD countries.

Proponents of this option relate the arguments to issues of life-style and critique of mass-consumption society. In this view high constant economic growth rates give rise to a myriad of problems like individual isolation, health problems and dissatisfaction; see e.g. Umweltbundesamt (1997). Moreover, the material basis of economic growth is exhausted at a too rapid rate, which would increase problems in the long run; see Koopmans (1974). In general, higher emissions are seen as one indication of a deeper lying problem.

Two different kinds of critique question this option. The first kind of arguments is based on welfare considerations and the second kind considers arguments related to the dynamics of production processes.

Welfare arguments are related to social conflicts in general and the low income levels in developing countries in particular. Economic growth is seen as a way of solving distributional conflicts by increasing the total income that has to be distributed. Moreover, the average income levels in developing countries are at a level that is too low to provide a valuable life for all individuals, even if the total income is distributed equally. Therefore, the option is seen to lead to too serious economic impacts compared to the benefit from reduced environmental damages. This argument questions the political feasibility of this option; see e.g. Edenhofer et al. (2004c).

Arguments considering the dynamics of the production process are related to the relationship between the structure of production and the level and growth of economic activity. The basis of this arguments is that the determinants of the Kaya-identity are not independent from each other.

The feedback relationship between pollution and the level of economic activity in the scientific literature is discussed along the hypothesis of the Environmental Kuznets curve (EKC).[9] The EKC hypothesis says that there is an inverted U-shape relation between the level of affluence and the level of pollution of an economy. A variety of arguments regarding the EKC-hypothesis can be found in the literature; see e.g. Brock and Taylor (2004), Copeland and Taylor (2004), Deacon and Norman (2004), Gerlinger (2004), Stern (2003) and Reusswig et al. (2004). Ch. 3.6.1 provides a contribution to the EKC discussion on theoretical grounds.

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[9] Originally, the negotiations of the North American Free Trade Area initiated the discussion that was related to trade in products with differing environmental pollution characteristics and regional pollution problems.

Different from that increasing the economic growth rate would increase the turnover of physical capital stocks, which in turn leads to accelerated replacement of older – hence inefficient – production technologies. Pearce and Atkinson (1993, p. 106) found that less developed countries are characterised by low depreciation and savings rates of physical capital, while the depreciation rate on natural capital is low. The situation is completely different in developed countries: depreciation of physical capital and savings rates are high and depreciation rates of natural capital are low. Moreover, accelerated growth can contribute to the development of less polluting technologies through endogenous technical change, which will be treated in Ch. 4.

In summary, reducing CO_2 emissions through the reduction of economic growth appears to lead to serious distributional conflicts and might reduce the ability of the economy to foster structural change, which in turn decreases the growth of energy productivity.

2.4.4 Energy Intensity

Reducing the energy intensity of an economy aims at substituting the use of energy inputs to produce economic output by other production factors, structural change of the composition of the aggregate economic output as well as increasing the efficiency of energy use. The option addresses increasing the productivity in terms of primary energy units per value units of economic income, which includes increasing the productivity in terms of primary energy units per unit of physical output. The broader concept regarding value units allows for qualitative improvements of products and changes in the composition of consumption goods.

Improving energy intensity with respect to physical productivity measures can be found in various production processes. The production sector of pig iron has reduced the energy input per ton by 1.4% p.a. from 1760 to 1990; see Beer et al. (2003, p. 5). The global average conversion efficiency of electricity production in coal fired power stations increased from 29% in 1971 to 32% in 2000; see Moomwa and Moreira (2001, p. 238). The leading edge technology reaches 47%; the technical potential is assessed up to 55 – 60%.

Improving energy intensity with respect to energy units per value unit is reported for several countries. For example Hamilton and Turton (2002, p. 64) found that the energy intensity in OECD countries decreased by 18% from 1982 until 1997, which is mainly attributed to decreasing energy intensities in the United States (US) and European Union (EU) industry and service sectors. The effect of structural change in the course of economic development has been highlighted in detail by Schäfer (2005). With respect to climate change this option is proposed espec. by Weizsäcker et al. (1999).

An important – yet not comprehensively analysed – issue is the significance of increasing the energy intensity, if the fossil energy system shifts from conventional oil and gas to their unconventional counterparts. The latter sources need higher energy input to extract the fuels and convert them into useable energy carriers; see e.g. BGR (2003, p. 82).

The contribution of reducing the energy intensity to the reduction of CO_2 emissions in the future is disputed. It is without doubt that the energy intensity will decrease, but it is unclear in how far this determinant could be influenced.

2.4.5 Carbon Intensity

Decreasing the carbon intensity of primary energy production aims at substituting primary energy carriers leading to changes in the technologies for energy use and conversion. The option regards substitution among fossil fuels as well as substitution away from fossil fuels towards non-fossil energy carriers.

Substitution between fossil fuels in order to decrease the carbon intensity is most often considered as a shift from coal to gas. The global carbon intensity of fossil fuel based electricity production increased from 1971 to 2000 by 20% due to a higher share of coal; see Moomwa and Moreira (2001, p. 238). The carbon intensity depends also on the choice of various types of coals that exhibit different carbon intensities. The carbon intensity of lignite is about 30% higher than that of hard coal; see BMWi (2003, p. 10 and 16).

Substitution between fossil fuels is not independent from the energy efficiency. Natural gas with a low carbon intensity is a high quality primary energy carrier that allows higher conversion efficiencies than the lower quality energy carrier coal with a high carbon intensity. Therefore, the energy intensity decreases, if – other things equal – the carbon intensity is decreased due to a shift from coal to gas.

Substitution between fossil fuels and non-fossil fuels in order to decrease the carbon intensity is usually considered as a shift towards a higher share of renewable energy sources or nuclear power. The global carbon intensity of electricity production from 1971 to 2000 decreased by 17%; see Moomwa and Moreira (2001, p. 238). The global carbon intensity decreased by 7.4% from 1971 until 1995; see Moomwa and Moreira (2001, p. 178).

A particular problem of assessing the carbon intensity is related to the accounting of primary energy consumption regarding renewable energy sources. The term primary energy consumption suggests that a physical amount of energy is dissipated. This concept is usually tied to the use of fossil energy carriers or nuclear fission. Production of usable energy from renewable sources is by definition not a dissipation of an energy source.

In order to make energy production comparable on the basis of primary energy units, renewable energy sources have to be accounted in some way. There are two different concepts. The first concept equals renewable primary energy with produced usable energy from these sources. The second concept weighs the produced amount of useable energy from renewable sources with a conversion factor that is taken from comparable fossil based energy production to compute the amount of renewable primary energy. In the field of electricity production this is a factor 2.5, if a conversion efficiency of 40% for fossil fuel based electricity production is assumed. The numbers of Moomwa and Moreira (2001) cited above follow the first concept. If the second concept is applied, the improvements of the carbon intensity would be more emphasised, but the effect on the energy intensity is in the opposite direction; see e.g. Enquete-Kommision (2002, Ch. 5).

Reducing the carbon intensity is seen as a major opportunity for the reduction of CO_2 emissions. This is mainly due to the possibility to change the structure of energy supply. However, it is disputed how much energy non-fossil fuels could supply.

2.4.6 Carbon Emission Intensity

Reducing the carbon emission intensity aims at capturing the produced CO_2 in order to avoid the emissions into the atmosphere. Keeping the captured CO_2 away from the atmosphere requires long-term sequestration in leak proof sites. The extended Kaya-identity does not account for delayed emissions, if leakage occurs.

CCS can be thought as a chain of several subsequent process steps:

1. ***Capture*** CO_2 is captured at a point source in highly concentrated form.

2. ***Compression*** The captured CO_2 is compressed as a prerequisite of pipeline transportation and injection.

3. ***Transportation*** The compressed CO_2 is transported via pipeline to a particular location.

4. ***Injection*** The CO_2 is injected into the deep underground, which might require some additional compression.

5. ***Sequestration*** If the location is suitable for long-term sequestration the CO_2 remains in that location. Leakage might occur depending on geological conditions and operation of injection.

CCS is a new technology and it is open to debate how much this option could contribute to the reduction of atmospheric CO_2 emissions. Since this thesis is devoted to CCS, the details will be laid out in Ch. 5.

2.4.7 Discussion

For the sake of a comprehensive discussion two groups of determinants are formed. The first group comprise population and per-capita income termed socio-economic determinants. The second group includes, the energy, carbon and carbon emission intensity called technological determinants.

The determinants of CO_2 emissions had contradicting effects on the the global CO_2 emissions in the past as is shown in Fig. 2.4. On the one hand the technological determinants have had a negative effect on the growth of CO_2 emissions and on the other hand the socio-economic determinants have had a positive effect on the growth of CO_2 emissions. The socio-economic determinants overcompensated the technological determinants, which has lead to a positive growth rate of CO_2 emissions over the 20^{th} century. A detailed discussion is given in Reusswig et al. (2004).

The assessment of options above suggests that controlling the CO_2 emissions via the socio-economic determinants is highly problematic due to ethical and political objections. If these determinants are expected and desired to increase over the course of the 21^{st} century, then the technological determinants have to equal this increase in order to stabilise the emissions and they have to overcompensate the socio-economic determinants in order to lead to decreasing CO_2 emissions. Since

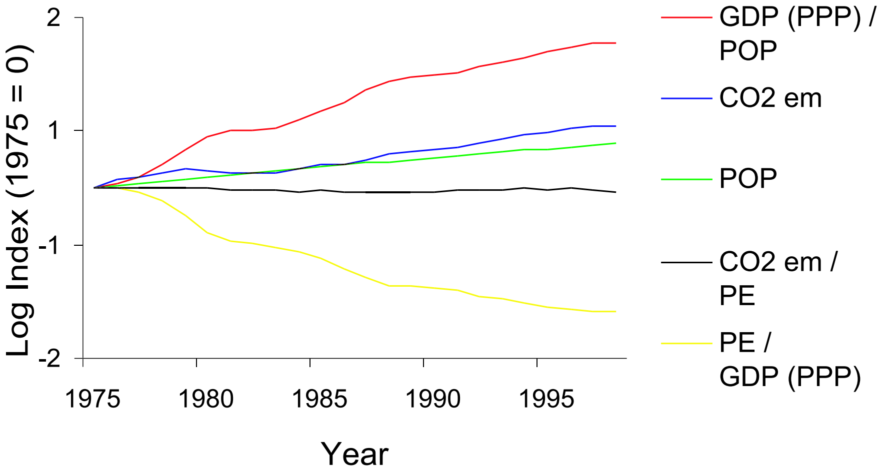

Figure 2.4: Global CO_2 emissions and decomposition of determinants 1975 – 1998 according to the Kaya-identity. Source: computation by Katrin Gerlinger based on data by Carbon Dioxide Information Analysis Center (CDIAC), World Bank and International Energy Agency.

this is beyond historical experience with respect to CO_2 emissions, it is worth to ask which role the technology option regarding the carbon emission intensity could play. There is positive historical experience with respect this option in field of local and regional air pollution like SO_x and NO_x emissions. In several countries these emissions decreased due to policies addressing all three technological determinants.

2.5 Objectives and Strategy Selection

This section introduces the problem to relate multiple objectives (Ch 2.5.1) and to select a particular strategy out of a set of alternatives (Ch 2.5.2). In dynamic problems like climate change the time horizon has to be considered explicitly (Ch 2.5.3).

2.5.1 The Measurement and Relation of Objectives

Decision problems become meaningful in an economic sense, if from a set of alternatives a particular choice has to be made that contributes to one or multiple objectives. This requires the aggregation of these objectives and to relate them to decision variables. Variables that are related to an objective are assumed continuous in this thesis.

There are two approaches to measure the level to which a particular objective is reached. The first approach is to define a continuous function mapping of one or several variables from the system into a scalar measure. The second approach is to define a permissable domain for a variable that the system is not allowed to leave.

In static problems measures aiming at different objectives can be related to another in three different ways: substitutive, complementary and indifferent. In dynamic problems measures aiming at different objectives can be short-term substitutive (complementary) and long-term complementary (substitutive). This is of particular interest for example, if investments are considered that have to be made in on order to develop technologies that support sustainable growth in the long run or the use of fossil energy carriers that support production but lead to future climate change.

There are three points that have to be considered for the aggregation of objectives. First, decision variables can enter the objective function directly. Second, decision variables can affect a objective function through several functional relationships like production functions or the climate system. Third, substitutive objectives could be either aggregated using a function that allows for substitution or the objectives could be ranked. The latter method is known as lexicographic aggregation; see Roy (1952), Chipman (1960), Encarnacion (1964), Encarnacion (1965) and Sinn (1989, p. 59 – 69). Here a decision maker aims to reach a higher order objective without paying attention to lower ranked objectives. If the higher ranked objective is reached, the next lower ranked objective is pursued. Usually, lexicographic objectives are formulated as permissible domains.

Lexicographic preferences are highly disputed in economic theory. It is justified through Kantian ethics that allows for the formulation of absolute values. Moreover, the complexity of the climate system and international law can serve as a basis for the justification of lexicographic objectives; see WBGU (2003, p. 114 – 134) for discussion of that. Nonetheless, the concrete formulation as guardrail or constraints is a normative setting.[10]

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[10] The Intergovernmental Panel on Climate Change (IPCC) states: "Natural, technical, and social sciences can provide essential information and evidence needed for decisions on what constitutes 'dangerous anthropogenic interference with the climate system'. At the same time, such decisions are value judgments determined through sociopolitical processes, taking into account considerations such as development, equity, and sustainability, as well as uncertainties and risk"; see Watson (2001, p. 2)

2.5.2 The Selection of Strategies

The selection of a strategy requires a rule to choose a particular solution from a given set of alternatives. There are at least three different rules for that.

1. ***Optimisation*** choose that element that optimises a scalar objective function. This corresponds to the social optimal solution in economics.
2. ***Equilibrium*** This requires to compute the equilibrium of various agents that pursue their individual objective functions. This is equivalent to the decentralised market solution.
3. ***Tolerable Window Approach*** The subset of alternatives is identified, which is consistent with the permissible domain defined by a set of constraints. This is known as the tolerable windows approach (TWA); see e.g. Bruckner et al. (2003).

The social opimal solution can be compared with the decentralised market solution. Under particular conditions both solutions are equivalent. Economic theory aims at comparing both solutions and to derive statements on the need for policy intervention. Both solutions could be a member of the solution set computed with the TWA. If so, the solutions are consistent with the constraints defined within the TWA. Moreover, the constraint used in the TWA could be imposed in the centralised as well as the decentralised setting.

A special problem is related to the feasibility of a problem, if lexicographic objectives using constraints are defined. If a solution is infeasible, there is no solution that obeys the constraints. The feasibility of such problem is a first important finding for the assessment of a problem. If a problem is infeasible the only way to reestablish the feasibility is either to relax the constraints, to change the model parameters or to allow the use of previously excluded options. Changing the model parameters would only be justified, if this could be reached through appropriate policies.

2.5.3 Time Scales

The problem of time horizon in economic models is intimately connected to the valuation of state variables at the end of the finite time horizon, if the economy is intended to sustain thereafter. The long-term development of state variables has consequences on short-term selection of corresponding control variables. The problem arising from extension of the time horizon is that computing time increases.

Long time horizons improve the assessment of dynamic problems for two reasons. First, a model should take into account the inertia of the climate system because the short-term action has to be consistent with these long-term dynamics. Second, a long time horizon is required, if endogenous technological change is taken into account. Both issues are discussed in the following.

The climate system is mainly characterised by state variables, which response with considerable delay to impulses from increases of CO_2 flows into the atmosphere. It is well known that the GMT approaches its new equilibrium value due to an increase of the atmospheric CO_2 concentration at time-scales up to several centuries; see Hasselmann et al. (1997, p. 358). Moreover, if the CO_2 concentration is reduced to the original level, then the GMT will not decrease to its original level.

These issues of CO_2 concentrations and GMT are related to the assessment of CO_2 emission mitigation. If a model aims at evaluating CO_2 emissions mitigation for the 21^{st} century and accounts for the climate dynamics only until 2100, then it ignores the long-term dynamics beyond 2100. Therefore, the model's time horizon should be extended beyond the time horizon that is of interest for CO_2 emission mitigation so that the longer term consequences are taken into account.

The issue becomes more important for the assessment of CCS, if leakage from geological formations is taken into account. CO_2 that is sequestered in geological formations could leak in subsequent periods and accumulate in the atmosphere. A sound assessment of GHG emissions mitigation has to take into account the effect on the climate system of such delayed CO_2 emissions.

The second reason requiring models with long time horizons is related to technological change. The problem is illustrated using an example of a discrete decision problem given in Tab. 2.1.

If we assume two technical CO_2 mitigation options A and B are available for achieving a moderate CO_2 emission reduction until 2030 and one that prolongs this with more emphasised reduction until 2100. Mitigation option A leads to little costs for small reductions in the first period, but high costs for more emphasised emission reductions in the second period. Mitigation option B leads to relatively high costs in the near-term, but endogenous technological change would induce lower costs in the longer term for the deeper emission reductions.

Table 2.1: Costs for a discrete dynamic decision problem; the values are chosen for illustrative purposes. The order of letters in the first column denotes the sequence of alternative strategies of options; i.e. (A,B) means that option A is chosen in the first period and B in the second.

	2000 – 2030	2030 – 2100	2000 – 2100
(A,A)	1	3	4
(A,B)	1	5	6
(B,A)	2	3	5
(B,B)	2	1	3

The setting suggests that taking into account the emission reduction until 2030 would favour mitigation option A. If the strategy has to be chosen for the entire time horizon, mitigation option B would be chosen in both periods. The higher costs of application in the near-term is an investment that pays-off in the long-term.[11]

Therefore, the assumption of the time horizon has an impact on the choice of mitigation options in the short-term. This clearly favours models with time horizons that are longer than the time horizon for which the strategy should be selected in order to take the full effect of technological change into account.

Optimal control theory (Ch. 3) takes these effects into account by valuation of state variables in the terminal period. The problem is to determine the price of a unit of a particular state variable that is consistent with the long-term solution, but this becomes untractable in complex models with various state variables and complex dynamic processes; Feichtinger and Hartl (1986, p. 19). A solution to this problem is to extend the time horizon of the model far beyond the time horizon that is of interest with respect to the control variables; see Nordhaus (1994) and Lau et al. (2002) on this issue.

2.6 Data and Calibration

The assessment of CO_2 emission mitigation strategies aims at quantitative statements regarding the timing and extent of realising a portfolio of options. Such state-

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[11] The setting could also be thought as a sequential decision process: first, the decision until 2030 is done without taking into account the longer term requirements for emission reductions, which induces to choose option A. In 2030 the choice has to be done until 2100. If the mitigation option B is not improved by application until 2030 it is favourable to choose the static option A again, although it would be optimal to choose option B in the non-sequential setting.

ments require assumptions of exogenous model parameters and model behaviour for which three sources are available that will be treated in the following.

The first source relies on quantitative studies to fit parameters based on empirical data by using regression analysis or validation procedures (see Ch. 2.6.1). The second source is related to techno-economic studies based on engineering studies and economic cost calculation (see Ch. 2.6.2). The third source is related to stylised facts of economic growth, which are a set of empirical regularities that a model should reproduce (see Ch. 2.6.3).

2.6.1 Empirical Studies

There are two different methods to relate exogenous model parameters to empirical data.

The first one is to estimate parameters in econometric models and set the corresponding model parameters to these findings. Usually regression equations are used that are derived from steady state analysis like growth models; for example:

$$y_i^D = \beta_0 + \sum_{j=1}^{n} \beta_j x_{ij}^D + \epsilon_i. \tag{2.2}$$

x and y represent variables, which are assumed deterministic-exogenous and stochastic-endogenous, respectively. The β_j's are the $(n+1)$ parameters, which have to be estimated by minimising the sum squares of the stochastic error-term $\sum_{i=1}^{m} \epsilon_i$. There are m data points, which distinguish time periods or cross-sectional units, e.g. firms, countries etc. Each single i is characterised by a data vector with $(n+1)$ entries, i.e. n entries for x and one for y. Both variables, x and y, represent empirical data, denoted with D for which this is called DD-approach. The major points of interest are (i) whether a model is able to fit the data and if so (ii) which βs are significant and (iii) what their distribution parameters are. This approach does not ask whether the model is able to reproduce the empirical time series.

The second method determines the model parameters by minimising the deviation of the model time paths from the empirical time series data. The set of computed paths y^M of a model G depends on a set of parameters α:

$$y^M = G(\alpha). \tag{2.3}$$

An optimisation algorithm searches for the optimal parameter set α^* that minimises a goodness of fit criterion C that depends on the deviation of y^M from empirical data y^D:

$$C = f(y^D - y^M). \tag{2.4}$$

Here model output is compared with empirical data and therefore called MD-approach. This approach guarantees that a model seeks for the best reproduction of time series data even if the system is far from its steady state. Various model variants can be validated with respect to their ability to reproduce the data. A shortcoming of the MD-approach is that it does not allow the application of statistical test theory that is provided by the Gaus-Markov theorem through the minimisation of the sum of the residual sum of squares; see e.g. Judge et al. (1988, Ch. 5). Moreover, the computational requirements are expensive with respect to computation time.

In this thesis several studies following the DD-approach are reviewed in order to justify exogenous model parameters. The MD-approach will be used for a validation study of a series of endogenous growth models using the newly built model validation environment (*MOVE*) in Ch. 3.6.3.

2.6.2 Techno-Economic Studies

Techno-economic studies on technologies and resource assessments rely on two different types of information. The first type are technical and geological studies on physical characteristics, which could be either taken from ongoing operation, experiments or from computer simulations. The second type are data on costs for investments as well as operation and maintenance (O&M) that are required to install and operate such facilities.

Techno-economic studies are espec. valuable to assess the significance of technologies in the future that are not widely in use today. Since this thesis deals with energy technologies not in use today several techno-economic studies will be reviewed espec. in Ch. 5.

2.6.3 The Sylised Facts of Economic Growth

Stylised facts of economic growth are empirical regularities that have been found in economic time series. Stylised facts are related to prices, growth rates, ratios or shares, but not to absolute quantities. A model should reproduce a set of stylised facts at least qualitatively and – if possible – quantitatively.

Kaldor (1961) introduced a set of stylised facts for developed economies that are near steady state conditions of economic growth. His considerations are related to variables of labour, capital and income. In the following Kaldor's stylised facts as well as two regarding energy are introduced:

1. ***Labour productivity*** Y/L is increasing at a positive growth rate; where Y is income and L is labour.
2. ***Capital coefficient*** K/Y is constant; where K is capital.
3. ***Capital intensity*** K/L is increasing.
4. ***Labour share*** wL/Y is constant; where w is the wage rate.
5. ***Interest rate*** r is constant.
6. ***Energy share*** $p_E E/Y$ is decreasing; where p_e is the price and E the amount of energy.
7. ***Bias of technological change*** induces the labour productivity E/Y to grow at a higher rate than energy productivity E/Y.

The stylised facts 1. – 5. are introduced by Kaldor. The constancy of growth rates, labour share and interest rate imply that the economies growth path satisfies steady state conditions. A discussion can be found in Maußner and Klump (1996, p. 1 – 13).

Stylised fact 6. has been introduced by Smulders and Nooij (2003) and Nordhaus (2004). Stylised fact 7. has been discussed in Edenhofer (1999). Fig. 2.5 shows the bias of technological change for the US in the 20th century: the labour productivity grows fast than the energy productivity.

2.6.4 Discussion

Three different sources of information for the assumptions on exogenous model parameters and the behaviour of models have been introduced. A model should be

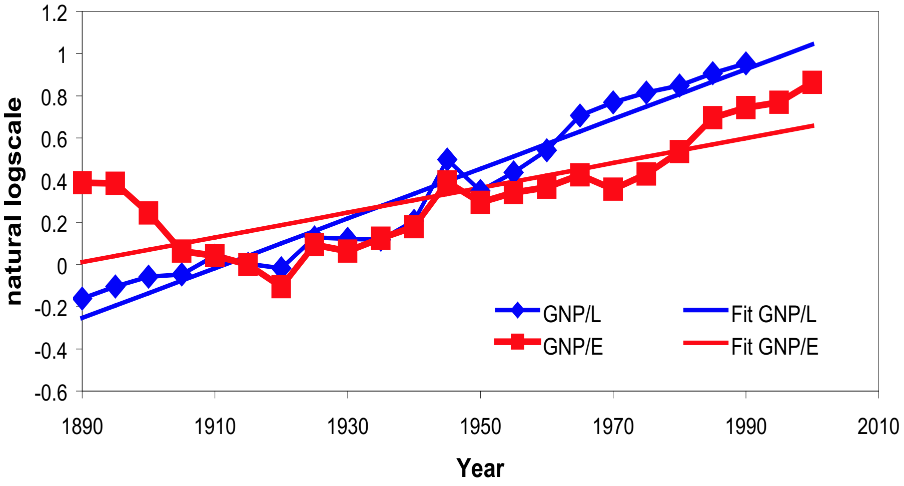

Figure 2.5: Biased technological change towards labour productivity and away from energy productivity in the US for the period 1890 – 2000. The figure contains the linear fits for both time series. Source: computation by Katrin Gerlinger.

based on empirically derived model parameters and reproduce time series of economic growth. This means that the model parameters are in accordance with empirical findings and that the model is well structured.

A great deal of research has dealt with the estimation of parameters using econometric techniques and techno-economic studies. The formulation of sets of stylised facts and building models that reproduce them qualitatively has also been advanced. A lack of research can be identified regarding the validation of models with respect to the question for which parameters a model reproduces a predefined set of economic time series simultaneously. Model validation helps to improve the choice of model formulations as well as to assume parameters that capture the overall dynamics of the economic system.

2.7 The Major Types of Modelling Approaches

2.7.1 Introduction

This subsection introduces modelling approaches that are applied to assess CO_2 emission mitigation strategies known as integrated assessment models (IAM). This denotes models that – in a very broad sense – integrate the knowledge of at least two of the economic, natural and engineering sciences in one framework. Integration means that models – developed by special branches of sciences – are coupled in order to gain insights into the interaction of the various systems; e.g. CO_2 emissions change the climate, which in turn leads to impacts on the economy.

This section introduces the various IAM approaches and the approaches for the integration of CCS. The modelling approaches that will be introduced in the following capture the variety of mitigation options (see Ch. 2.4) in different ways and use different methods for the selection of strategies (see Ch. 2.5.2).

The modelling approaches are different with respect to at least four characteristics that will be considered in the following:

1. ***Economy*** The economy is modelled at different levels. There are partial models that only capture the part of the economy that is of interest. General models take into account interaction with the remaining economic system and therefore allow better founded assessments of mitigation policies. Moreover, the representation of the economy has important implications on the solution and the evaluation of economic effects.

2. ***Energy System*** The energy system is a complex sub-system of the total economy. It supplies a good that is used by all economic entities and it demands production factors (espec. capital and fuels). The complexity of the sub-system arises from the combination of the several forms of energy and several alternatives to transform energy from one form of energy into another. The variety of technologies can be represented by an engineering based bottom-up approach that takes into account the details of each technology or by a top-down approach that summarises the technologies in aggregate functions.

3. ***Dynamics*** Economic growth, energy systems and climate change are inherently dynamic processes that act on different time scales. Models integrating these three systems have to represent the dynamic nature, which could be modelled either as a sequence of periods or by a forward looking intertemporal approach with perfect information.

4. ***Policy and Strategy*** The different model types deal in different ways with the assessment of policies and strategies. There are two different ways

analysing policy instruments in IAMs. First, in the policy evaluation analysis one is interested in the consequences of a particular policy instrument; e.g. what is the impact on CO_2 emissions of a $10\frac{\$US}{tC}$ tax until 2050. Second, in the policy optimisation analysis one is interested in the optimal timing and extent of policy variables; e.g. the optimal carbon tax until 2050. Policy optimisation could be either done in the cost-benefit or the cost-effectiveness mode. The cost-benefit mode computes the optimal strategy taking into account damage and mitigation costs. The cost-effectiveness mode computes the optimal strategy for obeying a specific environmental constraint representing lexicographic preferences. The policy variables are deduced from the optimal result in an additional step. See Weyant (1996) for this issue.

Introducing CCS into a model is related to changes of the energy system and the relationship to the economic and natural system. The modelling approach of CCS has a specific dynamic structure and the application of CCS within the model is induced by a particular CO_2 emission mitigation. The following introduces the most important modelling approaches and the way they deal with the above issues and the modelling of CCS.

2.7.2 IAM with Mitigation Cost Functions

Models using mitigation cost functions (MCF) require at least two steps. First, the MCF has to be defined and second a criterion for the choice of the mitigation level has to be applied.

MCF are well known in environmental economics of cost-benefit and cost-effectiveness assessments; see Perman et al. (2003). A MCF is a sequence of separate projects that are ordered according to their marginal costs, which implies that a MCF could not decrease. In studies of CO_2 emission mitigation the MCF determines the marginal mitigation costs to mitigate an additional unit of CO_2 emissions depending on the mitigation level. The CO_2 emission mitigation level is the relative difference between a pre-defined business as usual (BAU) scenario and actual CO_2 emissions; see e.g. Hourcade (1996). The BAU scenario represents the path of CO_2 emissions in the absence of the climate problem. Therefore, the economic consequences of long-term CO_2 emission mitigation are determined relative to a scenario without mitigation.

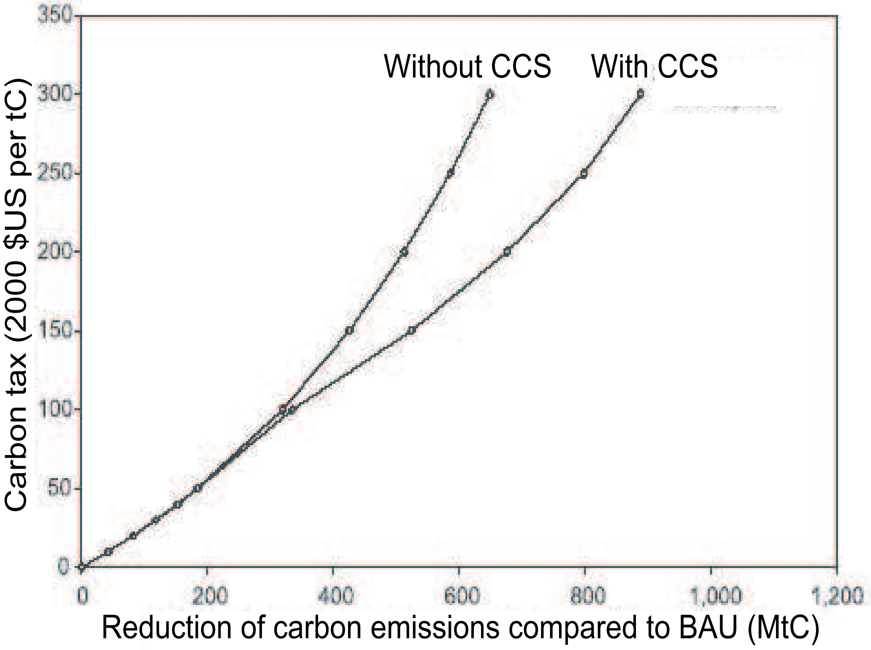

Figure 2.6: Integration of CCS into a mitigation cost curve for the United States of America (USA) in 2030. The BAU CO_2 emissions are 2.3GtC. Source: Sands (2004, p. 737).

The parameters of a MCF can be estimated from historical data regarding the relationship between energy prices and CO_2 emissions using regression analysis. An alternative is to summarise the information of large scale economic models in a MCF. This implies that the MCF is a reduced form model of the more complex model. The reason is that the large scale model might not be appropriate for the integration with models of the natural system into a single framework.

The MCFs follow the top-down approach, since the CO_2 emissions and the mitigation costs are represented at the aggregate level without endogenous choice of technologies. Moreover, the MCF is a partial economic concept, because the MCF can be interpreted as the supply for clean environment. With respect to the dynamic structure of CCS the MCF approach does not take into account that CCS requires large upfront investments prior to its utilisation and long lifetime of this capital.

For the sake of cost-benefit assessments a MCF can be combined with a damage cost function (DCF) that depends on a variable like GMT or the atmospheric CO_2 concentration that represents the natural system. The total cost function (TCF) is the sum of MCF and DCF. In the following the main focus is on MCF, since this thesis is devoted to CO_2 emission mitigation.

The introduction of CCS would simply imply changes of the MCF parameters. This effect is shown in Fig. 2.6 according to Sands (2004, p. 737). This is a study using a large scale model and deducing two MCF with and without CCS. The figure indicates that CCS decreases the slope of the MCF and therefore leads to more pronounced CO_2 mitigation as compared to the case without CCS, if the carbon tax exceeds $100\frac{\$US}{tC}$. This model approach does not explicitly compute the amount of CCS. It can be derived from the MCF, if the underlying information is available.

There are two different variants for the determination of the time path of CO_2 emissions mitigation. The first variant asks for the minimisation of the discounted cumulative TCF. The second variant integrates the MCF and DCF into a macroeconomic model that maximises a non-linear welfare criterion. The MCF and DCF are constraints that have to be taken into account by the welfare optimisation.

The Dynamics of Inertia and Adaptability Model (*DIAM*) belongs to the first model variant. The time path of CO_2 emission mitigation is determined by forward looking minimisation of the cumulative discounted total costs of climate change until 2300 with perfect information. The objective function is linear in the discounted mitigation costs. The constraints are the MCF, the DCF and a set of equations that represent the natural system; see Ha-Duong et al. (1997). This model approach of mitigation is partial for an additional reason: the mitigation costs do not presume a financing source that is allocated to competing uses.

In a recent version of *DIAM* Ha-Duong and Keith (2003) integrate CCS into the MCF by assuming that CCS is available at $150\frac{\$US}{tC}$. In the example given in Fig. 2.6 this would imply a MCF that is horizontally shaped at a carbon tax of $150\frac{\$US}{tC}$. The amount of CCS is computed from the emission mitigation level. The cumulative sequestered carbon is subject to leakage with a constant leakage rate and the leaked carbon adds to the anthropogenic emissions.

The model could be run in either the cost-benefit or the cost-effectiveness mode or an exogenous tax path can be imposed. This would imply that CCS would be applied, if the carbon tax exceeds $150\frac{\$US}{tC}$.

In the second variant the MCF and DCF are integrated into a Ramsey-type growth model to determine the optimal time path of CO_2 mitigation; see Ch. 3 for details of the Ramsey model. In such models the costs of climate change have to be financed from scarce income that alternatively finances investments or welfare improving consumption. However, this approach is misleading, since the MCF is essentially a static concept that ignores that CO_2 emission mitigation is related to investments. Examples for this variant of models are Nordhaus (1994), Nordhaus and Boyer (2000), Buonanno et al. (2003) and Leimbach and Toth (2003). CCS has not been introduced into models of that type and therefore they will not be pursued further.

Several IAMs based on the MCF concept are used to assess the timing and extent of long-term CO_2 emission mitigation, which is at odds with the static property of the MCF. A strength of the approach is the assessment of international climate policies in game theoretic frameworks, where economic agents are geo-political regions; see e.g. Buonanno et al. (2003) and Hackl and Pruckner (2002).

2.7.3 Energy System Models

Energy system models (ESM) apply linear programming (LP) methods and focus on the optimal choice of energy supply technologies. ESMs are used as planning tools since the 1970ies. The first application of ESM for the assessment of energy related issues has been reported in Häfele (1976). The two main families of ESM – *MESSAGE* and *MARKAL* – are derivatives of that basic model.

ESM are based on linear relationships that represent key characteristics of various energy supply technologies according to the bottom-up approach. These characteristics include investment costs, operation & maintenance O&M costs, conversion efficiencies, technical lifetimes, emission coefficients etc. pp. Moreover, ESM are able to represent features of the energy system that are related to the technical interrelationships between energy facilities that are taken into account in the model solution.

The objective function of an ESM is to minimise the discounted costs of energy production over a time horizon until 2050 or 2100 subject to a fixed energy demand. The model chooses forward looking the cost-minimal energy supply mix over the planning horizon with perfect information.

The investment costs describe the costs in monetary units needed to add a unit of capacity; e.g. $1200\frac{\$\mathrm{US}}{\mathrm{kW_e}}$ for a coal fired power plant. The available capacity (e.g. 1kW) describes the potential output for a year of operation (e.g. $1\mathrm{kW_e} \cdot 7000\frac{\mathrm{h}}{\mathrm{y}} = 7\frac{\mathrm{MWh_e}}{\mathrm{y}}$). The capital goods are combined with the input fuels using a Leontief production function. If the conversion efficiency is 40% the corresponding primary energy consumption for the example is $\frac{1}{0.4} \cdot 7 \frac{\mathrm{MWh_e}}{\mathrm{y}} = 17.5 \frac{\mathrm{MWh_e}}{\mathrm{y}}$. The CO_2 emissions depend on the carbon intensity of the fuel and are a by-product of energy production. If, for example, the input is coal with an carbon intensity of $94 \frac{\mathrm{gC}}{\mathrm{kWh_e}}$ the corresponding CO_2 emissions are $94 \frac{\mathrm{gC}}{\mathrm{kWh_e}} \cdot 17.5 \frac{\mathrm{MWh}}{\mathrm{y}} = 1.6 \frac{\mathrm{tC}}{\mathrm{y}}$. This modelling approach guarantees that input-output ratios are consistent with physical capacity constraints and the laws of thermodynamics. It is possible to take into account several emissions like NO_x, SO_x etc. related to the same process. Moreover, the framework is able to integrate technologies with multiple outputs like combined heat and power CHP.

The introduction of CCS is simply done by introducing energy technologies with the corresponding techno-economic characteristics. The captured CO_2 has to be transported and injected. The corresponding process steps are integrated into the model framework. The data about costs and technical features of the technologies can be taken from techno-economic studies. Examples for this are Gielen and Podkanski (2004) and Riahi et al. (2004). The problem is that long-term consequences that arise from leakage are not taken into account because ESM do not integrate the climate system and the time horizon is usually not long enough.

In a seminal paper Messner (1997) introduced learning by doing (LBD) in an ESM. LBD means that growing experience related to a production process reduces the costs of additional production units. The learning curve operationalises LBD for empirical and modelling studies. In that, the learning rate derived from regression analysis is the percentage reduction of costs of an output unit for each doubling of total cumulative output.

The integration of this concept is done by subdividing a learning curve into a sequence of linear parts, which requires mixed integer programming for the computation of the solution. The approach is now widely applied in ESM. In contrast to exogenous reduction of investment costs of a specific energy technology it requires learning investments in order to reduce the costs; see Wene (2000). This leads to early investments into that technology to reduce the costs of climate protection; see e.g. Grübler and Messner (1998). This is due to the endogenous evolution of the costs of energy supply technologies through LBD that lead to a lock-out of the energy system from carbon based energy carriers. This is a fundamental difference to the MCF approach because this concept does not represent the dynamics of technology within the energy system.

Two shortcomings of ESM are that the model is partial and that the objective function is linear. The partial nature of the model is related to the fact that several activities like O&M do not require scarce production factors, but induce monetary costs with fixed cost coefficients. The resulting costs are not financed by a limited income that has to be produced. The linearity of the objective function is problematic because it does not take into account that the marginal burden of monetary investments decreases as an economy becomes wealthier, if a welfare function with diminishing marginal utility of consumption is assumed.

Moreover, ESM do not integrate the climate system explicitly because it is not possible to represent the corresponding non-linear relationships in the LP format. In the cost-effectiveness analysis an ESM can integrate a cumulative emission budget over a time period or an atmospheric CO_2 concentration constraint. For the policy evaluation mode an emissions constraint could be imposed or an emission tax is added to the objective function that adds the costs of CO_2 emissions.

The LP format has considerable drawbacks with respect to optimal time paths of technology because of the linear functional relationships. Suppose a given electricity demand and two supply technologies: one has low costs and high emissions and the other high costs and low emissions. If an emission tax is introduced that increases over time the ranking of both technologies will reverse at some time. At that time the investments will completely switch from the former to the latter technology. This sharp switch can be smoothed by imposing a constraint on the maximum rate at which new technologies can be introduced or the old technology fades out. These constraints are usually based on empirical evidence of technology introduction (see e.g. Grübler et al. (1999, p. 256 – 260)) and are not founded in economic theory. Barreto (2001, p. 72) and Kypreos and Barreto (2000) analyse such constraints in an ESM.

Another drawback is that the energy demand is inelastic. Therefore, an ESM does not take account of demand side reactions due to increasing energy prices. This problem is addressed in two ways. First, the portfolio of technology choices is broadened to technologies that reduce energy demand; see Fahl et al. (2002, Anhang 1, p. 8). Second, a demand curve for energy is introduced that is integrated into the objective function; see Loulou and Lavigne (1996).

The strength of ESM is the technological detailed representation of the energy sector, which allows to undertake technologically detailed assessments of investments and choice of energy carriers and energy transformation technologies. The drawback is the partial nature and that the functional relationships are linear. Therefore, the economic impacts of the technology choice on other sectors and the economy as a whole are not assessed. The linearity of the model questions espec. the welfare theoretical foundation of the model, since it implicitly assumes linearity between monetary costs and social welfare.

2.7.4 Computable General Equilibrium Models

Computable general equilibrium (CGE) models put the focus on consequences of climate policy on the structure of energy producing and using sectors, implications on income distribution and political measure to deal with these issues by re-distribution of tax revenues; see e.g. Kemfert and Welsch (2000). The CGE modelling approach subdivides the total economy in various firm and household sectors that interact on markets. The solution is a decentralised market equilibrium.

Dynamics in a CGE model is modelled using the so called recursive dynamic approach. Here the CGE model computes a vector of equilibrium prices for goods and production factors for one period. The households saving are a parameterised function of income. The savings are transferred to the next period and allocated on a capital market to the firms. The households receive capital income from the firms; see e.g. Klepper and Springer (2003).[12]

CGE models are flexible in building multi-sectoral models of the economy. The sectors demand the production factors according to their production function, the factor price and the demand prices. The sector specific production functions are characterised by the ease of substitution between the production factors and the intensity with which each production factor is required. Capital in these production functions is expressed in terms of monetary units. The economic production functions determine the distribution of the produced output among the production factors using highly non-linear functions; see Ch. 4.2.2 for details.

CGE models that deal with climate change put emphasis on the energy sector and the interaction with energy demanding sectors as well as households. Although CGE models provide the analysis of multi-sector economies, the production functions follow the top-down philosophy because the investments are related to the

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[12] An alternative approach assumes an intertemporal budget constraint; see Bernstein et al. (1999, p. 405). Since this approach is not extended by CCS it is not further pursued here.

macro-economic production functions of specific sectors. Moreover, it is possible to integrate a sector that represents exactly one technology, e.g. a CCS technology. This approach is introduced by McFarland et al. (2001). However, the result of CGEs can be summarised in even more aggregate MCFs as Fig. 2.6 provides an example.

CGEs are inherently weak in dealing with the intertemporal nature of the problem with respect to three issues:

1. The recursive solution method implies that the capital market is not integrated into the model structure, which means that CGEs are partial in this respect. Therefore, CGE models are appropriate for short to mid-term assessments.

2. The main mitigation option in CGE models is related to the improvement of energy and carbon intensity through substitution of production factors and structural change. Technological change is usually assumed exogenous for the growth of labour and energy productivity; see e.g. Bernstein et al. (1999) and Babiker et al. (2001). Kemfert (2002) provides an approach for endogenising technological change through research and development (R&D) investments. Endogenous changes of technology characteristics like learning by doing – as considered in ESM – are not modelled.

3. The intertemporal nature of the climate problem requires mitigation of CO_2 emissions prior to irreversible changes of the climate system. If long-term climate change is not anticipated, there are no changes on short to mid-term behaviour induced. This issue implies that CGE models are used for policy evaluation analysis.

CGE models share a common feature with the MCF approach that is related to exogenous technological change. The economic system of a CGE is also a locked-in fossil energy system, as long as there are no exogenous forces that trigger the improvement of the relative competitiveness of the carbon free energy technologies. Therefore, the economy would always switch back to the BAU scenario – different to MCF models with a delay – as soon as the climate protection policy is removed.

CGE models have particular strengths with respect to the assessment of economic consequences of short to mid-term climate policy on the structure of the economy, trade and income distribution. The model type is inherently weak for the assessment of long-term issues of climate change like technological development and the integration of a climate model.

2.7.5 Hybrid Models

There are several combinations of the modelling approaches that are called hybrid models. This subsection refers to the integration of macro-economic growth models and energy system models ESM because this type is essential for the assessment of CCS and in this thesis.

The integration aims to overcome two problems pointed out above already. First, models integrating MCF lack the explicit modelling of energy as a production factor and the choice of energy supply technologies. Second, ESM do not take into account the financing of investments into energy technologies and that energy is a production factor necessary for the production of income.

The fundamental approach is to introduce energy as a production factor that can be substituted by labour and capital. The energy demand implied by this production function meets the energy supply that is characterised by energy technologies as represented in a ESM. The energy supply has to be financed from the gross world product of the economy. Therefore, the energy supply sector is in competition with the alternative uses of income for consumption and investments into the macro-economic capital stock. The notion of financing here means that some part of income is devoted to the production of energy. It does not imply the explicit notion of money, credit or stock markets.

The Model for Evaluating Regional and Global Effects of GHG reduction policies (*MERGE*) is an early example for this type; see Manne et al. (1995). The model integrates the climate system and there are several energy technologies that incur costs per output unit and emissions per output unit. There are no stocks of capacities. The inertia of energy supply technologies and therefore the mix of primary energy carriers is taken into account through constraints that limit the introduction and fading out of each technology. Other examples of that type are Peck and Teisberg (1993) and Messner and Schrattenholzer (2000).

This approach also allows to introduce stocks of capacities; see Kypreos (1996). Moreover it is possible to model learning by doing either without (see Manne and Richels (2004)) or with capacity stocks (see Zwaan et al. (2001) and Kypreos and Bahn (2003)). These models show drastically lower mitigation costs for reaching a pre-defined climate protection goal compared to models following the other approaches.

Hybrid models have overcome several problems of ESM. The improved integration of the energy system into the economic system increased the reliability of the assessment and the welfare theoretic foundation. This comes at the expense that the level of technological detail has to be reduced relative to large scale ESM. Nonetheless, learning effects are still represented in the models.

2.7.6 Discussion

In this section four modelling approaches have been introduced that are important in the assessment of long-term CO_2 emission mitigation strategies and are used to study CCS within an integrated framework.

The overview suggests that hybrid models are the most appropriate type to assess the significance of CCS. This is due to the possibility to represent technology characteristics in detail within a macro-economic growth framework. It includes the flexibility of energy demand, the endogeneity of technological choice and the macro-economic interrelationship of production and disposition of income. Moreover, hybrid models fully integrate the dynamics of the climate system as well as leakage of captured carbon.

2.8 Summary and Conclusion

The problem of climate change can be thought as a cause-effect chain. Policies addressing climate change could approach at different links. This thesis addresses emission mitigation. Several emissions of GHGes and aerosols that are by-products of economic activities influence the climate system at different intensities and over different time scales. Since CO_2 is the most important GHG this thesis focuses on them as well as the corresponding aerosol emissions. A considerable share of global CO_2 emissions originates from large point sources that are considered for the application of CCS.

The (extended) Kaya-identity has been used to make the several CO_2 emission mitigation options transparent by identifying the most important determinants of CO_2 emissions. Although the concept of the (extended) Kaya-identity is questionable because of interrelationships among the determinants, it provides important insights into the major CO_2 emission mitigation options. Addressing the CO_2 emissions by influencing the technological determinants is superior to the socio-economic determinants because it requires less serious intervention into individual rights and leads to less economic effects related to welfare. Since the growth of the socio-economic determinants outweighed the technological determinants in the past, leading to increasing CO_2 emissions it is worth to focus on the CCS option in order to avoid the produced CO_2 to reach the atmosphere.

The assessment of CO_2 emission mitigation requires the use of models, which presupposes the formulation of objectives and their aggregation, a system through which control variables are related to variables that enter the objective function and a rule for the selection of particular solution. The sound assessment of dynamic problems deals with state variables that have to be valued appropriately at the end of the considered time horizon. Analytical problems of valuing the terminal state variables can be overcome by extending the time horizon considerably at the price of higher computational requirements.

An assessment aiming at quantitative statements requires assumptions on exogenous model parameters and the validation whether the model is suitable for the explanation of economic time series. There are several sources for the justification of model parameters and different levels of quality to validate a model. Especially with respect to the latter point research has to be improved in the future.

Several model approaches have been developed with particular advantages and drawbacks. Models applying the MCF approach are suitable to study international climate policy in game theoretic frameworks. ESM choose among a considerable portfolio of energy supply technologies, but do not represent the energy demand explicitly and do not take into account the source of financing the energy system. CGE models are suitable to assess the macro-economic consequences of CO_2 emission mitigation policies at the sectoral level through substitution mechanisms, but fail to take account of the intertemporal nature of the climate problem as well as capital markets and technological change.

Hybrid-type models integrating the dynamics of the macro-economy, the energy and the climate system into a growth theoretic framework are found to be the most suitable approach for the assessment of CO_2 emission mitigation options. A model containing these various aspects of the climate problem is reasonable because it captures the use of several emission mitigation options and the assessment of the interrelationship with the economy as well as the climate system. Such model has to rely on several sources for the exogenous model parameters and should at least satisfy a predefined set of stylised facts of economic growth and energy use.

Chapter 3

The Ramsey Model

The Ramsey model is the starting point for the model *MIND*, since the latter is an extension of the former. The Ramsey model of optimal economic growth is recapitulated in Ch. 3. After an introduction in Ch. 3.1 the structure of the model is presented in Ch. 3.2. The solution and stability of the model are derived in Ch. 3.3. In Ch. 3.4 the result is interpreted. In Ch. 3.5 the features that make the model particularly suitable for extensions to assess climate protection strategies are elucidated. In Ch. 3.6 three conceptual extensions are introduced in order to show the relationship to the theoretical basis of the Ramsey model. Ch. 3.7 concludes and discusses the chapter.

3.1 Introduction

In 1928 Frank Ramsey asked a fundamental question: "How much of its income should a nation save?" The question is of great interest in various fields of economics, because it structures a problem, which can be solved with optimisation methods. The original problem had been to minimise the intertemporal burden of reaching an exogenously given consumption level, the so called *state of bliss*.[1] The main finding of the original paper has been the Keynes-Ramsey rule of optimal saving. It is the solution of the saving path for a given initial capital stock taking societies current and future interests into account and obeying the constraints of production

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[1] In principle, this is a problem of most rapid approach. Spence and Starrett (1975) provide a rigours treatment of this class of problems.

possibility.

Apart from the great enthusiasm expressed by John Mynard Keynes about this work, it has been barely mentioned for nearly forty years. A remarkable exception is Dorfman et al. (1958, Ch. 12) extending the original problem to multiple capital-stocks. The interest re-established in the mid-1960ies *inter alia* because new solution methods had been developed. Ramsey (1928) used the calculus of variation to solve the problem; see e.g. Papageorgiou (1996, Ch. 13). Cass (1965) and Koopmans (1965) reformulated the original Ramsey model using the maximum principle developed by Pontrjagin et al. (1964). In the following the term Ramsey model refers to the version by Cass and Koopmans.

In contrast to Ramsey's original work, Cass and Koopmans assumed an intertemporal utility function depending on the consumption path rather than the state of bliss. They proofed the uniqueness of an investment path equivalent to the Keynes-Ramsey rule within which the economy reaches a steady state consumption level that is determined endogenously. It is different from Ramsey's original state-of-bliss because extended models with technological change usually imply a constant growth rate of consumption instead of a constant consumption level.

Since the reformulation and the re-established interest in growth theory, the Ramsey model has been employed on different problems. Blanchard and Fischer (2000, p. 38) state that it is "the prototype for the optimal intertemporal allocation of resources". Beside the numerous applications in growth theory (see e.g. Barro and Sala-i Martin (1999), Maußner and Klump (1996) and Arrow et al. (2003)), optimal fiscal theory (see e.g. Blanchard and Fischer (2000)), theories on aging society and social security (see e.g. Fougere and Merette (1999) and Stiller (2000)) and optimal taxation (see e.g. Arrow and Kurz (1970) and Sinn (1985)), it has become an important tool in the field of sustainable environmental development, particularly pertaining the issue of global climate change.

3.2 The Model Structure

There are two different ways of formulating Ramsey-type models and finding solutions: a decentralised market economy and a centralised social optimal solution. The solution of the former is equivalent to the latter, if it belongs to a class of models that obeys particular conditions. Equivalence means that the outcome of the decentralised market economy is Pareto optimal and maximises a social welfare function; see e.g. Becker and Boyd (1997, p. 220). This implies that the solution paths of quantities as well as (shadow) prices of either are equivalent to the other; see Debreu (1959), Sinn (1985, Ch. 2), Aubin (1998), Barro and Sala-i Martin (1999, p. 71), Stiglitz (1994) and Leonard and Long (1992, p. 39 – 42). In environmental economics with external effects this class of models has the property that policies can be derived from the social optimal solution, which would induce Pareto optimal solutions in the corresponding model of a decentralised market economy. Inequivalence can be induced by learning by doing etc.; see Arrow (1962) and Spence (1981).

The economy is closed and no government exists that demands or supplies goods. The economy is distinguished in the two sectors households and firms that will be treated in the following.

The number of individuals in the household sector is given exogenously. The households preferences are aggregated into a intertemporal social welfare function that is the objective function of the social planning problem. The aggregation of preferences needs some assumptions that will be considered next.

The preference orderings of the households are assumed to be cardinal. There are two reasons for this assumption. First, the selection of an optimal path from a set containing a continuum of alternatives requires a cardinal preference ordering. The consumption/saving decision is of this kind.

The second reason for cardinal preference orderings is due need for interpersonal preference comparison, which arises form intergenerational equity issues. The determination of consumption and saving that is transferred to subsequent generations requires the comparison of utility received from both by different generations. In overlapping generation models this problem is addressed by integrating the utility of future generations into the utility function of the present generation, which implies complete altruism between generations; see Maußner and Klump (1996, p. 132 – 140).

Since the individuals are aggregated in the household sector rather than treated individually, a concept is required for the aggregation of preferences intratemporally across households and intertemporally over time. The method of intratemporal aggregation has to meet fundamental axioms addressing the equality and freedom of each single individual in order to guarantee the existence of a social welfare function that represents the preferences of the individuals. Socially optimal solution of that sector is equivalent to the decentralised action of its individuals. Therefore, maximisation of the social welfare function leads to a Pareto optimal solution for the sector. The assumptions are discussed in Arrow (1951), Dixon (1975, Ch. 2) and Roemer (1996, Ch. 1).

Like Maußner and Klump (1996, p. 115) all possible problems arising from the intratemporal preference aggregation are evaded by employing the concept of the representative household. It assumes that all households are equal in every respect, i.e. initial endowment of resources and preferences. This allows the aggregation of individual preferences by summing individuals utilities in each period. This results in a social welfare function for each period.

The intertemporal aggregation of an individuals utilities – or the social welfare – in each period requires assumptions on the preference ordering of utilities received at different times. The usual procedure that is also employed in this thesis and that is common practice in assessments of CO_2 emission mitigation, is to sum the discounted utilities of different periods. The discounting is exponential, i.e. the valuation of utility decreases at a constant rate. There is still – and will be – dispute on the issue of intertemporal preference aggregation that are not subject of this thesis. The relevant literature on that is Lind (1982), Becker and Boyd (1997), Heal (1998) and Portney and Weyant (1999).

In the Ramsey model the households cardinal utility of each period is a function denoted $u(\cdot)$. Derivatives are assumed to be continuous at least up to the second order. The aggregation scheme is as follows. The $u(\cdot)$ of households are aggregated into a social welfare function of a period by summing over all households. The social welfares of several periods are aggregated into an intertemporal social welfare function W by summing the discounted social welfares of each period. The discounting is exponential with discounting rate ρ.

The argument of $u(\cdot)$ is the per capita consumption of a period $c = \frac{C}{L}$, where $C \geq 0$ is societies consumption and L the population size. The function u satisfies the neo-classical conditions and the Inada-conditions; see Inada (1963). The neo-classical conditions require u to be a concave function in c. The Inada-conditions require the shape of a function to have infinite partial derivatives, if an exogenous variable approaches zero, and a partial derivative equal to zero, if an independent variable approaches infinity.

The curvature of $u(c)$ is related to the intertemporal elasticity of substitution IES, which is defined as the inverse of the marginal elasticity of utility η. The IES measures the households preference to transfer consumption in periods of high consumption levels to periods of low consumption levels. Households prefer a flatter consumption path the greater the IES is. In the following the IES of $u(c)$ is assumed to be constant. For details see Barro and Sala-i Martin (1999, p. 64) and Maußner and Klump (1996, p. 119 – 121).

Therefore, the intertemporal social welfare function is defined as:

$$W = \int_0^\infty e^{-\rho t} L(t) u\left(c(t)\right) dt, \qquad \text{with } W \in \mathbb{R} \text{ and } u(\cdot) \in \mathbb{C}^2; \tag{3.1}$$

$$u' > 0, u'' < 0; \lim_{c \to 0} u' \to \infty, \lim_{c \to \infty} u' \to 0.$$

Households supply labour L and capital K to the firm sector, i.e. the households accumulate capital and the firms have to pay a rent for using it. The supply of labour of each household is price-inelastic and constant over time. Therefore, the amount of labour is assumed to equal the number of population. From these supplies the households receive income $wL + rK$, where w and r are wage and interest rate, respectively. The income can be distributed either on consumption C or saving, which equals investment I. The capital stock is increased by I and depreciates time-dependent with depreciation rate δ. Therefore, we have a capital motion equation Eq. 3.2 with an initial condition and a budget constraint Eq. 3.3 that has to be fulfilled every time:

$$\dot{K} = I - \delta K, \qquad K(t=0) = K_0 > 0; \tag{3.2}$$

$$Y(t) = C(t) + I(t), \qquad \forall t. \tag{3.3}$$

Firms produce output Y by using the two production factors K and L combined in a neo-classical production function $F(\cdot)$. The production function is assumed to have continuous second order derivatives and to be linear homogenous of degree one, see Eq. 3.5. Homogeneity of degree one implies two important consequences. First, Y is distributed among the production factors according to their marginal productivity. Second, the model can be written in intensive form; i.e. per capita production y depends on per capita capital – the *capital intensity* k. This assumption implies that y depends on k and the shape of the per capita production function $f(k)$; see

Neumann (1995, p. 66 – 69) and Chiang (1984, p. 410 – 414). Therefore, we can formulate the production function and its implications on income distribution:

$$Y = F(K, L) = Ly = Lf(k) = wL + rK, \qquad f \in \mathbb{C}^2; \tag{3.4}$$

$$f' > 0, f'' < 0, \underset{k \to 0}{f'} \to \infty, \underset{k \to \infty}{f'} \to 0;$$

$$\lambda Y = F(\lambda K, \lambda L) \text{ for some } \lambda \in \mathbb{R}; \tag{3.5}$$

$$r = f(k)', \qquad w = f(k) - f'(k)k. \tag{3.6}$$

The assumptions on the use of an aggregated capital stock, labour, output and production function are are quite strong. Since capital, labour, production technologies and outputs are heterogenous in the real world one has to put assumptions on the disaggregated quantities and functional relations. Ch. 3.5 provides detailed discussion about the assumptions of capital stock aggregation. More detailed discussion on the aggregation problem is given Ch. 3.6.2.

The social planning problem is to maximise the aggregate intertemporal welfare function W of all individuals over the infinite planning horizon. Eq. 3.3 is solved for I and substitute it into Eq. 3.2. Therefore, the control variable of the social planning problem is $c = \frac{C}{L}$; i.e. the question for saving is transformed into one for consumption. The assumption is made that $L(t) = 1$. This leads to the state-dependent optimal control problem in intensive form:

$$\underset{0 \le c(t) \le y(t)}{\text{Max}} W = \int_0^\infty e^{-\rho t} L(t) u\left(c(t)\right) dt \tag{3.7}$$

subject to:

$$\dot{k} = f(k) - c - \delta k, \qquad k(t = 0) = k_0. \tag{3.8}$$

3.3 Solution and Stability

The solution of Eq. 3.7 – 3.8 using the maximum principle, the steady state and the stability is provided in this section. The analytic solution method of Ramsey-type models employed since Cass (1965) and Koopmans (1965) is the maximum principle developed by Pontrjagin et al. (1964). The approach is to formulate a Hamiltonian function $\mathcal{H}(\cdot)$. The current value Hamiltonian is:

$$\mathcal{H}(k, \lambda, c, t) = e^{-\rho t} u(c) + \lambda(f(k) - c - \delta k). \tag{3.9}$$

Finding the optimal control path $c(t)$, the state path $k(t)$ and the path of the newly introduced co-state $\lambda(t)$. The maximum principle provides rules for solution (see Feichtinger and Hartl (1986, p. 28) for details), but one has to assume the existence of the solution; i.e. the steady state and the optimal transition towards the steady state. This assumption is important, because the maximum principle does not guarantee the existence, although a solution is found. Unfortunately, there is – up to my knowledge – no rigorous proof for conditions guaranteeing the existence of a solution for arbitrary optimal control problems. Usually, the existence is assumed. Nevertheless, the Ramsey model introduced above exhibits features, which imply conditions for the existence of the solution as will be shown below.

Following Maußner and Klump (1996, p. 130 – 32) the optimal solution satisfies a system of equations:

$$\begin{aligned} \frac{\partial \mathcal{H}}{\partial \lambda} &= \dot{k} = f(k) - c - \delta k; && (3.10) \\ \rho\lambda - \frac{\partial \mathcal{H}}{\partial k} &= \dot{\lambda} = \lambda(\rho + \delta - f'(k)); && (3.11) \\ \frac{\partial \mathcal{H}}{\partial c} &= 0 = u'(c) - \lambda. && (3.12) \end{aligned}$$

Obviously, Eq. 3.10 is the original capital motion equation Eq. 3.8. Differentiating the optimality condition Eq. 3.12 with respect to time and dividing the result by Eq. 3.12 gives:

$$\frac{u''}{u'}\dot{c} = \frac{\dot{\lambda}}{\lambda}.$$

This can be substituted in Eq. 3.11. This means that the optimality condition is linked with the differential equation of the co-state variable. Taking this together leads to the canonic system of differential equations, where $\frac{1}{\eta}$ is intertemporal elasticity of substitution IES:

$$\begin{aligned} \frac{\dot{c}}{c} &= \frac{1}{\eta}(f'(k) - \delta - \rho), \qquad \eta \equiv -\frac{u''}{u'}\,c; && (3.13) \\ \frac{\dot{k}}{k} &= \frac{f(k) - c}{k} - \delta. && (3.14) \end{aligned}$$

Eq. 3.13 is the Keynes-Ramsey rule. It is the optimal path of c depending on k. The rule combines the information of the household and the firm sector. It says that consumption shall increase at a rate equal to the difference of the marginal product with respect to the capital-intensity $\frac{\partial f}{\partial k}$ and the sum of δ and ρ multiplied

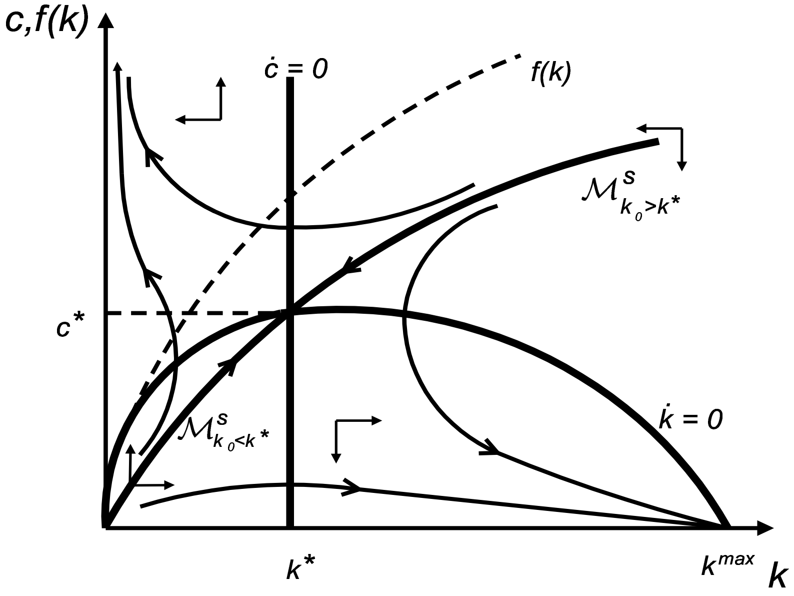

Figure 3.1: Stability analysis and transitional dynamics of optimal capital accumulation in the Ramsey model with major isoclines $\dot{k} = 0$ and $\dot{c} = 0$, $\mathcal{M}^s$, steady state (k^*, c^*) and production function $f(k)$ (dashed line). Source: based on Feichtinger and Hartl (1986, p. 207).

with the inverse of η. Since marginal productivity equals prices in the optimum, the Keynes-Ramsey rule gives a clear determination of the steady state ($\dot{c} = 0$) interest rate $f'(k)$. Eq. 3.14 is a simple manipulation of Eq. 3.10.

In the following the stability of the system is analysed and necessary conditions for the existence of the solution are given. The stability analysis around the steady state is interesting for at least three reasons. First, it allows for the study of transition dynamics. Second, the stability analysis suggests reasons for the choice of numerical solution methods. The third reason – not discussed here – is the relation between stability properties and the sufficiency conditions of an optimal solution.

The illustration of the stability analysis is given in Fig. 3.1. The first thing to do is to find the major isocline for $\dot{c} = 0$ and $\dot{k} = 0$.

The major isocline for $\dot{k} = 0$ is described by $c = f(k) - \delta k$. This isocline begins in the origin, rises, reaches a maximum, falls afterwards and touches the abscissa at k^{max}. This is because (i) there is no capital accumulation, if $f(k = 0) = 0$. (ii) Per capita consumption increases with capital intensity, if there is zero net investment, when $f'(k) - \delta > 0$. (iii) the maximum consumption with constant capital intensity is possible, if $f'(k) = \delta$,[2] and (iv) if k further increases, c has to decrease in order to keep k constant, because of increasing depreciation. (v) k^{max} is, where $f(k) = \delta k$; i.e. all income is devoted to the maintenance of the maximum possible capital stock k^{max} and consumption is zero. The inverted U-shape of the isocline $\dot{k} = 0$ follows from the neo-classical production function and the positive depreciation rate.

The major isocline for $\dot{c} = 0$ is a straight line parallel to the ordinate. It is located, where k^* fulfills $f'(k) = \delta + \rho$. It is left to the maximum of $\dot{k} = 0$ if $\rho > 0$. In combination with the form of the major isocline $\dot{c} = 0$ there is exactly one intersection with positive quantities of c and k. The steady state is determined by the intersection of the two major isoclines at (k^*, c^*). Therefore, the unique existence of the steady state is implied by the assumptions of the model setup without any further restriction. If $\rho < 0$, the major isocline $\dot{c} = 0$ moves to the right and it is possible that both isoclines do not intersect. In that case the solution does not exist.[3]

The next task is to determine the transition dynamics, which proofs the existence of an optimal transition path. The two major isoclines delimit four sectors in which the qualitative behaviour is different. The four pairs of straight arrows indicate the qualitative behaviour in each sector. In principle, the system is allowed to move from one sector to the other.

The arrows indicate that the steady state is a saddle point; i.e. for every k, there is one c, which will lead to the steady state. The set of k and c, where this is satisfied, is called the *stable invariant manifold* $\mathcal{M}^s$. A control path on $\mathcal{M}^s$ is optimal. This property of the solution becomes clear by proofing that the opposite cannot be true.

The task is to determine the optimal c qualitatively for all k. Qualitative determination is related to either the intersection of the major isoclines or to one of the four regions delimited by them. Two cases are of interest, since the steady state

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[2] In the Solow-model this is denoted as the golden rule capital intensity of capital accumulation; see e.g. Maußner and Klump (1996, p. 125).

[3] Koopmans (1965) gives an overview on the conditions for the discounting rate and the parameters describing exogenous population growth and technological change (additionally introduced into the Ramsey model) that guarantee the existence of the solution. If the latter two growth rates are positive, the discounting rate should exceed the sum of both. In this way, the trade-offs between current and future interests guarantee the existence of the solution in problems with infinite planning horizon.

$k_0 = k^*$ is trivial with respect to transition dynamics:

1. $k_0 > k^*$: Obviously, it is not optimal to decrease c in order to increase k until it reaches k^{max} as is indicated in the region below $\dot{k} = 0$. Therefore, we have to be somewhere above $\dot{k} = 0$.
2. $k_0 < k^*$. Choosing c above $\dot{k} = 0$, would imply to increase consumption, which would lead to decreasing k. At some point in time this would imply that $c > f(k)$, which violates the assumption in Eq. 3.7. Therefore, $k_0 > k^*$ implies to keep c below $\dot{k} = 0$ and to increase k.

For every $k_0 \neq k^*$ there is one region, which is cancelled out and one that is not. For every k the optimal c is determined with respect to one of two possible regions. We can restrict the systems dynamic even more, since it can not be optimal to choose a path that leads into one of the cancelled regions. Such behaviour is implied aside $\mathcal{M}^s$ as is indicated by the dynamics towards infinite consumption or the maximal capital stock. The solution consists of three different regions that are distinguished by $k_0 \lesseqqgtr k^*$. The optimal path is to stay on $\mathcal{M}^s_{k_0>k^*}$, $\mathcal{M}^s_{k_0<k^*}$ or to stay in the steady state, when $k_0 = k^*$.

The saddle-point property implies that for every initial capital stock there is a unique solution for the optimal path of consumption that leads the system towards the steady state. When the system starts at $k_0 \neq k^*$, then k^* will be approached asymptotically. Economies starting at a relatively low capital intensity have an incentive to accumulate capital. The incentive to accumulate capital decreases with the capital stock.

An important issue is the time path of the saving rate s/y. For the trivial case $k^0 = k^*$ the saving rate will remain constant. If $k^0 \neq k^*$ the time path of the saving rate depends on the shape of production and utility functions. Barro and Sala-i Martin (1999, p. 89 – 90) showed analytically for the case of an iso-elastic utility function and a Cobb-Douglas production function that the saving rate is either monotonically increasing or decreasing for $k_0 < k^*$ depending on the IES $\frac{1}{\eta}$. When $\frac{1}{\eta} > s^*$ ($\frac{1}{\eta} < s^*$) the saving rate is decreasing (increasing) over time, where s^* is the steady state saving rate. Smetters (2003) analysed the case of an iso-elastic utility function and a constant elasticity of Substitution (CES) production function.[4] He proofed that the saving rate could increase in the beginning, reach a

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[4] The CES production function will be introduced in detail in Ch. 3.6.2.

maximum and decrease there after, when k_0 is sufficiently smaller than k^*.

3.4 Interpretation

The interpretation of the basic Ramsey model goes in two directions. First, the interpretation of the shadow price is needed for modelling several stocks with miscellaneous characteristics. Second, the saddle point property of the optimal solution implies the use of optimisation algorithms for numerical solutions.[5]

The Bellman optimality principle is a good starting point for the interpretation of the shadow prices. This principle clarifies the consistency of a partial plan of a sub-period $(0, t)$ with the total plan over the infinite time horizon $(0, \infty)$. This requires the correct valuation of $k(t)$ in partial plan, which is accounted in the objective function of the partial problem. Every partial plan will bring the system to a point with a new $k(t)$. When $k(t)$ is valued with $\lambda(t)$ of the infinite horizon solution, then the partial solution is consistent with it. This allows to split the infinite time horizon into various partial problems, which in turn could be merged to form the original problem.[6]

This leads to the definition of the Bellman equation: the value of the remaining planing horizon $V(k, t)$ depends on t and the state variable k. Using the Bellman equation, we look for the supremum of the variable $V(k, t)$ by choosing c for the remaining planning horizon (t, ∞); Feichtinger and Hartl (1986, p. 24 – 27):

$$V(k,t) = \sup_{c(\tau);\, t \leq \tau \leq \infty} \left\{ \int_t^\infty e^{-\rho\tau} L(\tau) u(c(\tau)) d\tau \right\}. \tag{3.15}$$

At every point in time t the partial derivative $\frac{\partial V(k,t)}{\partial k(t)}$ equals $\lambda(t)$. It indicates the scarcity of the corresponding state variable and can be interpreted as the willingness-to-pay for a marginal amount of k at time t. If $k(t)$ is valued with $\frac{\partial V(k,t)}{\partial k(t)}$ for the partial problem over the time horizon $(0, t)$ then it is consistent with the solution for the problem with the horizon $(0, \infty)$.

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[5] A discussion – not extended here – of the saddle point property, consistency and efficiency in a decentralised economy with relations to rational expectations and the existence of a complete set of future markets is given in Stiglitz (1994, p. 18-20).

[6] Pontrjagin et al. (1964) called this the synthesis problem. A great deal of the proof by Pontrjagin et al. (1964) is devoted to the mathematical conditions that allow the formulation of a sequence of partial problems and their merging.

This analysis implies two conclusions. The first conclusion is that the Ramsey model could be extended to several state variables, be it capital stocks, stocks of resources, etc. pp. Every stock is equipped with a co-state variable, which is interpreted as its shadow price; see Dorfman et al. (1958, p. 317 – 18 and 339 – 40), Pontrjagin et al. (1964, Ch. 1 and 2), Pitchford (1979) and Feichtinger and Hartl (1986, p. 24 – 28). In the following Ch. 3.5 three such extensions will be introduced. The second conclusion is that optimal control theory solves the problem introduced in Ch. 2.5.3. If the planning horizon is sufficiently long, events in the distant future are anticipated and short-term action is motivated through shadow prices of the stock variables.

Next, the interpretation points on numerical solution methods. The analytical tools used above allow for general conclusions within an important class of problems. The problem is that increasing complexity of a model reduces our ability to deduce model behaviour of a solution analytically; espec. aside the steady state. Moreover, assessing the significance of options of a particular problem asks for quantitative statements, which requires numerical methods.

The saddle point property is constitutive for choosing among two different methods for numerical solutions: optimisation methods or simulation techniques. Using simulation methods for initial value problems applied on the canonic system of differential equations derived from the optimal growth model in Eq. 3.13 – 3.14 will not result in a path on $\mathcal{M}^s$. Unfortunately, optimisation methods restrict the extent of a model in terms of detailed disaggregation. This is due to the much greater need of computational time for solving models of comparable size. The size of a model can be measured by the number of differential equations, which set up a model. This means that the model has to be simple (compared to simulation models) in order to receive results, which satisfy intertemporal optimality.

Numeric methods require time discrete formulations of a model and to solve over an entire planning horizon and to anticipate future events triggered by earlier action. Such problem can be interpreted as a static non-linear optimisation problem, where the values of a control variable in two different periods are interpreted as independent variables. Therefore, a growth model with perfect foresight can be solved with non-linear optimisation methods. Details on algorithms for dynamic optimisation problems can be found in Feichtinger and Hartl (1986, p. 487 – 503) and Judd (1999, Ch. 12).[7]

3.5 Rational of the Ramsey Model for Climate Change Mitigation Modelling

This section serves to discuss the basic Ramsey model as a starting point for the assessment of strategies addressing climate change. Although the model has been introduced at the most fundamental level so far, several properties are not changed and serve for a discussion.[8]

The first property is the basic problem of weighting current and future interests, which exhibits the obvious relation to sustainability, noted above already. In particular, future constraints and opportunities are *anticipated* in social planning problems through shadow prices. Although long-term problems like climate change will become pressing in the future, the implications on short-term action can be derived within an optimisation framework. The maximum principle enables us to weigh interests temporarily consistent. Therefore, we can select strategies in a transparent way according to an objective criterion.

This is due to the mathematical analogon of the Ramsey model to the ethical principle of sustainability. The most cited formulation of that ethical principle has been published by the World Commission on Environment and Development chaired by Gro Harlem Brundtland in 1987 and says to "meet the needs of the present generation without compromising the ability of future generations to meet their needs". Some consensus has been reached that the ethical principle of sustainability and the question asked by Frank Ramsey share the same idea of weighing present and future interests; for a discussion on sustainability and optimality see e.g. Heal (1998).

Following from this the second property is: the Ramsey model allows the researcher to study transition dynamics. This point is of special interest, if we think of the timing of introducing new technologies, because relative scarcities are changed in the growth process, which increases the attractiveness of some technologies and

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[7] Alternatively, the model could be solved using algorithms searching for an equilibrium. These algorithms put limitations on the size of a problem; see Lau et al. (2002) and Rasmussen and Rutherford (2004).

[8] A broader discussion of economic models and climate change can be found in Dowlatabadi (1995) and DeCanio (2003).

decreases that of others. The introduction of new technologies could imply macroeconomic disruptions to some extend. The magnitude of the disruptions and the measures dealing with them are of interest.[9]

The Ramsey model has some serious shortcomings, too. First, the intragenerational aggregation concept of the representative household is very questionable, when we ask for global strategies addressing climate change. Households are all but equal with respect to initial endowments and preferences. The introduction of new technologies might benefit some households, but there are costs for others, if the new technology replaces an existing one that becomes uncompetitive. This argumentation is in line with the idea of *creative destruction* founded by Joseph A. Schumpeter; for a formal analysis see Aghion and Howitt (1992). This phenomenon asks for mechanisms of compensation. On the other hand, the impacts of climate change are also distributed unequally. Some households – especially in developing countries – will suffer from climate change, while others might benefit.

The second shortcoming is due to the fact that there is no binding intergenerational contract. Since future generations are simply not able to make their claims, but will be affected from earlier actions, there is the serious problem to prevail future interests in todays actions. This intergenerational problem is solved by the assumption of the intertemporal social welfare function that has to be maximised.

The third shortcoming is that the model lacks of an explicit state sector with respect to the demand and supply of production factors, goods and services. The model computes social optimal solutions and the policy variables that would induce such behaviour, but it does not take into account the effort that is needed to implement and to enforce the policy.

The fourth shortcoming is that the Ramsey model deals with highly aggregate variables. The possibility for disaggregation of economic, social and environmental phenomena is very limited because the computational requirements increase rapidly with disaggregation. Unfortunately, the requirements for the aggregation of production factors as well as economic output are very restrictive. Ch. 3.6.2 below discusses the issue of capital stock aggregation.

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[9] Another important feature in this respect is that we are able to look at development transitions in the sense that developing countries catch up with developed countries. Reasons, bottlenecks and the transition dynamics in particular are of great interest for economists. Since this thesis is devoted to the global scale, it is left at that.

3.6 Extensions

This section pursues three objectives. First, the essential extensions of the Ramsey model that characterise *MIND* are introduced that are related to the hybrid model approach discussed above; see Ch. 2.7.5. The *MIND* model can be reduced to each of the three variants. This improves the understanding of the complex numeric model. Third, each extension contributes to discussions in particular economic research areas.

The section is structured as follows. In Ch. 3.6.1 the Ramsey model is extended by stock pollution that arises from utilisation of natural resources that is a production factor. In Ch. 3.6.2 the Ramsey model is extended by an energy sector, which is characterised by a production function requiring fuels and capital. In Ch. 3.6.3 the Ramsey model is extended by endogenous technological change and validated against time series data.

3.6.1 The Stock Pollution

In this section the Ramsey model is extended by a stock pollution that catches the main economic feature of global climate change. The model is a reduced form model of a more complicated one in Perman et al. (2003, Ch. 16). Ploeg and Withagen (1991) developed a similar model. The model used here is analysed with a special focus on transition dynamics. In the following the model set up is developed. Then results of the steady state solution and transition dynamics are presented and discussed.

The model and the analysis in the following provide a contribution to the theoretical basis of the environmental Kuznets curve EKC hypothesis. The question to be answered is whether the model could serve as a theoretical basis from which the EKC hypothesis can be derived. The model focuses on the interplay between a growing economy, the adverse stock pollution and input of production. The question is whether factor substitution and capital accumulation subject to a social optimal pollution control could generate an EKC style emission path.

The framing of the problem in the following is that of a fossil fuel rich, atmosphere scarce economy. The macro-economic production function F of the Ramsey model demands a natural resource R. The production of R is associated with constant marginal extraction costs χ and the emissions lead to accumulation of the pollution stock M. The stock M is reduced by the amount $\alpha \cdot M$, where α is a natural regeneration parameter.

In each period the utility $U(\cdot)$ decreases with M and increases with consumption C. The marginal damage increases with M, i.e. $U_{MM} < 0$; where U_{MM} is the second order partial derivative of U with respect to M. The utility function is concave in C. The cross derivatives $U_{MC} = U_{CM}$ are less than zero. The Inada conditions are assumed to hold, which means that $\underset{M\to\infty}{U_M} \to -\infty$ and $\underset{M\to 0}{U_M} \to 0$. The functions F and U are assumed to have continuous derivatives up to at least the second order. The model setup is summarized in the following equations:

$$\underset{R,C}{\text{Max}}\ W! = \int_0^\infty e^{-\rho t} U(C,M)dt; \tag{3.16}$$

$$\dot{M} = R - \alpha M, \qquad R \geq 0, \quad M(t=0) = M_0; \tag{3.17}$$

$$\dot{K} = F(L,K,R) - C - \chi R - \delta K, \qquad C \geq 0, \quad K(t=0) = K_0. \tag{3.18}$$

There are at least three interesting questions concerning this model. First, the steady state solution and its interpretation. Second, whether the transition dynamics of R in the K-R-space towards the steady state could follow the EKC hypothesis. The third question asks for the existence of the solution that can be answered as a by-product of the stability analysis.

Again, we can employ the rules implied by the maximum principle for solving the problem; see Feichtinger and Hartl (1986, p. 28). The current value Hamiltonian is:

$$\begin{aligned} \mathcal{H}(R,C,\lambda_M,M,\lambda_K,K,t) = {} & U(C,M)+ \\ & \lambda_M(R-\alpha M)+ \\ & \lambda_K(F(L,K,R) - C - \chi R - \delta K). \end{aligned} \tag{3.19}$$

For the time, the existence of the solution is assumed. The next equations are the optimality conditions Eq. 3.20 – 3.21 and the differential equations for the co-state variables Eq. 3.22 – 3.23. The equations right of the arrows (⇒) in the first two equations are the result of the derivatives with respect to time and subsequent division by the original equation. The equation right of the arrow in Eq. 3.23 is gained by substituting the optimality conditions of Eq. 3.20 and Eq. 3.21:

$$\frac{\partial \mathcal{H}}{\partial C} = U_C - \lambda_K \overset{!}{=} 0 \quad \Rightarrow \quad \frac{\dot{\lambda}_K}{\lambda_K} = \frac{U_{CC}}{U_C}\dot{C}; \tag{3.20}$$

$$\frac{\partial \mathcal{H}}{\partial R} = \lambda_M + \lambda_K(F_R - \chi) \overset{!}{=} 0 \quad \Rightarrow \quad \frac{\dot{\lambda}_M}{\lambda_M} = \frac{F_{RR}\dot{R}}{F_R - \chi} + \frac{\dot{\lambda}_K}{\lambda_K}; \tag{3.21}$$

$$\frac{\dot{\lambda}_K}{\lambda_K} = \rho + \delta - F_K; \tag{3.22}$$

$$\frac{\dot{\lambda}_M}{\lambda_M} = \rho + \alpha - \frac{U_M}{\lambda_M} \quad \Rightarrow \quad \frac{\dot{\lambda}_M}{\lambda_M} = \rho + \alpha + \frac{U_M/U_C}{F_R - \chi}. \tag{3.23}$$

The task is to find differential equations for the control variables (C, R) that do not contain any co-state variable. This is easy for C, since one can apply the same procedure as in Ch. 3.3. For the differential equation of R we can equate the manipulated Eq. 3.21 and Eq. 3.23 and then substitute the right hand side of Eq. 3.22 for $\dot{\lambda}_k/\lambda_k$:

$$\rho + \alpha + \frac{U_M/U_C}{F_R - \chi} = \frac{F_{RR}\dot{R}}{F_R - \chi} - \Delta_{KRR}\,, \qquad \text{with } \Delta_{KRR} = F_K - \rho - \delta. \tag{3.24}$$

Note, the term Δ_{KRR} is part of the Keynes-Ramsey rule in Eq. 3.13. Rearranging the equation in order to get $\dot{R}$ on the left hand side:

$$\dot{R} = \frac{1}{F_{RR}}\left[\frac{U_M}{U_C} + (F_R - \chi)(\rho + \alpha + \Delta_{KRR})\right]. \tag{3.25}$$

The steady state solution of Eq. 3.25 requires $\dot{R} = 0$:

$$F_R = \chi - \frac{U_M/U_C}{\rho + \alpha + \Delta_{KRR}}. \tag{3.26}$$

For the moment assume $\Delta_{KRR} = 0$. The marginal product of the resource has to equal the marginal extraction costs that are corrected by an addend. This is the fraction in Eq. 3.26 termed stock externality that equals a social optimal emission tax. This implies, that the use of energy carriers would be smaller than without environmental damage, i.e. $U_M = 0$. This is due to the neo-classical production function $F(\cdot)$, which assumes that a higher marginal factor productivity is reached by decreasing the amount of that production factor.

The fraction suggests a capital theoretic interpretation. It is the weighted marginal damage in the period at which the stock M is increased in terms of monetary units per physical unit; e.g. \$US/tC. The valuation of the marginal damage has to take into account the overall dynamics through the discounting factor and the stock dynamics by dividing the immediate marginal damage by $\alpha + \rho$. Obviously, this approach is analog to the computation of the present value of a financial asset V_{asset} with a constant nominal payment P_{asset} subject to the interest rate r and an infinite time horizon: $V_{asset} = \frac{P_{asset}}{r}$; see e.g. Perridon and Steiner (1995, p. 199).

Next, the transitional dynamics is analysed. It serves for the remaining two questions of the qualitative behaviour of the social optimal emissions path and the conditions for existence of the solution. This requires the analysis of the transition behaviour in the $M - R$-space and the $K - R$-space.

The* $M - R$*-space The steady state and the qualitative transition behaviour of the system in the $M - R$-space is shown in Fig. 3.2 and explained in the following. Assume $\dot{C} = \dot{K} = 0$. The major isocline for $\dot{M} = 0$ comes from Eq. 3.17. The major isocline for $\dot{R} = 0$ is derived from Eq. 3.25, where $\Delta_{KRR} = 0$. Therefore, the two isoclines are:

$$\left(\frac{dR}{dM}\right)_{\dot{M}=0} = \alpha > 0; \tag{3.27}$$

$$\left(\frac{dR}{dM}\right)_{\dot{R}=0} = -\frac{\frac{U_{MM}U_C - U_M U_{CM}}{U_C^2}}{F_{RR}(\alpha + \rho)} < 0. \tag{3.28}$$

The isocline in Eq. 3.27 is a simple consequence of exponential regeneration of the pollution stock. It is linearly increasing in M and crosses the origin. The sign of the isocline in Eq. 3.28 is negative. The crossing with the ordinate is determined by $F_R = \chi$. From these properties we can conclude that there is a unique intersection of both isoclines in any case, which implies the existence of the solution in the $M - R$-space.

There are two different steady states depending on the internalisation of the external effect. One for the uncontrolled market economy (R^{extern}, M^{extern}) and the other for the social optimal solution (R^{social}, M^{social}). In the former case R^{extern} is the resource extraction, where the marginal productivity equals the extraction costs. The corresponding steady state stock pollution depends on α. The steady state of the socially optimal solution is characterised by a lower level of resource extraction and therefore a lower stock of pollution.

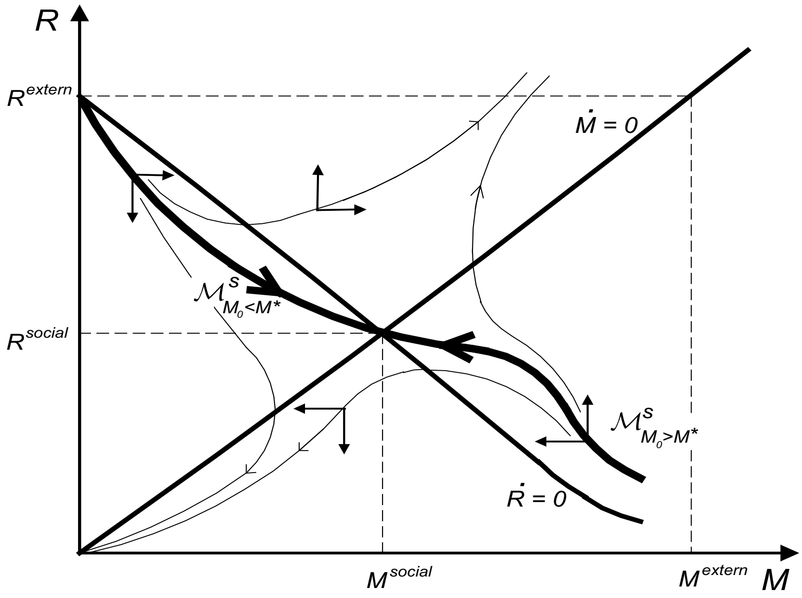

Figure 3.2: Stability analysis and transitional dynamics of optimal stock pollution within the extended Ramsey model. The figure shows the major isoclines $\dot{R} = 0$ and $\dot{M} = 0$, stable invariant manifold $\mathcal{M}^s$, steady state of social planning problem (M^{social}, R^{social}) and decentralised market economy (M^{extern}, R^{extern}).

Starting at $M_0 < M^{social}$ a decreasing resource extraction leads towards the steady state (R^{social}, M^{social}). This is the *pollution effect* on $R(t)$. Additionally, in that case R will never be lower than R^{social}, because otherwise the dynamics would lead the system to the origin, where there is no production. The optimal transition path for R is at odds with the EKC hypothesis, if $\dot{C} = \dot{K} = 0$.

The $K - R$-space Now the question is for the dynamics in the $K - R$-space. Assume $\dot{C} = \dot{M} = 0$. This implies $\Delta_{KRR} = 0$. The isoclines for $\dot{K} = 0$ and $\dot{R} = 0$ are derived from Eq. 3.18 and Eq. 3.25, respectively. We get:

$$\left(\frac{dR}{dK}\right)_{\dot{K}=0} = -\frac{F_K - \delta}{F_R - \chi} < 0; \tag{3.29}$$

$$\left(\frac{dR}{dK}\right)_{\dot{R}=0} = -\frac{F_{RK}}{F_{RR}} > 0. \tag{3.30}$$

Eq. 3.29 implies a negative slope of the isocline for $\dot{K} = 0$. The isocline in Eq. 3.30 is monotonously decreasing in K. Therefore, the existence of the solution with respect to the $K - R$-space requires the absolute slopes of both isoclines to be sufficiently large. The case that the steady state level χR exceeds the output is not possible, because of the assumption that F is linear homogenous of degree one.

Fig. 3.3 illustrates the dynamics of the system. If M is at its steady state level and the initial capital stock is lower than the steady state level, then the resource extraction will be increasing. This is the *capital accumulation effect* on $R(t)$. The arrows indicating the dynamics make clear that the condition for an EKC-path would be that the system moves from the left hand sector to the lowest sector. This dynamic leads to an suboptimal solution, since the capital stock has to increase in order to allow for arbitrary small resource extraction.

The two isoclines in Eq. 3.29 and 3.30 suggest that there is no inherent dynamic that leads to an EKC-style trajectory. This is due to absent interaction with the utility function, since $\dot{M} = 0$. The transition of R is monotone in K.

From the stability analysis so far we can summarise two answers that are related to the EKC-hypothesis. First, in the no policy case, there is no internal force that decreases the emissions, when $M_0 < M^{extern}$. Second, in the social optimal solution there can not be an EKC-style transition path, when either $M_0 = M^*$ or $K_0 = K^*$. We cannot analyse the transition dynamics with the method of isoclines, when $M_0 \neq M^*$ and $K_0 \neq K^*$.

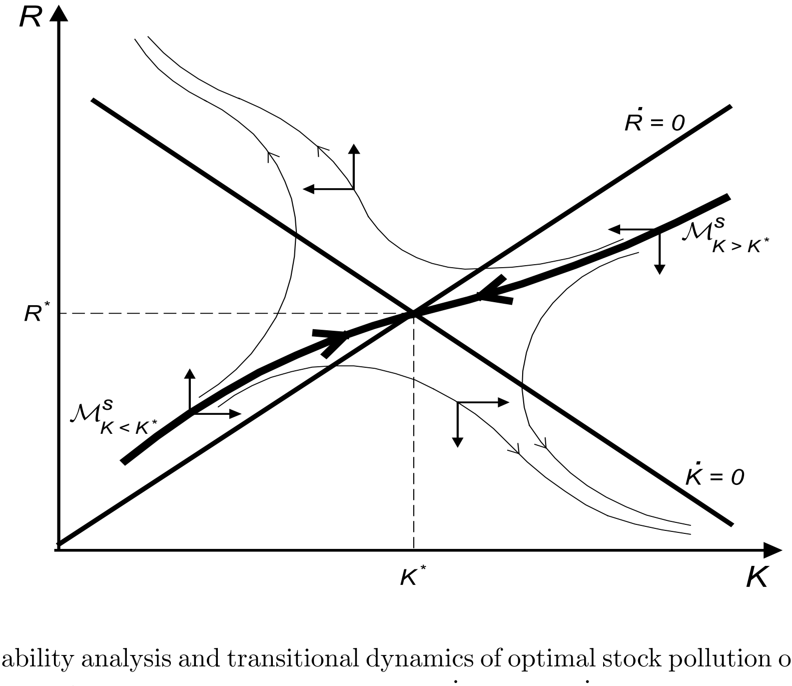

Figure 3.3: Stability analysis and transitional dynamics of optimal stock pollution of the extended Ramsey model. The figure shows the major isoclines $\dot{R} = 0$ and $\dot{K} = 0$, stable invariant manifold $\mathcal{M}^s$ and the steady state (K^*, R^*).

The question whether the model could serve as theoretical basis for the EKC-hypothesis is whether $\frac{\partial R}{\partial K} = 0$, if $M \neq M^*$ and $K \neq K^*$. Note that this deviates from the original EKC-hypothesis, which focuses on income. The question can be answered by dividing Eq. 3.25 through Eq. 3.18:

$$\frac{\partial R}{\partial K} = \frac{\dot{R}}{\dot{K}} = \frac{\frac{1}{F_{RR}}\left[\frac{U_M}{U_C} + (F_R - \chi)(\rho + \alpha + \Delta_{KRR})\right]}{F(K,R) - C - \chi R - \delta K}. \tag{3.31}$$

Increasing R require that the square bracket is negative, since $F_{RR} < 0$. This implies:

$$F_R - \chi < -\frac{U_M/U_C}{\rho + \alpha + \Delta_{KRR}}. \tag{3.32}$$

This is reasonable in economies with small K because utilisation of R gives rise to significant welfare improvements. In such a situation the difference $F_R - \chi$ is smaller than the stock externality as given in Eq. 3.32. At some point in time the steady state condition Eq. 3.26 holds with $\Delta_{KRR} > 0$; i.e. K keeps on growing. Afterwards it is optimal that the difference $F_R - \chi$ is greater than the stock externality, which leads to decreasing emissions implied by inversion of the inequality in Eq. 3.32. In the long run the steady condition for R is reached with $\Delta_{KRR} \rightarrow 0$; i.e. capital and the pollution stock reach their steady state values.

The switch of the sign of Eq. 3.31 is reasonable, since $\frac{\partial R}{\partial K} = 0$ does not imply $\Delta_{KRR} = 0$ *et vice versa*. Therefore, the EKC style growth pattern of economic affluence and pollution emissions is reasonable, if the stock pollution is controlled intertemporally optimal. The reason is that the social optimal solution takes into account the relative scarcities of capital and the pollution stock and treats them on different time scales. The development problem is initially pressing and solved in the short-term. During this period the wedge between F_R and χ is smaller than the stock externality. The pollution problem becomes pressing in the course of economic development and is addressed in the longer term. This induces the overshooting of emissions and therefore the EKC-style development pattern.

3.6.2 The Energy System

In this section the Ramsey model is extended by an energy sector that is modelled with a sector specific capital stock. The section shows that a multi-sector model can be transformed into a model with multiple capital stocks and only one sector.

This in turn leads to the question of aggregation of production factors; espec. the aggregation of capital stocks. The discussion of this issue is related the separability conditions of production factors. Checking the conditions for separability suggests that modelling energy sector specific capital stocks within a macro-economic framework is reasonable, if environmental policies affect energy production.

The Ramsey model is extended by the inclusion of secondary energy E_S as a production factor that enters the macro-economic production function. E_S in turn has to be produced by means of sector specific capital stock K_E and primary energy carrier E_P with the production function $E(\cdot)$. The production of E_P requires constant marginal production costs χ. The costs χE_P and the investments in energy related capital I_E are alternative uses of output Y that compete with consumption and investments I into the capital stock K. Therefore, the model can be written:

$$\underset{I,I_E,E_P}{\text{Max}}\, W! = \int_0^\infty e^{-\rho t} U(C) dt; \tag{3.33}$$

$$\dot{K} = I - \delta K, \qquad I \geq 0, \quad K(t=0) = K_0; \tag{3.34}$$

$$\dot{K}_E = I_E - \delta_E K_E, \qquad I_E \geq 0, \quad K_E(t=0) = K_{E,0}; \tag{3.35}$$

$$E_S = E(K_E, E_P), \qquad E_P \geq 0; \tag{3.36}$$

$$F(L, K, E_S) = C + I + I_E + \chi E_P, \qquad C \geq 0. \tag{3.37}$$

The important point in this model is that we can transform it easily into a simpler one by substituting Eq. 3.36 into the right hand side of Eq. 3.37. Additionally, we can – without loss of generality – remove the explicit notion of $E(\cdot)$. Therefore, the production function of Y is $\hat{F}$:

$$Y = \hat{F}(L, K, K_E, E_P). \tag{3.38}$$

The interesting point in Eq. 3.38 is that there are two different capital stocks with two different capital motion equations in Eq. 3.34 – 3.35. The solution of the investment paths depend on the production function and the depreciation rates. We cannot exclude from the above model setup that investments into one or the other capital stock is zero in the short run or in the steady state. If we assume the Inada-conditions[10] for all production factors to hold, then the steady state investments in

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[10] See Eq. 3.4 in Ch. 3.2.

each capital stock will be positive. Additionally, the shadow prices of each capital stock will reach the same steady state level; see Pitchford (1979) and Ch. 3.3 for details.

Aggregation of two production factors requires their separability from other production factors. The question is whether the two capital stocks (K, K_E) can be separated from L or E_P in $\hat{F}$ so that the resulting $\tilde{F}$ reproduces the results using the aggregation function $H(\cdot)$:

$$Y = \tilde{F}(L, H(K, K_E), E_P). \tag{3.39}$$

If the separability conditions hold the model Eq. 3.33 – 3.36 would reduce to the original Ramsey model with E_P as an additional production function. If the separability conditions do not hold one has to consider both capital stocks explicitly.

In the following the model is analysed with respect to its static and dynamic properties. The static properties are related to the separability of production factors. This requires the introduction of the concept of elasticity of substitution and a specific form production function with the property of constant elasticity of substitution CES. Then the conditions for separability are stated, which will be applied to Eq. 3.39 specified as a CES function. Then the dynamic properties are clarified by solving and analysing the optimal control problem. Both properties lead to the conclusion that energy sector specific capital stocks have to be modelled within a macro-economic framework in order to assess the impacts of energy related CO_2 emission mitigation.

The elasticity of substitution[11] is a static feature of a production function of a firm. In a cost-minimisation problem with constant factor and output prices the factor demands of the firm are such that the marginal productivity of each factor equals its factor price. The elasticity of substitution is related to the reallocation of factor demands due to changes in the factor price ratio in order to produce the given output level at minimum costs.

Fig. 3.4 illustrates the problem of a cost-minimising firm confronted with a changing factor price ratio, say from $\tan \pi^*$ to $\tan \pi^{\#}$, with $\tan \pi = -p_i/p_j$. Given the production function and $\overline{y}_l$ the minimal cost combination changes from (x_i^*, x_j^*) to

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[11] This terminus has been introduced by Hicks (1932). His original aim has been to characterise the changes of income shares of capital and labour within a growing economy by a single scalar – the elasticity of substitution – if the ratio of wage to interest changes.

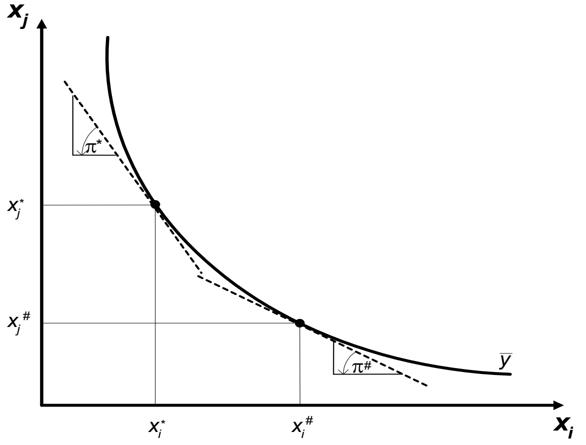

Figure 3.4: Minimal cost combinations of two production factors for a production function, when the price ratio changes.

$(x_i^\#, x_j^\#)$. The elasticity of substitution σ at (p_i^*, p_j^*) is defined as the ratio of relative changes of the input factor ratio to relative changes of the factor price ratio expressed:

$$\sigma = \frac{\partial(\frac{x_j^*}{x_i^*})\frac{x_i^*}{x_j^*}}{\partial(\frac{p_i^*}{p_j^*})\frac{p_j^*}{p_i^*}} \tag{3.40}$$

The elasticity of substitution is interesting for at least two reasons:

1. ***Essential production factor*** Fig. 3.5 illustrates the cost-minimal factor combinations for small firms with production functions characterised by three different σ. If $\sigma < 1$, minimum amounts of each x are required to produce $\overline{y_l}$; denoted $x_{i,l}^{min} > 0$. In this case each production factor is essential. If $\sigma > 1$, then one of each factor of production $x_{i,h}^{max} > 0$ is enough to produce the output $\overline{y}_h > 0$. The demand for the other production factor can be zero. In the special case $\sigma = 1$ – the Cobb-Douglas production function – every $\overline{y}_{cb} > 0$ can be produced with an arbitrary small amount of one production factor, when the amount of the other is sufficiently large.

2. ***Income distribution*** σ explains the quantitative shift of income distribution, if the relative factor price ratio changes. Suppose the wage-interest ratio increases. The cost-minimising firm will reallocate the production plan. This leads to a relative change of the ratio of capital and labour input. Suppose

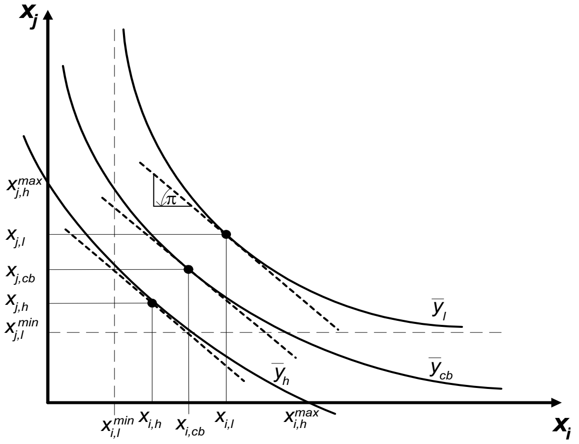

Figure 3.5: Minimal cost combinations of two production factors for production functions with different elasticities of substitution.

$\sigma < 1$: the effect of increasing relative factor price ratio exceeds the resulting relative increase of input factor ratio. In the example, this implies an increasing labour share $\frac{wL}{Y}$.

CES-type production functions are characterised by constant σ between each pair of production factors for all pairs of prices (p_i, p_j) and output levels.[12] The CES-functions used here exhibit constant returns to scale and are, therefore, linear homogenous of degree one. For the case of n production factors $x_i, i = 1, ..., n$, it is defined:

$$y = \left(\sum_{i=1}^{n} \xi_i x_i^{\tilde{\sigma}} \right)^{1/\tilde{\sigma}}, \qquad \tilde{\sigma} = 1 - \frac{1}{\sigma}. \tag{3.41}$$

The parameters ξ_i are distribution parameters and $\tilde{\sigma}$ is a parameter that is determined by σ. A specific production factor in turn can be the output of a CES

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[12] Arrow et al. (1961) first treated the elasticity of substitution within a parameterised production function. It implies – under the assumption of a competitive equilibrium prices – a unique determination of the distribution of income. The CES-production function has been the derived from a simple regression equation. The time series regression for 24 US-industries asked for the parameter of the log of real wage onto the log of labour productivity. The parameter has been different from zero at the 90% significance level for all industries and different from one for 14 industries; see Arrow et al. (1961, p. 228). This is in conflict with Leontief and Cobb-Douglas production functions, respectively. The CES-function is then developed directly from this regression equation. It is known that Leontief and Cobb-Douglas production function are special cases of the CES; see Maußner and Klump (1996, p. 50 – 59) and Chiang (1984, p. 425 – 430).

function with a different elasticity of substitution. This has been introduced by Sato (1967) and is termed nested CES production function; each CES function of the production function is called a CES nest and the output of a CES nest, which is input to a higher level CES nest, is called a CES composite. Such functions represent the complexity of the production structure of a sector.

Separability asks whether the ease of substitution between two production factors (x_i, x_j) is affected by variations of a third x_k. These conditions have been developed by Leontief (1947). For a production function f with n production factors $x_i, i = 1, ..., n$ the condition that x_i and x_j are separable from x_k requires (Felipe and Fisher, 2003, p. 224):

$$\frac{\partial}{\partial x_k}\left(\frac{\frac{\partial f(x_1,\ldots,x_n)}{\partial x_i}}{\frac{\partial f(x_1,\ldots,x_n)}{\partial x_j}}\right) = 0. \tag{3.42}$$

This implies that the marginal rate of technical substitution (MRTS) between x_j and x_i – the term in the bracket – is unaffected by changes in the availability of x_k. The MRTS is a measure for the ease of substitution for a decrease of x_i by increasing x_j to maintain the same level of output. It can be shown that this implies that a change of the price of x_k does not affect the factor ratio x_i/x_j. Moreover, if the separability condition holds, the elasticity of substitution between x_i and x_k equals that between x_j and x_k; see e.g. Frondel and Schmidt (2000).

For the example in Eq. 3.39 this condition can be checked using a nested CES-type production function of the following form:

$$Y = \left\{ \xi_A^L L^{\tilde{\sigma}} + \xi_A^K K^{\tilde{\sigma}} + \xi_{E_S}\left[\left(\xi_{K_E} K_E^{\tilde{\sigma}_E} + \xi_{P_E} E_P^{\tilde{\sigma}_E}\right)^{1/\tilde{\sigma}_E}\right]^{\tilde{\sigma}} \right\}^{1/\tilde{\sigma}}, \tag{3.43}$$
$$\text{with } \tilde{\sigma} = 1 - \frac{1}{\sigma} \quad \text{and} \quad \tilde{\sigma}_E = 1 - \frac{1}{\sigma_E} .$$

Applying the condition in Eq. 3.42 leads to the following equation, where E_S is the CES nest in the square bracket in Eq. 3.43:

$$\frac{\partial}{\partial E_P}\left(\frac{\frac{\partial Y}{\partial K}}{\frac{\partial Y}{\partial K_E}}\right) = \left(\frac{1}{\sigma} - \frac{1}{\sigma_E}\right)\frac{\xi_{E_P} E_P^{\tilde{\sigma}_E - 1}}{\xi_{K_E} K_E^{\tilde{\sigma}_E - 1}}\,\frac{\xi_K K^{\tilde{\sigma}-1}}{\xi_{E_S} E_S^{\tilde{\sigma}}} . \tag{3.44}$$

This equation shows that the separability condition holds, if and only if the elasticities of substitution σ and σ_E are the same. The reasonable case $0 < \sigma_E < \sigma < 1$ Eq. 3.44 implies that a decrease in E_P leads to a decrease of the MRTS between the two capital stocks. Note that this result is based on a nested CES production function that assumes separability of K and L from E_S.

Next, the original model in Eq. 3.33 – 3.37 is analysed in order to provide the qualitative insights into the steady state and the transition dynamics of investments into the two capital stocks. The Hamiltonian function $\mathcal{H}^E(\cdot)$ has to be analysed presumed that the solution exists:

$$\begin{aligned}\mathcal{H}^E(I, K, \lambda, I_E, K_E, \lambda_E, E_P) = U(F(L, K, E(K_E, E_P)) - I - I_E - \chi E_P) + \\ \lambda(I - \delta K) + \lambda_E(I_E - \delta_E K_E).\end{aligned} \tag{3.45}$$

λ and λ_E denote co-state variables of K and K_E, respectively. The optimal solution satisfies the system of equations:

$$\frac{\partial \mathcal{H}^E}{\partial I} = -U_I + \lambda \overset{!}{=} 0 \quad \Rightarrow \quad \frac{\dot{\lambda}}{\lambda} = \frac{U_{II}}{U_I}\dot{I}; \tag{3.46}$$

$$\frac{\partial \mathcal{H}^E}{\partial I_E} = -U_{I_E} + \lambda_E \overset{!}{=} 0 \quad \Rightarrow \quad \frac{\dot{\lambda}_E}{\lambda_E} = \frac{U_{I_E I_E}}{U_{I_E}}\dot{I}_E; \tag{3.47}$$

$$\frac{\dot{\lambda}}{\lambda} = \rho + \delta - \frac{U_F}{\lambda}F_K \quad \Rightarrow \quad \frac{\dot{\lambda}}{\lambda} = \rho + \delta - F_K; \tag{3.48}$$

$$\frac{\dot{\lambda}_E}{\lambda_E} = \rho + \delta_E - \frac{U_F}{\lambda_E}F_E E_{K_E} \quad \Rightarrow \quad \frac{\dot{\lambda}_E}{\lambda_E} = \rho + \delta_E - F_E E_{K_E}. \tag{3.49}$$

One immediately can conclude from the left hand equations of Eq. 3.48 and 3.49 that in the steady state the net rates of return are the same with respect to both capital stocks:

$$r = F_K - \delta = F_{K_E} - \delta_E = F_E E_{K_E} - \delta_E. \tag{3.50}$$

r is the steady state net rate of return that – below – turns out to equal ρ. Burmeister (1980, p. 131 – 134) shows that in the steady state multiple capital stocks K_i can be aggregated to K with the property $dK/dr < 0$, if:

$$\frac{\sum_i dK_i}{dr} < 0 \quad \text{and } F_{K_i K_i} < 0. \tag{3.51}$$

By forming the total differential of Eq. 3.50 and making some minor manipulations, it follows that in the steady state:

$$\frac{1}{F_{KK}} = \frac{1}{F_{K_E K_E}} = \frac{dK}{dr} = \frac{dK_E}{dr} < 0. \tag{3.52}$$

It is easy to see that this equation satisfies condition Eq. 3.52. Note, that this aggregation condition is valid for the steady state.

In the following the dynamics of the system are analysed, if the initial capital stocks are not in the steady state. If the left hand equations of Eq. 3.46 and 3.47 are equalised with the left hand equations of Eq. 3.48 and 3.49, respectively, one can derive the following two useful differential equations:

$$\frac{\dot{I}}{I} = \frac{1}{\eta}\left(F_K - (\rho + \delta)\right), \qquad \eta = -\frac{U_{II}}{U_I}\, I; \tag{3.53}$$

$$\frac{\dot{I}_E}{I_E} = \frac{1}{\eta_E}\left(F_K E_{K_E} - (\rho + \delta_E)\right), \quad \eta_E = -\frac{U_{I_E I_E}}{U_{I_E}}\, I_E. \tag{3.54}$$

These equations show that the growth rate of I_E exceeds that of I, if E_S is assumed to be relatively scarcer because investment into K_E leads to a higher rate of return than into K. The accumulation process leads to decreasing differences of the net return rates of the capital stocks, which causes the growth rates of investments to converge. This implies that the share $I_E/(I + I_E)$ decreases and asymptotically approaches its steady state in which the condition in Eq. 3.50 holds.

Obviously, the steady state condition Eq. 3.50 does not hold, if the initial capital stocks do not equal the steady state level.[13] Therefore, in the case of diminishing returns of both capital stocks the aggregation condition Eq. 3.51 is not fulfilled and therefore the capital stocks cannot be aggregated. This implies that both capital stocks have to modelled explicitly, if the interest is in transition dynamics.

The analysis above regards the coverage of models that consider energy related CO_2 emission mitigation. If the static separability condition is assumed not to hold, then models that employ marginal cost functions MCF and energy system models ESM are questionable for the analysis of the economic consequences of climate policies; see Ch. 2.7. The reason is that both model types do not represent the macro-economic feedbacks with the energy system, which might change the income distribution. Moreover, the dynamic analysis beyond the steady state suggests that modelling disaggregated capital stocks within a framework of economic growth is necessary, since the relative scarcity of capital stocks have implications on the investment dynamics. The primary guiding question of this thesis addresses the temporary role of CCS being essentially a transitory phenomenon beyond the

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[13] Except for an obvious special case.

steady state. Thus, the sound assessment of CCS and other CO_2 emission mitigation options has to take account of the macro-economic feedbacks.

Two points should be noted. First, even in the case of heterogenous capital goods the decentralised market solution leads to a Pareto optimal equilibrium, if a complete set of future markets is present. Moreover, the saddle point property of the decentralised system is maintained, even if the initial conditions of multiple capital stocks do not coincide with their steady state values; see Dorfman et al. (1958, Ch. 11) and Burgstaller (1994, Ch. 2). This implies that the social welfare maximisation replicates the market solution with respect to the steady state and the transition dynamics. Second, the discussion above does not comprise the question of the aggregation of various sectors producing various end-use goods like food, movies, houses etc. into an aggregate production function with an aggregate capital stock; see Burmeister (1980).

3.6.3 Endogenous Technological Change

In the following the Ramsey model is extended to an endogenous growth model. The primary focus is to validate the model variants against empirical data series in order to discriminate between model variants and to ask for parameter values of particular functional relationships. In the end the implications for the *MIND* model are discussed.

In this section the Ramsey model is extended by endogenous labour augmenting technological change that is represented in the variable A. Increasing A shifts the labour demand curve, which increases the willingness to pay for the same amount of labour as the productivity is higher. There are four different variants by which technological change is induced that lead to an increase of A. Two are related to research, development and deployment (RD&D) or physical capital investments:

1. ***RD&D investments*** RD induce direct effect on the labour productivity; see Jones (1995a), Jones and Williams (2000) and Edenhofer (1999).

2. ***RD&D investment share*** RD/Y induces direct effect on the labour productivity.

3. ***Capital investments*** I induce an external effect on the labour productivity; see Scott (1989), Greiner and Semmler (2001) and

Greiner and Semmler (2002).

4. ***Capital investment share*** I/Y induces an external effect on the labour productivity.

The model and its variants can be stated as follows:

$$\underset{I,RD}{\text{Max}}\, W! = \int_{\tau_0=1970}^{\tau_1=2050} e^{-\rho t}\log\left(\frac{C}{L}\right) dt; \tag{3.55}$$

$$Y = \Phi\left[\xi_L (A\cdot L)^{\tilde{\sigma}} + \xi_K K^{\tilde{\sigma}}\right]^{1/\tilde{\sigma}}, \quad \tilde{\sigma} = 1 - \frac{1}{\sigma}; \tag{3.56}$$

$$\dot{K} = I - \delta K, \qquad I \geq 0, \qquad K(t=t_0) = K_0; \tag{3.57}$$

$$Y = C + I + RD \qquad C \geq 0; \tag{3.58}$$

$$\dot{A} = \alpha_3 RD^{\beta_3} A^{\phi}, \qquad RD \geq 0, \qquad A(t=t_0) = A_0; \tag{3.59}$$

$$\frac{\dot{A}}{A} = \alpha_4\left(\frac{RD}{Y}\right)^{\beta_4} - \delta_{A_4}, \qquad RD \geq 0, \qquad A(t=t_0) = A_0; \tag{3.60}$$

$$\dot{A} = \alpha_1 I - \delta_{A_1}, \qquad RD = 0, \qquad A(t=t_0) = A_0; \tag{3.61}$$

$$\frac{\dot{A}}{A} = \alpha_2, \left(\frac{I}{Y}\right)^{\beta_2} - \delta_{A_2} \qquad RD = 0, \qquad A(t=t_0) = A_0. \tag{3.62}$$

In the two cases with RD&D investments the variable RD enters the budget equation in order to take account of the trade-off with consumption. The investments in physical capital are different from the RD&D expenditures from a conceptual point of view. The physical investments built up production capacities in the respective sectors, while the RD&D expenditures increase the efficiency of production factors. The RD&D investments are assumed to be financed by a social optimal lump-sum tax. The RD&D activity does not require production factors.

The initial period of the models time horizon is 1970. The terminal period 2050 is chosen for computational reasons that are related to the terminal value problem and are discussed in detail in Ch. 2.5.3.

The functions are given in parametric form because the model is computed numerically. In Eq. 3.55 the logarithmic function is a specific form of the utility function in each period. In Eq. 3.56 the production function is of the CES-type. The Eq. 3.59 – 3.62 are alternatively applied for the four modelling approaches. For the model variants 3. and 4. the RD&D expenditures RD equal zero. The initial condition A_0 is calibrated to reproduce the data in the initial period. The other parameters will be introduced next.

The parameter α is a productivity parameter. The parameter β is a dampening factor that represents intra-period diminishing returns; Jones and Williams (2000) called it the stepping-on-toes parameter. The parameter ϕ is an inter-temporal dampening factor that controls the negative impact of accumulated knowledge on the subsequent accumulation; Jones and Williams (2000) called it the standing-on-shoulders parameter. The parameter δ_A represents the obsolescence of knowledge through time or if it is negative it indicates exogenous technological progress.

The goodness of validation criterion V is as follows:

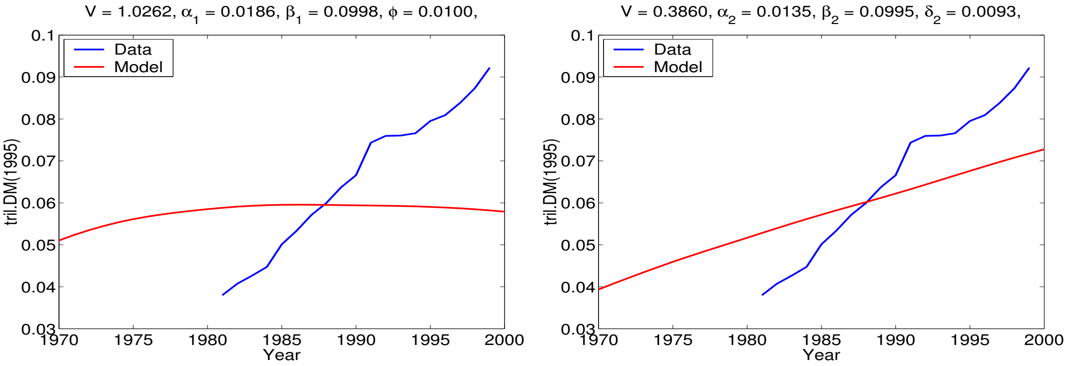
$$V = \left(\sum_t \left(\frac{I(t) - I^D(t)}{I^D(t)}\right)^2\right)^\omega + \left(\sum_t \left(\frac{RD(t) - RD^D(t)}{RD^D(t)}\right)^2\right)^{1-\omega}. \tag{3.63}$$

Variables with the superscript D denote the time series data. The relative deviations between the model results and the data for each time step have been chosen in order to avoid a bias that could arise within a growing economy and to avoid a bias that arises from differences of the nominal magnitude of the variables I and RD. The weighting factor ω is set to 1 for the model variants 1. and 2. and set to 0.5 for the model variants 2. and 4.

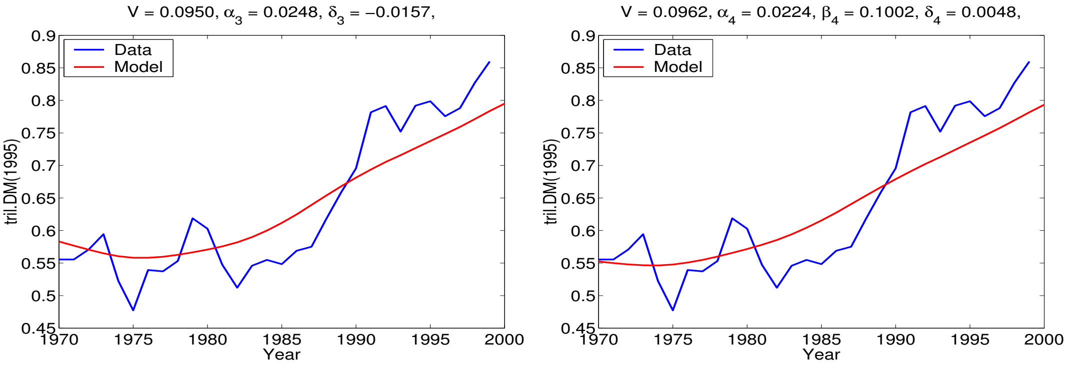
The criterion V is minimised by varying the parameters in one of Eq. 3.59 – 3.62, depending on the model variant. The minimisation procedure is taken from Judd (1999, p. 114 – 115) and implemented in *MatLab*, which in turn calls the optimisation for the particular model variant written in *GAMS*. This program structure is embedded into the simulation environment (*SimEnv*), which is able to validate various model variants, for several countries and data sets on a parallel computing machine. This software environment is called ***MO***del ***V***alidation ***E***nvironment (*MOVE*). So far, *MOVE* is only able to validate single economies without trade and knowledge spill-overs.

The validation has been undertaken for a number of OECD countries based on time series from the OECD database. In the following the results for Germany are presented (see Fig. 3.6) because an extensive presentation of the results of all countries would be too space consuming. The results for the discrimination between the model variants are similar for these countries.

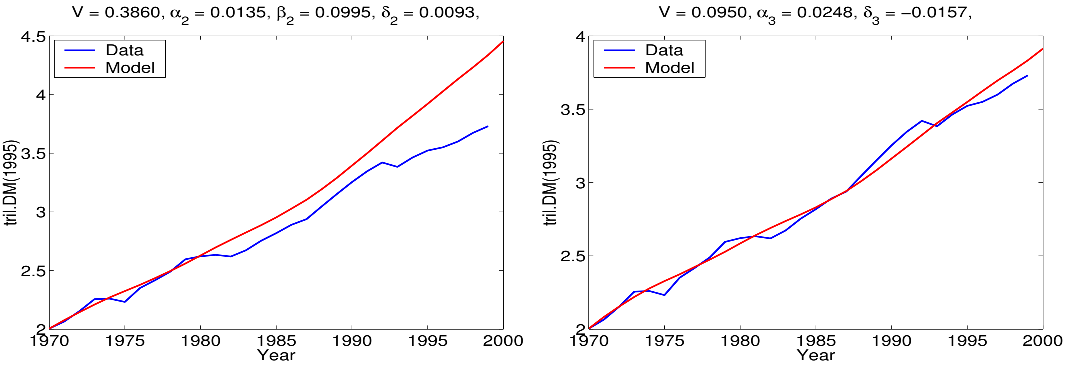
Fig. 3.6(a) and 3.6(b) show the validation results for the RD&D expenditures for the model variants 1. and 2. Obviously, the agreement between data and model



(a) RD for variant 1. (RD) (b) RD for variant 2. (RD/Y)



(c) I for variant 3. (I) (d) I for variant 4. (I/Y)



(e) Y for variant 2. (RD/Y) (f) Y for variant 3. (I/Y)

Figure 3.6: Validation of the Ramsey model with endogenous growth for the four model variants. The example here is Germany and the monetary units are tril. Deutsch Mark (DM) deflated to 1995. The figures show the comparison of empirical data and model variables for the optimal parameter sets found with *MOVE*. The parameter values and the validation criterion are given in the figures.

is better for variant 2., but both variants seem not to reproduce the data very well. Variant 1. exhibits an inverted-U shape although the RD&D expenditures increase over time. The much higher validation criterion of this variant is also due to the worse reproduction of the investment time series (not shown). Therefore, within the class of models with RD&D investments, the variant with RD&D share is superior to that with absolute RD&D investments.

Fig. 3.6(c) and 3.6(d) show the validation results for the capital investments for the model variants 3. and 4. Both variants are comparable with respect to the validation criterion; variant 3. seems a bit superior. During the seventies the data on investments stagnate and increase during the eighties until today. The sharp take-off in the late eighties can not be reproduced.

Fig. 3.6(e) and 3.6(f) show the comparison for income Y for variants 2. and 3. Although this variable does not enter the validation criterion, both variants are able to reproduce the time series quite well. Variant 3. shows a very close matching, while in variant 2. the model economy grows faster than the empiric time series.

This validation exercise indicates that endogenous growth models based on RD&D investments are not really appropriate to reproduce historic time series. The modelling approach that assumes an external effect from capital investments on labour productivity is much better for explaining historical time series.

The model *MIND* is different from the model structure given above, since energy enters the production function. It is reasonable that the productivity of energy also increases endogenously according to the concept of Harrod-neutrality. This means that in *MIND* the bias of productivity growth between labour and energy is modelled. The endogenous determination of two productivity increases is difficult to model, if both depend on the same single variable for investments. Therefore, in *MIND* the endogenous growth of labour and energy productivity is determined by specific RD&D investments for these two distinct purposes. In Edenhofer et al. (2004b) an approach based on externalities from capital investments is developed to overcome this problem and still to represent the bias in productivity growth.

There are two alternative modelling approaches of endogenous technological change related to the macro-economic production function in the scientific literature on CO_2 emission mitigation. First, in Nordhaus (2002) the R&D expenditures increase one capital stock, which affects the emission intensity factor that translates economic output into carbon emissions, without account for energy as a production factor. In Buonanno et al. (2003) this knowledge capital stock additionally affects the total factor productivity of production. In this approach there is no bias in technological change and an effect on distribution is not taken into account, explicitly. The endogenous bias in technological change has not been integrated into integrated assessment models. Analytical models of the bias have been discussed in Edenhofer (1999) and Smulders and Nooij (2003).

3.7 Discussion and Conclusion

This chapter dealt with the Ramsey model at the analytical level and has been extended into three direction. The Ramsey model is the economic backbone of the *MIND* model that will be introduced in the next chapter. *MIND* integrates *inter alia* the three extensions into one framework.

The Ramsey model is a growth model that takes account of the intertemporal effects of saving and consumption. The intertemporal effect of saving on current well-being is taken into account through shadow prices attributed to stock variables. In the basic Ramsey model this has been the capital stock. The maximum principle solution technique by Pontrjagin leads to an intertemporal optimal solution for the control variables. The social optimal solution is equivalent to the market solution.

The model is augmented by the production factor fossil fuels, which leads to emissions that accumulate in a stock pollution that harms welfare. This mimics the basic mechanism of climate change. As expected, the analysis shows that the decentralised market solution does not lead to the social optimal solution, which is due to the environmental stock pollution. The steady-state solution suggests a capital theoretic interpretation, since the current emissions lead to long lasting reductions of welfare that have to be internalised into the calculation of fossil fuel use. The interesting thing in the transition analysis is that the social optimal policy could allow an overshooting of the emissions. This is due to relative scarcities of the capital and the pollution stock that lead to an intertemporally consistent solution that allows initially increasing and then decreasing emissions. This is a contribution to the theoretical foundation of the environmental Kuzents curve EKC.

Since the production of useable secondary from primary energy is a capital intensive production process, the focus is put on the sectors that supply and demand secondary energy within a Ramsey model with multiple capital stocks. This leads to the question whether the capital stocks in the two sectors could be aggregated or should be modelled separately. Application of standard conditions of aggregation in a static setting revealed that this requires a very restrictive assumption: the elasticity of substitution between capital and primary energy in the supply sector has to be the same as that between capital and secondary energy in the demand sector. Moreover, the investment dynamics into two capital stocks has to be modelled explicitly, if the system starts at arbitrary initial capital stocks, which is required by dynamic conditions for capital stock aggregation. This is a contribution to the theory of production and capital aggregation.

Assessments of CO_2 emission mitigation targets should be based on models that reproduce time series of empirical data. For this purpose four model variants of an endogenous growth model are validated against data. The validation is done by finding the set of parameters that lead to optimal reproduction of the data by the model. It has been found that models that are based on positive externalities of capital investments on labour productivity are superior to models that model technological progress as directly improving labour productivity due to specific RD&D expenditures.

This leads to the conclusion that hybrid-type models are necessary, if long-term assessment of CO_2 emission mitigation options are studied. This is related to the explicit representation of the climate system as well as the energy system within a growth theoretic framework. The validation of such models requires additional research.

Chapter 4

MIND – The Model of Investment and Technological Change

In the preceding Ch. 3 the treatment of capital and investment within the Ramsey model has been introduced and extensions to take account of climate change, energy and endogenous technological change were presented. In this chapter the model *MIND1.0* is developed.[1]

The section is organised as follows. First, an overview is given in Ch. 4.1 of the model structure and the integration of the climate and the energy system with the economic system. Then the model is laid out in detail with respect to the mathematical representation in Ch. 4.2 and the exogenous assumptions on parameter values and exogenous scenarios in Ch. 4.3. Computational issues are discussed in Ch. 4.4. Next, results and sensitivity analysis with and without exogenous CCS are presented in Ch. 4.5. In the end conclusions are drawn (Ch. 4.6).

4.1 Overview of the Model

This model integrates the three extensions of the Ramsey model introduced above into a single framework, adds renewable energy technologies with learning by doing and adds CCS as an exogenous path. Therefore, it is a Ramsey-type growth model with sectoral disaggregation, explicit treatment of energy, endogenous technological change and a climate model. Implications on macro-economic variables – like

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[1] This is an extension of Edenhofer et al. (2005).

investment rates and income distribution – caused by climate protection strategies can be assessed. The effects of climate change on the economic system is modelled by imposing guardrails on endogenous environmental variables.[2] The model deals with variables at the global level; i.e. there is no explicit treatment of trade.

The population number in *MIND* is given exogenously. SRES population scenarios common in the literature are used; therefore the comparability with other models is assured. The modelling approach applies the concept of the representative household.

The economic system in *MIND1.0* is essentially characterised by a multi-sectoral production structure; see Fig. 4.1. There is a vertical as well as a horizontal disaggregation of the economy. At the highest level there is the aggregated production sector. The three production factors capital, labour and energy are inputs to that sector. The physical units of labour and energy can be increased by RD&D investments.

Energy has to be produced by three alternatives. First, secondary fossil energy is produced with capital and fossil primary energy carriers. Second, renewable energy is produced with capital. Third, traditional non-fossil energy (large hydro power, nuclear energy, traditional biomass) is introduced exogenously. Fossil energy carriers have to be produced, too, which requires capital.

There are two concepts of technological development in *MIND*. First, the augmentation of energy and labour is due to specific investments into the development of the corresponding efficiency parameters. This implies that the technical progress is Harrod-neutral. Second, technological development takes place in this model through physical investment in the renewable energy and the fossil resource sector. This is represented through the concept of learning by doing. The experience depends on cumulative investments. Moreover, the fossil energy extraction sector is subject to increasing scarcity, which opposes the learning effect.

Fig. 4.1 shows that there are eight first order input factors: two of them are given exogenously, two are knowledge capital and four are physical capital. The dynamics of these six capital stocks are determined by investment flows and depreciation. In each period the income is allocated either to consumption or to specific investments.

The multi-sectoral production function is embedded in a broader context implied

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[2] Alternatively, a damage function could be introduced, which has negative effects on economic variables.

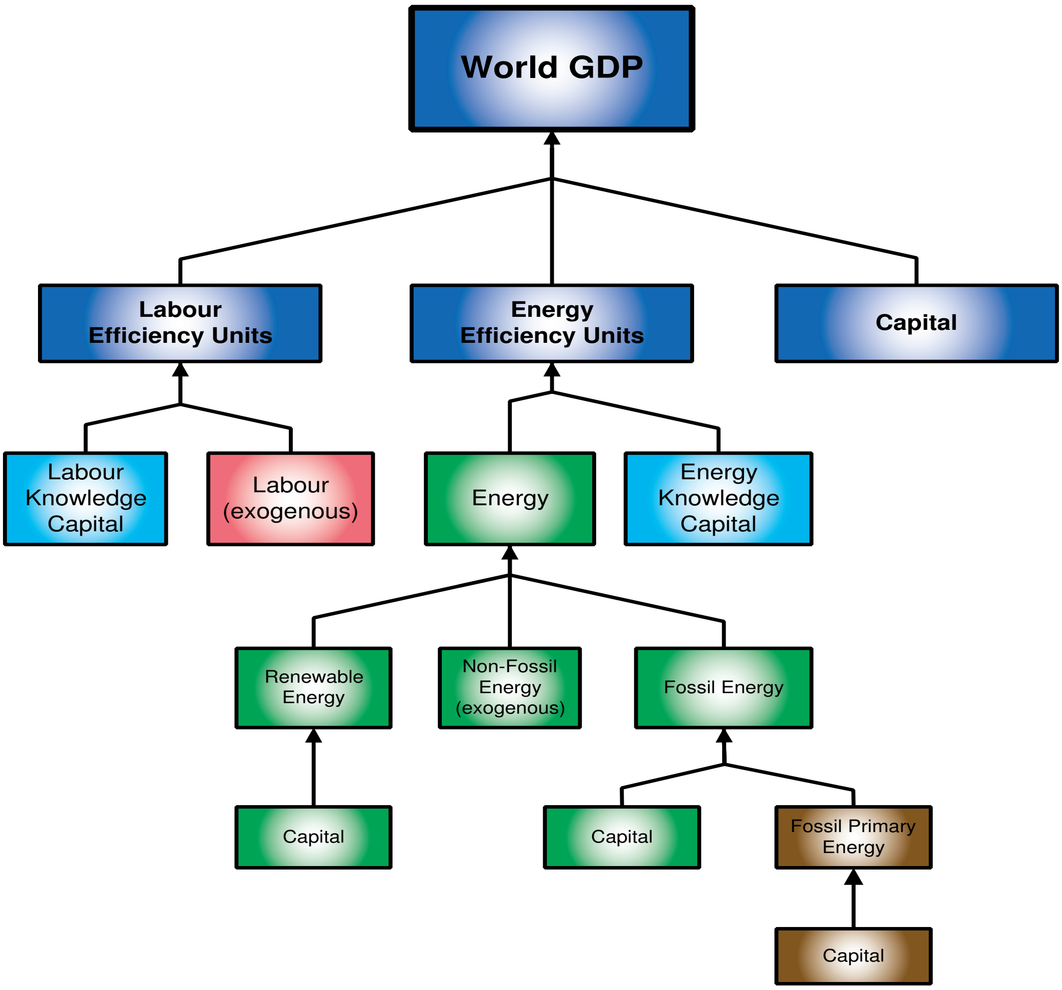

Figure 4.1: Multi-sectoral structure of *MIND1.0*.

by the investment flows, the emissions and the constraints of the climate system. The overall structure is given in Fig. 4.2, which consists of three parts. The global world product GWP is allocated to consumption and investment in order to maximise the welfare of the world population, as can be seen in the south-east part. The maximisation is subject to constraints from the economic system (the middle part) and constraints that are imposed on the climate systems (north-west part).

The explicit treatment of energy in the context of climate change is due to the significance of energy related CO_2 emissions as has been emphasised in Sec. 2.3, the significance for production and the long duration of energy related investments.

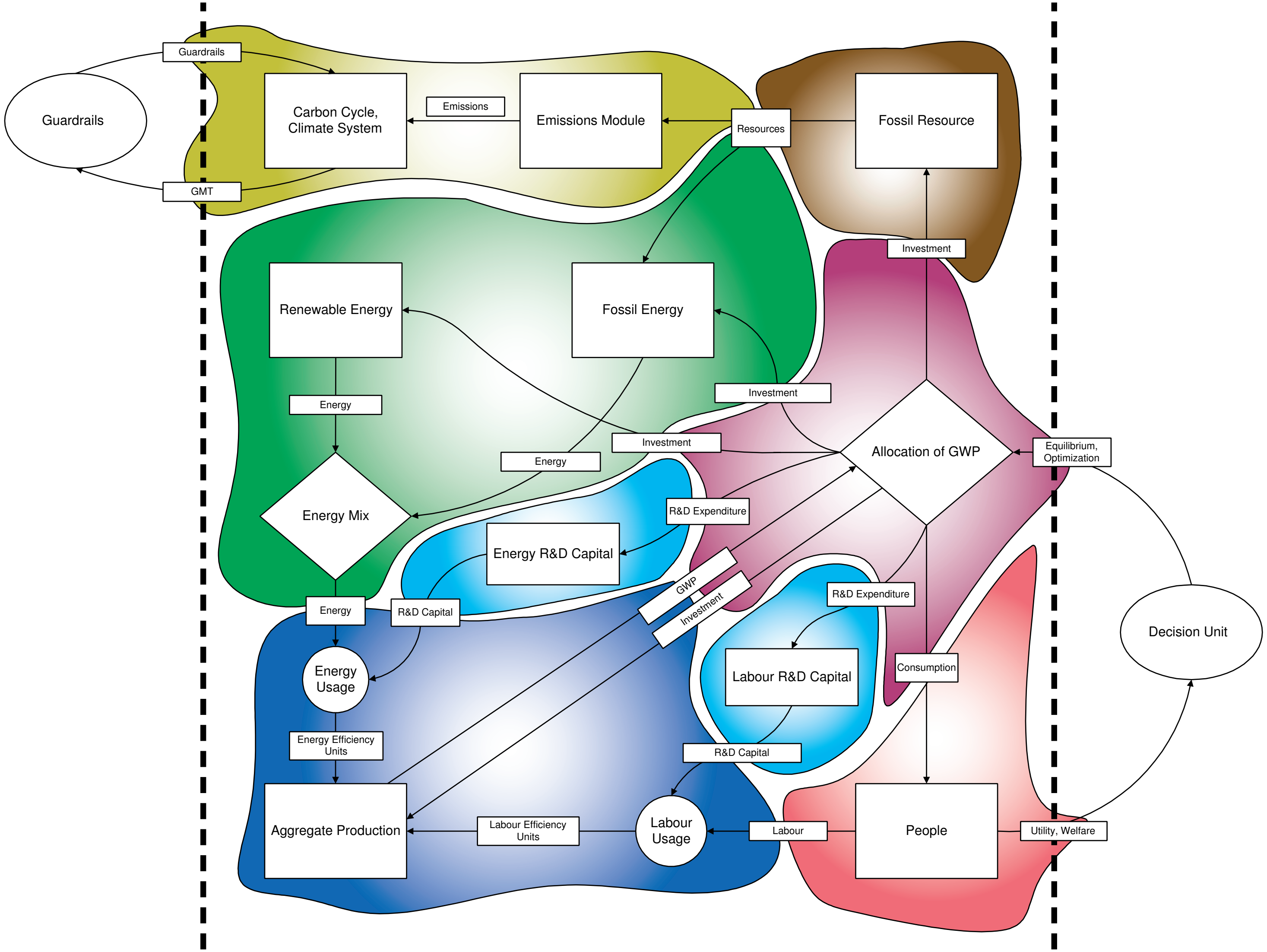

Figure 4.2: Integrated scheme of *MIND1.0*.

Therefore, CO_2 emissions can be seen as the by-product of using fossil energy carriers. Aerosol emissions are also modelled as by-product of fossil primary energy use.

The CO_2 emissions accumulate in the atmosphere over long time horizons, while aerosols remain in the atmosphere for a short time, only. Both change the radiative forcing, but with opposite signs. Additionally, other than CO_2 GHG (OGHG) are introduced exogenously. The increase of radiative forcing changes the GMT subject to inert dynamics caused by the oceans.

In this thesis the model computes the social optimal CO_2 emission mitigation strategy subject to constraints on environmental variables. This means that the domain for optimisation is restricted. The constraints are lexicographic preferences in accordance with the German Scientific Advisory Board for Global Change. This board advices that the GMT should not exceed 2°C above pre-industrial levels and the rate of temperature change should not exceed 0.2°C per decade.

4.2 The *MIND* Modules

This section develops the model structure of *MIND1.0* in detail. The organisation follows the modular structure given in Fig. 4.1 and Fig. 4.2.

4.2.1 The Household Sector

The household sector lies at the heart of *MIND* for four reasons that are discussed in more detail below. First, the household sector's intertemporal social welfare is the objective that is maximised. Second, the household sector receives income for the supply of production factors that are allocated to alternative purposes in order to maximise the social intertemporal welfare function. Third, the demographic development of the population is contained in the household sector. Fourth, the climate protection constraint is imposed in the interest of the household sector.

The household's intertemporal social welfare measure W is based on the concept of the intra- and intertemporal preference aggregation introduced in Ch. 3.2. The implementation for numerical computations requires a specific form for the per capita utility function in each period. As in most IAMs of the Ramsey-type this is assumed to be the natural logarithm of per capita consumption c implying an intertemporal elasticity of substitution IES equal to one. The intertemporal social welfare function is time discrete with a finite time horizon (τ_1, τ_2) and the discounting rate is ρ:

$$W = \sum_{t=\tau_1}^{\tau_2} e^{-\rho(t-\tau_1)} L(t) \log(c(t)); \qquad W \in \mathbb{R}. \tag{4.1}$$

The second point given above considers the allocation of a scarce income on alternative purposes summarised in the budget equation:

$$Y(t) = C(t) + \sum_m I_m(t) + \sum_n RD_n(t) + \Omega(t), \qquad \forall\, t. \tag{4.2}$$

The income Y can be allocated to the following purposes. First, consumption C that enters the welfare measure, second, the investments I_m in physical capital stocks and third RD&D expenditures RD_n. The indices m and n distinguish the several investments in physical and knowledge capital, respectively. The variable Ω represents other expenditures that are introduced as exogenous paths like for non-modelled energy sources.

The third point making the household sector important is related to labour income. The labour supply is closely connected to demographic development. The population number of the household sector is given exogenously and the supply of labour is inelastic with respect to wages and wealth; there is no labour-leisure choice. The concept of the representative household states that the labour productivity – and therefore the wage – is the same for everybody. This implies that the demographic structure of the population has no influence on economic growth.

The fourth point given above is that the climate protection constraint is imposed in the interest of the household sector. Two constraints are imposed on the development of the global mean temperature GMT that is denoted T. The first constraint limits the GMT to stay below GR_T and the second limits the rate of change of GMT $GR_{\Delta T}$:

$$T(t) \leq GR_T, \qquad \forall\, t \in [\tau_1, \tau_2]; \tag{4.3}$$

$$T(t+1) - T(t+1) \leq GR_{\Delta T}, \qquad \forall\, t \in [\tau_1, \tau_2]. \tag{4.4}$$

This approach follows the cost-effectiveness mode of policy optimisation analysis. Alternatively, the change of climate or other environmental variables affect welfare directly. This seems plausible, since climate change might affect the private property values, the health and well-being of households to a considerable extent. The cost-effectiveness mode is chosen because the selection of damage functions is highly questionable.

The social planning problem is to allocate Y to the alternative purposes in order to maximise W subject to economic and natural functional relationships and – if considered – the climate protection constraints. The functional relationships will be introduced in the following subsections.

A point of critique of the household sector with respect to climate protection policy is that households do not directly demand energy. Consumption goods are the only argument of the welfare function, which are homogenous. This is at odds with the fact that households in the real world do demand energy. A great amount of this energy demand stems from the use and application of durable consumption goods: space heating and warm water in houses, fuel for cars and electricity for household appliances like refrigerator and washing machines. In *MIND* this is related to the macro-economic production function and its elasticity of substitution. Since the household energy demand stems to a large part from the use of durable consumption goods, this is an argument for a low elasticity of substitution. See Tab. 4.3 in Ch. 4.3.2 for empirical findings of this issue.

In summary, the welfare measure in *MIND* is in principle the same as in other Rasmey-type IAMs. Therefore, the general objections against this approach apply to the *MIND* framework, too. The allocation of income depends on the features of various economic sectors that will be introduced in the following sub-sections. With respect to the assessment of global climate protection strategies, there are particular points of critique on the model approach of the household sector due to energy demand, climate impacts and the demographic development.

4.2.2 The Aggregated Production Sector

The aggregate production sector describes the transformation of production factors into output and its distribution among production factors. The model *MIND* deals with energy related CO_2 emissions mitigation within a macro-economic setting, where the demand of energy is modelled in the aggregated production sector. The aggregate production sector considers static and dynamic features that will be treated in the following.

The macro-economic production function contains the static aspects of the aggregate production sector. It is of the CES-type, which has been introduced above (Ch. 3.6.2). The production function is:

$$Y = \Phi_A \left[\xi_A^L (A \cdot L)^{\tilde{\sigma}_A} + \xi_A^E (B \cdot E)^{\tilde{\sigma}_A} + \xi_A^{K_A} K_A^{\tilde{\sigma}_A}\right]^{\frac{1}{\tilde{\sigma}_A}}, \quad \tilde{\sigma}_A = 1 - \frac{1}{\sigma_A} . \tag{4.5}$$

Three production factors – capital K_A, labour L and secondary energy E_A^S – are required to produce the global world product GWP Y; the subscript A denotes the aggregate production sector. Φ_A is a time invariant scaling factor; ξ_A^i, with $i = K_A, L, E$, are distributional parameters; A and B are technological parameters affecting the production factors L and E, respectively.

The energy E_A^S is delivered by three sources: fossil energy production $E_{S,F}$, renewable energy production $E_{S,R}$ and other $E_{S,other}$. The latter is assumed exogenously and the former two are determined endogenously, which will be described later. The secondary energy balance equation is:

$$E_S^A = E_{S,F} + E_{S,R} + E_{S,other} . \tag{4.6}$$

The static production function is related to four dynamic processes. First, the capital motion equation is the time discrete version of the Ramsey model:

$$K_A(t+1) = I_A(t) + (1 - \delta_A) K_A(t), \qquad K_A(t = \tau_1) = K_A^0 . \tag{4.7}$$

δ_A is the constant capital depreciation rate; K_A^0 is the initial capital stock. Investment I_A is related to the budget constraint Eq. 4.2.

The remaining dynamic aspects are treated in other sections:

1. Labour force: This is the exogenous path as described in Ch. 4.2.1.
2. Endogenous Technological Change: The development of A and B over time has implications on production and distribution in this sector. The endogenous determination of the parameters is given in Ch 4.2.3.
3. Energy: The production of energy is modelled explicitly and subject to endogenous dynamics. It is discussed in detail in Ch. 4.2.4 – 4.2.6.

4.2.3 The RD&D Sectors

The RD&D sectors are modelled according to variant 3. as has been introduced in Ch. 3.6.3. Specific RD&D expenditures improve the efficiency parameters A and B

of the aggregate sector production function Eq. 4.5:

$$A(t+1) = \left(1 + \alpha_A \left(\frac{R_A}{Y}\right)^{\beta_A}\right) A(t), \qquad A(t = \tau_1) = A^0; \tag{4.8}$$

$$B(t+1) = \left(1 + \alpha_B \left(\frac{R_B}{Y}\right)^{\beta_B}\right) B(t), \qquad B(t = \tau_1) = B^0. \tag{4.9}$$

The parameters α_A and α_B determine the productivity of the RD&D expenditure rates. The parameters β_A and β_B determine the dampening of the RD&D expenditure rates. The dampening is due to the diminishing returns of RD&D within a period. Jones and Williams (2000) named this effect *stepping on toes* and addressed the following phenomena to it: patent races of competing firms, double work due to poor organisation and decreasing productivity because of hiring of less innovative researchers.

There is no depreciation of knowledge as soon as it is incorporated in either A or B. This effect is known as *standing on shoulders*. Since there is no dampening factor on A and B the productivity of constant RD&D expenditure rates does not change. There is an diminishing productivity effect with respect to the RD&D expenditures, if the economy is growing, which is equivalent to a growing Y. In this case, while keeping the RD&D expenditures constant, the RD&D rates decrease with time and so do the growth rates of A and B.

The initial conditions for A and B are chosen in order to reproduce data of the aggregate production function; see Ch. 4.2.2. They do not exhibit an interpretation.

4.2.4 The Fossil Resource Sector

Fossil primary energy carriers R are located in the earths crust and have to be extracted prior to their utilisation. The exploration of deposits is not modelled endogenously; see Pindyck (1978) for modelling approaches. It is modelled as a production process that demands sector specific capital K_R. The production function is a linear relationship of sector specific capital with productivity parameter κ:

$$R = \kappa \cdot K_R. \tag{4.10}$$

The productivity parameter κ develops endogenously due to two processes. The first effect is the scarcity effect; summarised in κ_s. The second effect is learning within the sector; summarised in κ_l. While the scarcity effect decreases the productivity of capital, learning increases it. Both effects are combined by multiplication and will be described below:

$$\kappa = \kappa_s \cdot \kappa_l. \tag{4.11}$$

The scarcity effect: Scarcity is due to the exhaustion of easily exploitable deposits.[3] The accessibility includes four aspects. First, the geological underground and natural conditions vary between deposits. Second, the locations and the ease of transporting them to the place of utilisation are different. Third, the quality of the energy carriers differ with respect to the ease of transformation. Fourth, resource extraction trades off with alternative utilisation of land, where the energy carriers are located underground. This is especially important for open cast mining of coals or oil sands. The four characteristics influence the need of production factors for extraction of fossil primary energy.

It is assumed that these four effects can be aggregated in order to imply a sequence of extraction of deposits. This sequence puts the deposit with the highest capital productivity at the highest position followed by deposits with lower capital productivity. The following parameterised form is based on Nordhaus and Boyer (2000, p. 54):

$$\kappa_s(t) = 1 + \frac{\chi_2}{\chi_1}\left(\frac{\sum_{\tau=\tau_1}^{t} R(\tau)}{\chi_3}\right)^{\chi_4}. \tag{4.12}$$

The parameters serve different purposes. χ_1 indicates the costs of extracting a ton of carbon today. χ_2 indicates the additional costs of extracting a ton of carbon at some benchmark level. This benchmark is χ_3, which is a characteristic amount of cumulative resources extraction. χ_4 is a parameter, which governs the increase of costs. For varying χ_4 all functions intersect at $\sum_\tau R = \chi_3$. For $\sum_{\tau=\tau_1}^{\tau=\tau_1} R(\tau) = 0$ it follows that $\kappa_s(t = \tau_1) = 1$.

The conditions for aggregation of various deposits leading to Eq. 4.12 are strong and rely on the concept of a unique sequence of single deposits; see e.g. Solow (1974) and Herfindahl (1967) for a rigorous proofs. This concept is highly problematic on theoretical and empirical grounds. From the theoretical point of view the main

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[3] This is different from the scarcity effect usually addressed to the increasing shadow price of a finite resource with zero extraction costs in the Hotelling model; see Hotelling (1931) and Heal (1976).

problem is that the uniqueness of an optimal sequence of deposits requires constant production factor prices. Kemp and Long (1980) showed that the sequence is not necessarily unique, if the factor prices are allowed to change over time. Amigues et al. (1998) showed that the extraction from a low cost exhaustible resource is delayed, if the output per period of a high cost backstop is limited.

The learning effect: The learning effect κ_l increases the capital productivity κ due to accumulation of experience. The experience is modelled as the cumulated extraction of fossil primary energy carriers. The time discrete motion equation of κ_l has the following form that will be explained in detail below:

$$\kappa_l(t+1) = \kappa_l(t) + \frac{\kappa_l(t)(\kappa_l^{max} - \kappa_l(t))}{\tau_{R,l}\kappa_l^{max}} \left(\left(\frac{R(t)}{R^0} \right)^{\beta_{R,l}} - 1 \right), \tag{4.13}$$
$$\text{with } \kappa_l(t = \tau_1) = \frac{R^0}{K_R^0}.$$

The learning process is described by two factors that are contained in the second addend of the right hand side of Eq. 4.13. First, the parenthesis is best described as a learning enhancement factor. Second, the fraction is the natural learning factor.

For the explanation of the natural learning factor assume $R(t) = R^0$ for the moment; i.e. learning is not enhanced. Natural learning contains two parameters $\tau_{R,l}$ and κ_l^{max}. The parameter $\tau_{R,l}$ is a velocity parameter that determines the time frame that is needed to realise a particular learning effect. κ_l^{max} is the maximum possible capital productivity at which κ_l saturates. $\tau_{R,l}$ is the time needed to realise $\sim$50% of κ_l^{max}, if the initial condition is at $\sim$25% of κ_l^{max}. Fig. 4.3 illustrates this mechanism.

The natural learning process can be accelerated through the learning enhancement factor. The term $R(t)/R^0$ simply represents the indexed increase of $R(t)$ above the initial level R^0. The parameter $0 \leq \beta_{R,l} \leq 1$ dampens this ratio. The learning enhancement factor can become negative, if $R(t) < R^0$.

Accumulation of K_R starting at K_R^0 requires investment I_R and is subject to the depreciation rate δ_R:

$$K_R(t+1) = I_R(t) + (1 - \delta_R)K_R(t); \qquad K_R(t = \tau_1) = K_R^0. \tag{4.14}$$

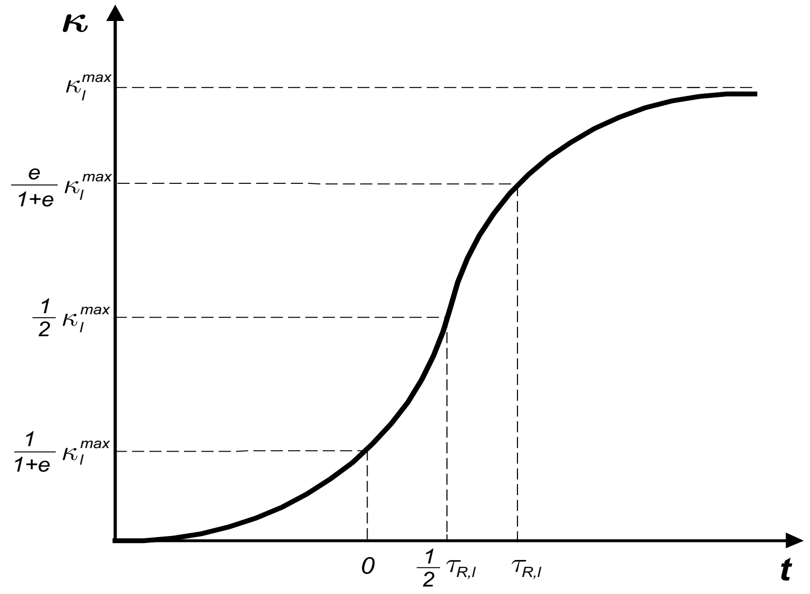

Figure 4.3: Learning process with a logistic learning curve with $\tau_{R,l}$ and κ_l^{max}, if the learning enhancement factor is constantly one.

4.2.5 The Fossil Energy Sector

The production of secondary energy $E_{S,F}$ demands fossil primary energy carriers $E_{P,F}$ and capital capital K_F, additionally. A CES-production function serves for the transformation of primary into secondary energy. The capital stock starts at an initial level K_F^0. Investments I_F increase K_F and it depreciates depending on time with the exogenous depreciation rate δ_F. Therefore, the equations of the fossil energy sector are:

$$E_{S,F} = \Phi_F \left[\xi_F^E(\epsilon_F E_{P,F})^{\tilde{\sigma}_F} + \xi_F^K K_F^{\tilde{\sigma}_F}\right]^{\frac{1}{\tilde{\sigma}_F}}, \quad \tilde{\sigma}_F = 1 - \frac{1}{\sigma_F}\ ; \tag{4.15}$$

$$K(t+1) = I_F(t) + (1-\delta_F)K_F(t), \qquad \text{with } K_F(t=\tau_1) = K_F^0. \tag{4.16}$$

The parameters Φ_F and ϵ_F are necessary for scaling and are constant over time. The parameters ξ_F^E, ξ_F^K and $\tilde{\sigma}_F$ are analogous to the corresponding parameters in the CES-production function for the aggregate production function.

The amount of $E_{P,F}$ is related to the fossil fuel extraction R in a linear way. The parameter M translates the carbon units extracted in primary energy units; i.e. it is the inverse of the carbon intensity:

$$E_{P,F} = M \cdot R. \tag{4.17}$$

$M(t)$ is not necessarily constant. It serves as a way to incorporate exogenous scenarios of the fossil energy mix of oil, gas and coal.

4.2.6 The Renewable Energy Sector

The renewable energy sector produces secondary energy with capital, only. The sector is characterised by learning that depends on the accumulation of experience in producing renewable energy capital goods. The production of renewable energy $E_{S,R}$ is as follows:

$$E_{S,R}(t) = \sum_{\tau=1}^{\tau^{max}} \nu_{ren} \omega \nu_{ren}(\tau) K_{ren}(t-\tau). \tag{4.18}$$

Eq. 4.18 contains two indices that are related to time. t denotes the actual period and τ looks back into the past in order to consider vintages added in $(t-\tau)$, where a vintage describes a capacity addition in a period. The sum includes τ^{max} terms, where this number represents the number of past vintages and that are still producing at time t. $\omega_{ren}(\tau)$ is the fraction of initially installed capacity that is available in t and that has been installed in $t-\tau$. ν_{ren} is the number of full load hours.

The installation of new capital vintages requires investments. Capacity additions $K_{ren}(t)$ are translated into monetary investments $I_{ren}(t)$ by multiplying $K_{ren}(t)$ with an investment cost factor $\iota_{ren}(t)$:

$$K_{ren}(t+1) = \frac{I_{ren}(t)}{\iota_{ren}(t)}. \tag{4.19}$$

The experience is measured by the cumulative installed capacity:

$$CK_{ren}(t) = \sum_{\tau=\tau_1}^{t} K_{ren}(t-\tau), \qquad \text{with } CK_{ren}(t=\tau_1) = CK^0_{ren}. \tag{4.20}$$

CK_{ren} affects ι_{ren}. The learning process does not follow the conventional approach, where the learning rate λ_{ren} is assumed constant. This approach is employed in empirical studies as well as in numerical modelling approaches:

$$\iota_{ren}(t) = \iota_{ren}(t=\tau_1)\left(\frac{CK_{ren}(t)}{CK^0_{ren}}\right)^{-\tilde{\lambda}_{ren}}, \qquad \text{with } \tilde{\lambda}_{ren} = -\frac{\log(1-\lambda_{ren})}{\log 2}. \tag{4.21}$$

This approach exaggerates the flexibility of the learning process, because it is possible to move down the learning curve instantaneously. Therefore, a similar one as in Ch. 4.2.4 is pursued in which the learning rate is decreased, if the growth of CK_{ren} is increased. The learning process is implemented in differential rather than the direct form of Eq. 4.21:

$$\iota_{ren}(t+1) = \iota_{ren}(t) + \left(\frac{\iota_{ren}(\tau_1) {CK^0_{ren}}^{\lambda_{ren}}}{CK_{ren}(t+1)^{\lambda_{ren}}} - \frac{\iota_{ren}(\tau_1) {CK^0_{ren}}^{\lambda_{ren}}}{CK_{ren}(t)^{\lambda_{ren}}} \right) \left(\frac{CK_{ren}(t)}{CK_{ren}(t+1)} \right)^{\beta_{ren}} . \tag{4.22}$$

The natural learning factor is the first large parenthesis of the second addend on the right hand side and the learning enhancement factor is the second large parenthesis that is subject to the dampening factor $\beta_r en$.

4.2.7 The Climate System

MIND includes a simple climate model that translates the anthropogenic emissions of CO_2 and sulfate aerosols into a change of the global mean temperature GMT. The emissions of CO_2 accumulate in the atmosphere according to a carbon cycle model. The emissions of sulfate aerosol do not accumulate due to their short lifetime in the atmosphere; i.e. every amount of sulfates will be removed from the atmosphere until the next period starts. The emission of sulfates is directly linked to the combustion of fuels in the fossil energy sector. In addition, the model takes into account an exogenous scenarios for land-use change CO_2 emissions and for the radiative forcing of greenhouse gases other than CO_2 OGHG.

The model is an energy-balance model that calculates the response of GMT to a perturbation of the radiation balance at the top of the atmosphere due to anthropogenic emissions of GHG; see Watterson (2000). For the basic model equations see Petschel-Held et al. (1999) and Kriegler and Bruckner (2004).

E_{CO_2} comprises two different sources: CO_2 emissions from burning fossil fuels and those due to land use change $E_{CO_2,LUC}$. The former equal the fossil resource extraction R and the latter are introduced as an exogenous scenario. The CO_2 emissions can be decreased by CCS R_{CCS}:

$$E_{CO_2} = R + E_{CO_2,LUC} - R_{CCS}. \tag{4.23}$$

The sulphate emissions are linked to the utilisation R. The coupling factor $C2SO_2$ relates the carbon emissions into the atmosphere to the sulphate emissions. This means that captured carbon is not related to sulphate emissions. Ch. 5.1 shows that this is reasonable due to technical reasons. Therefore, the sulphate emissions are:

$$E_{SO_2} = C2SO_2(R - R_{CCS}). \tag{4.24}$$

The anomaly of CO$_2$ in the atmosphere C due to anthropogenic emissions E_{CO_2} is according to a simple 1-box model.

$$\begin{aligned} C_{cs}(t+1) - C(t)_{cs} = \beta_{cs} + B_{cs}CE_{CO_2}(t) - & \qquad\qquad (4.25) \\ \alpha_{cs}(C_{cs}(t+1) - C_{cs}(t)), &\qquad \text{with } C_{cs}(t=\tau_1) = C^0_{cs}; \\ CE_{CO_2}(t) = \sum_{\tau=\tau_1}^{t} E_{CO_2}(t-\tau), &\qquad \text{with } CE(t=\tau_1) = CE^0. \quad (4.26) \end{aligned}$$

The CO$_2$ in the atmosphere is translated into atmospheric concentrations C_{cs} using the constant factor β_{cs}. The parameter α_{cs} is the regeneration rate of the atmosphere. The notion of the cumulative emissions CE_{CO_2} is due to the fact that only a fraction of a carbon disturbance is removed from the atmosphere and the residual $\frac{B_{cs}}{\beta_{cs}\alpha_{cs}}$ will remain in the atmosphere in the long run.

The accumulation of GHG and sulphate aerosol in the atmosphere affects the radiation balance relative to the pre-industrial era, when the climate has been assumed in equilibrium. The disturbance of the radiation balance F_{CO_2} is a logarithmic function of the anomaly of CO$_2$ in the atmosphere with the parameter $F_{2\times CO_2}$ that represents the increase of the radiative forcing due to a doubling of the pre-industrial CO$_2$ concentration. The influence of the sulphate aerosol is a function of the actual emissions E_{SO_2}. There is an anthropogenic and a natural effect of the sulphate aerosol, since there are naturally occurring aerosols, too. The effects are parameterised with $F^{anthro}_{SO_2}$ and $F^{natural}_{SO_2}$. The total disturbance of all emissions is the sum of the isolated effects, including an exogenous scenario for the other GHG OGHG:

$$F_{CO_2} = F_{2\times CO_2}\frac{\ln(C/C^0)}{\ln 2}; \tag{4.27}$$

$$F_{SO_2} = F^{anthro}_{SO_2}\frac{E_{SO_2}}{E^0_{SO_2}} + F^{natural}_{SO_2}\left(\frac{\ln\left(1+\frac{E_{SO_2}}{E_{nat,SO_2}}\right)}{\ln\left(1+\frac{E^0_{SO_2}}{E_{nat,SO_2}}\right)}\right); \tag{4.28}$$

$$F_{tot} = F_{CO_2} + F_{SO_2} + F_{OGHG}. \tag{4.29}$$

The disturbance of the radiation balance influences the GMT, denoted T; the pre-industrial GMT is T_0. An energy balance model represents the complex dynamics of the climate system:

$$\frac{d(T-T_0)}{dt} = \frac{1}{C_{OC}}(F_{tot} - F_{2\times CO_2}\frac{T-T_0}{T_{2\times CO_2}}). \tag{4.30}$$

There are two parameters. $T_{2\times \mathrm{CO}_2}$ is the climate sensitivity, which is the steady state temperature that is reached for a doubling of atmospheric CO_2 concentrations. C_{OC} is the oceanic heat capacity, which determines the speed of convergence to a new steady state temperature.

The model models the short and long-term effects of the utilisation of fossil fuels carriers, since the CO_2 emissions and accumulation of long-lived CO_2 and the emissions of short lifed sulfate aerosols are modelled as well as the dynamics of the natural carbon cycle and the climate system. Moreover, the model is able to deal with leakage of sequestered carbon that can be introduced in Eq. 4.23 as will be shown later.

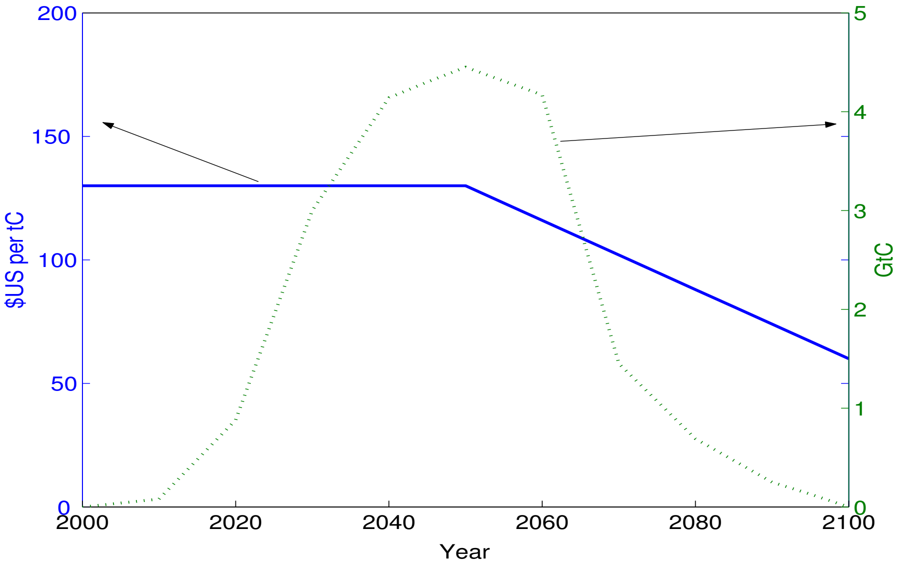

Figure 4.4: Assumptions of the exogenous paths of the WBGU scenario. Source: WBGU (2003, p. 137).

4.2.8 Carbon Capture and Sequestration – Exogenous

As already mentioned above, in this chapter CCS is treated as an exogenous path. The CCS scenario has been adopted from Wissenschaftlicher Beirat Globale Umweltveränderungen WBGU (2003, Ch. 4). Fig. 4.4 shows the path of the amount of CCS. The path increases until the middle of the 21^{st} century and decreases to zero in 2100. In 2030 the total amount of CCS is $3\frac{\mathrm{GtC}}{\mathrm{y}}$ and the maximum is $4.5\frac{\mathrm{GtC}}{\mathrm{y}}$ in 2050.

The quantitative path is related to a cost path and extra energy demand. The assumptions are that the costs of CCS are $130\frac{\$\mathrm{US}}{\mathrm{tC}}$ and start to decrease linearly to $60\frac{\$\mathrm{US}}{\mathrm{tC}}$ in 2050. The energy penalty is assumed to be 25%, which is the extra primary energy needed to capture a unit of carbon. The leakage of captured carbon is assumed to be zero.

It comes from the assumption of the exogenous path that neither the amount nor the associated costs are intertemporally optimal, simply because CCS is no control variable. Analysis of the sensitivity of costs and quantities of the exogenous paths show that these are important assumptions for the question if this option is favourable or not.

4.3 The Calibration of *MIND1.0*

In the following subsections the calibration of exogenous mode parameters and exogenous scenarios used in *MIND* are introduced. The sequence of sections corresponds to Ch. 4.2, with the exception that Ch. 4.2.8 does not require additional specifications. The term base case – used frequently in the following – is a set of parameter values and exogenous scenarios that will be used for different scenarios like the business as usual BAU scenario.

The exogenous assumptions in the following should be seen as choices of parameter values that are reasonable on empirical grounds. Each choice of a particular parameter value is disputable and could lead to more or less significant changes of the results. This is the reason to test the robustness of the base case results.

This approach leads to the citation of various sources and numbers that are not in agreement, which mirrors the disputes in the empirical literature. It is not the task to make the final judgment about these disputes in this thesis. There are two reasons to cite all the numbers. First, it is necessary to ask in how far the model is able to capture essentials that are found in the literature from a more conceptual point of view. Second, it is necessary to base the choice of parameter values on empirical findings.

4.3.1 The Household Sector

The calibration of the household sector contains four steps:

1. the exogenous path of population $L(t)$;
2. the delimitation of the planning horizon (τ_1,τ_2) and the time step of a period Δ_t;
3. the parameters of the intertemporal social welfare function; i.e. the discounting rate ρ and the IES;
4. the guardrails GR_T and $GR_{\Delta T}$ of the climate window.

As pointed out in Ch. 4.2.1 the household sector lies at heart of the model *MIND*, although the population number is assumed exogenous. *MIND* uses standard assumptions about population numbers $L(t)$. The numbers are used in several studies and cited e.g. in the IPCC SRES; see Nakicenovic and Swart (2000a). Fig. 4.5 shows the four global population scenarios used in SRES. The base case is the B2 scenario. Assuming an exogenous path of population is a common method in models of economic growth and climate change; an exception is Murota and Ito (1996).

The discrete time model with finite time horizon requires the specification of the time step Δ_t and the time horizon (τ_1, τ_2). The time steps are 5 years over the whole planning horizon. τ_1 is 1995 and τ_2 is 2300. The results are presented for the time horizon until 2100, but the model will optimise until 2300 in order to take into account the value of state variables beyond 2100. The reasons for this choice have been given in Ch. 2.5.3.

Next, the focus is on parameters of the intertemporal social welfare function. The discounting rate ρ is assumed to be 0.01. Usually, integrated models of climate and the economy assume $\rho = 0.03$. There are two reasons for the assumption of the lower value. First, the model asks for social optimal solutions of a problem with a long run nature that shall anticipate future threats and possibilities for short-term behaviour. The outcome of estimations of the discounting rate depend on the

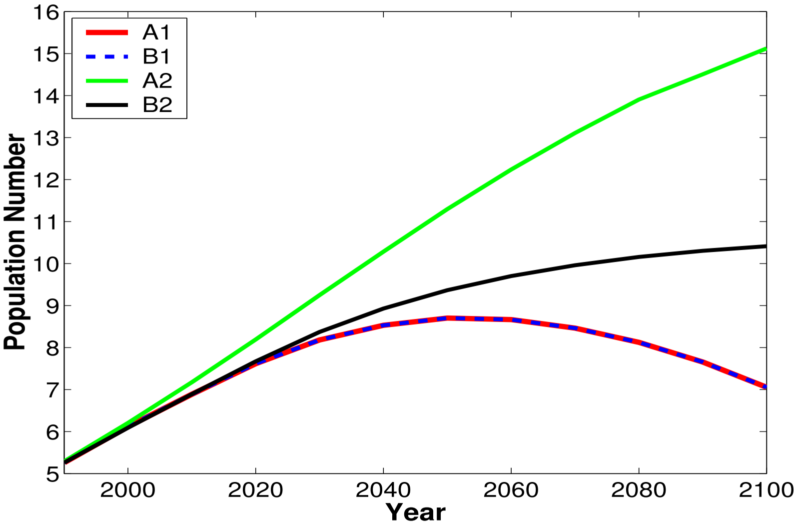

Figure 4.5: The four SRES population scenarios in bil. people. Source: Nakicenovic and Swart (2000a).

specification of the model and the data used. Lawrance (1991) found it to vary between zero to nineteen percent. The choice of ρ being less than the empirically estimated value is reasonable in a normative a study, which is based on ethical grounds as given for example by Ramsey (1928) and Solow (1974). The second reason is due to computational issues that are related to the time step and the time horizon that will be treated in Ch. 4.4.

Ch. 4.2.1 introduced the utility per capita in each period, which is assumed to be a logarithmic function of per capita consumption. This implicitly assumes that the IES equals one. This is the usual assumption in Ramsey-type IAMs; see e.g. Nordhaus (1994), Manne et al. (1995) and Gerlagh and Zwaan (2003). An exception of this is Goulder and Schneider (1999), who assume 0.5. Unfortunately, the authors do not point out the effects of this. Empirical studies on the IES suggest that it is smaller than one. The widely recognised study by Hall (1988) concludes that the IES probably does not exceed 0.1 and could even be zero. Atkeson and Ogaki (1996) found 0.4 for the USA and 0.27 for India for the period 1960 – 1987. Moreover, Ogaki and Reinhart (1998) found the IES at 0.4 in the USA for the period 1929 – 1960. This means that the households have a lower willingness to accept uneven consumption paths than the model computes.

The importance of the IES in growth models is that it influences the way of temporary transitions towards the steady state. The significance for determination of the steady state is of minor importance; see Ch. 3.3. Since *MIND* deals with economic growth with initial conditions below the steady state growth path as well as the timing of investment into energy technologies it is worth to look at the sensitivity of this parameter; see Ch. 7.

The guardrails of the climate window are chosen at $GR_T = 2\text{C}^\circ$ and $GR_{\Delta T} = 0.2\text{C}^\circ$ per decade in accordance to WBGU (2003). This is a normative setting that is based on scientific evaluation of an advisory board. Due to this arbitrary choice the guardrails will be varied in order to assess the effect of less stringent guardrails.

4.3.2 The Aggregated Production Sector

In the aggregate production sector several parameters have to be assumed:

1. the elasticity of substitution σ_A;
2. the initial capital stock K_A^0 and the capital depreciation rate δ_A;
3. the factor shares, which are related to the distribution parameters ξ_i, with $i = L, K, E$;
4. the initial conditions of the efficiency parameters A_0 and B_0 and the constant scaling factor Φ_A.

A rich literature emerged on econometric estimations of production function parameters. Over at least three decades a great deal of research focused on the substitution elasticity between the three production factors capital, labour and energy,[4] is a major indicator of an economy, that characterises the dependence on energy. There are conflicting approaches with regard to functional forms, estimation techniques and data, which lead to results that do not provide a clear picture. The most important discussion arose in the 1970ies about the question, whether

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[4] When the elasticity of substitution is estimated at the sectoral level materials additionally enter the production function in order to take account of intermediate products. Some studies do disaggregate the energy production factor in electricity and non-electric energy. Moreover, there are some studies that deal with interfuel substitution in industrial sectors, only.

capital and energy are complements or substitutes, which is equivalent to the question of the sign of the substitution elasticity; see Berndt and Wood (1975), Berndt and Wood (1979), Griffin and Gregory (1976), Hunt (1986), Kinitis and Panas (1989), Apostolakis (1990), Thompson and Taylor (1995), and Frondel (2000).

There are two different approaches in the literature for the estimation of elasticity of substitution that will be reviewed in the following.[5] Most studies use flexible form approaches like the translog cost function approach. The term flexible means that the elasticity of substitution could vary with output and factor proportions; see Heathfield and Wibe (1987, Ch. 6). In the second approach using nested CES production functions the elasticities of substitution are constant by assumption.

Reviewing the empirical literature of the flexible form approach comes with a problem that is related to the use of translog functions[6]. The translog approach is not related to a particular functional form like the (nested) CES functions. The translog function is a Taylor expansion of a general production function $f(\cdot)$. Therefore, in translog approaches the elasticity of substitution is derived from estimated parameters using the concept of Allen-Uzawa partial elasticity of substitution between two factors $\sigma_{AU_{ij}}$. The partial elasticities $\sigma_{AU_{ij}}$ are defined in terms of factor shares and the effect of relative price changes on factor shares that are estimated; see Berndt (1991, Ch. 9). $\sigma_{AU_{ij}}$ are widely used and lead to broad ranges of estimates. Additionally, $\sigma_{AU_{ij}}$ are symmetric for two factors; i.e. $\sigma_{AU_{EK}} = \sigma_{AU_{KE}}$.

In a theoretical study Blackorby and Russell (1989) pointed out that the Allen-Uzawa approach only works for production functions with two factors. They concluded that the Morishima elasticity of substitution $\sigma_{M_{ij}}$ gives the correct elasticity

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[5] In recent studies of elasticities of substitution another promising approach is employed based on linear logit models; see Considine and Mount (1984). The approach is able to deal with short- and long run substitution elasticities consistently. A feature not captured neither by the translog nor the nested CES approach. Unfortunately, the approach is applied on inter-fuel substitution, only, and not macro-economic or sectoral production functions containing capital and labour; see Considine (1989), Jones (1995b), Jones (1996) and Urga and Walters (2003).

[6] In this approach Shepards-lemma (see Mas-Colell et al. (1995, Ch. 3))is used to derive demand functions within a cost-minimisation framework of the firm. Duality of optimisation allows the factor prices and the amount of output as independent variables determining the costs. Within the approach a number of restrictions have to be imposed for reasons of consistency with economic theory. Considerable effort has been spent on econometric methods dealing with these restrictions; see e.g. Koschel (2000, p. 20 – 22).

of substitution for production functions of more than two production factors. $\sigma_{M_{ij}}$ depend on cross and own price elasticities of the production factors that are also estimated in the translog approach. The Morishima elasticities of substitution are asymmetric; i.e. $\sigma_{M_{EK}} \lesseqgtr \sigma_{M_{KE}}$.

Thompson and Taylor (1995) (in short TT95) applied the argument on studies about energy and capital substitution based on the translog approach that allow to compare $\sigma_{AU_{EK}}$ on the one hand and $\sigma_{M_{EK}}$ and $\sigma_{M_{KE}}$ on the other. This is not allways possible, because the price- and cross-price elasticities are not reported in all studies.

The summarising statistics of TT95 are given in the upper four rows of Tab. 4.1. TT95 found that the average of all Morishima elasticities of substitution between capital and labour is higher than the corresponding $\sigma_{AU_{EK}}$. Moreover, the variance is smaller for the Morishima elasticity of substitution and the extreme divergence of results of negative and positive numbers for $\sigma_{AU_{ij}}$ is reduced.

Selected studies from TT95 are given in the following rows. Some studies are added to the table that are originally not included in TT95, because they either address important countries like India or because the studies were published more recently. Additionally, numbers for the elasticity of substitution of capital-labour and labour-energy are reported because the production function Eq. 4.5 does contain them, too, and the elasticities of substitution are not necessarily the same.

The results of the studies reported here show great diversity. There seems to be no obvious pattern for substitution elasticities between the three factors. The most robust finding in Tab. 4.1 is that each of three elasticities of substitution for labour, capital and energy of substitution is greater than zero and smaller than one.

The separability of production factors can be evaluated using the elasticities of substitution as has been pointed out in Ch. 3.6.2: a factor of production – say energy – is separable from capital and energy, if the elasticity of substitution between energy and labour is the same as between energy and capital. A close look at Tab. 4.1 reveals that most studies do not support the separability of any factor; an exception is Williams and Laumas (1981) for India. More elaborate testing methods confirm the conjecture with respect to separability of capital and labour from energy; see Berndt and Wood (1975), Magnus (1979), Hazilla and Kopp (1986), Apostolakis (1987), Frondel and Schmidt (2000) and Medina and Vega-Cervera (2001). In terms of econometric estimation the omission of energy would lead to a specification error; see e.g. Apostolakis (1987). Despite this finding the production function assumes separability of the three production function.

Table 4.1: Overview on elasticities of substitution between energy, labour and capital based on Allen-Uzawa σ_{AU} and Morishima σ_M, respectively. Source: Thompson and Taylor (1995) and see footnotes.

	$\sigma_{AU_{KE}}$	$\sigma_{M_{EK}}$	$\sigma_{M_{KE}}$	$\sigma_{AU_{KL}}$	$\sigma_{M_{LK}}$	$\sigma_{M_{KL}}$	$\sigma_{AU_{LE}}$	$\sigma_{M_{EL}}$	$\sigma_{M_{LE}}$
Mean	.17	1.01	.76						
Variance	20.6	.54	.25						
Minimum	-22.4	-.09	-.07						
Maximum	18.6	3.42	1.93						
BW75[a]	-3.22	.31	.32	1.01	.56	.47	.65	.64	.48
GG76[b]$_{\text{USA}}$	1.07	.92	.33	.06	.19	.17	.87	.76	.9
GG76$_{\text{FRG}}$	1.03	.9	.76	.5	.55	.53	.78	.67	.88
GG76$_{\text{France}}$	1.05	.91	.64	.41	.48	.47	.82	.71	.88
GG76$_{\text{UK}}$	1.04	.92	.64	.39	.47	.45	.84	.73	.89
M79[c]	-2.63	-.06	.14	.67	.48	.69	.95‡	.9‡	.35‡
WL81[d]		1.	1.08		1.01	1.02		.83	1.06
TFU82[e]	2.26	.28‡	1.38	2.	1.04	1.13	-2.66	-.42	.58
A87[f]$_{France}$	.86	.91	.64	.95	.94	.84	1.	.97	.66
A87$_{Italy}$	.83	.94	.55	.95	.8	.49	1.09	.62	1.08
A87$_{Spain}$	.74	.75	.6	.94	.91	.41	1.	.88	.2
K00[g]$_{EIS,El}$		.01‡	.2		.47	.37		.03‡	.09†
K00$_{EIS,NEl}$		.06‡	.52		s.a.[h]	s.a.		.0‡	-.01‡
K00$_{NEIS,EL}$		.01‡	.09‡		.29	.32		.05	.68
K00$_{NEIS,NEl}$		.02‡	.32		s.a.	s.a.		.01‡	-.23†
K00$_{S,El}$		.05†	1.1		1.14	1.22		.09	1.4
K00$_{S,NEl}$		.06‡	1.17		s.a.	s.a.		-.02†	-.28
CNP04[i]$_{near}$	0.74	.83	-.3	.87	.86	.70	-1.42	-.42	-.46
CNP04$_{long}$	0.92	.82	1.05	.73	.74	.76	1.19	.99	1.07

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[a] Berndt and Wood (1975): Time series of US manufacturing 1947 – 71 with capital, labour, energy and materials using a translog function. Citation is for 1965.

[b] Griffin and Gregory (1976): Cross section of manufacturing for 9 OECD countries and 5 years with capital, labour and energy using a translog function. Citation is for 1965. The standard deviation for the parameters explaining AES_{KE} are more than ten times the corresponding value.

[c] Magnus (1979): Time series of Dutch economy (excluding energy producing sectors) 1950 – 76 with capital, labour and capital using a generalised Cobb-Douglas function. Citation is for 1976. Originally not included in TT95. ‡ indicates that the result is based on insignificant (95%) parameters.

[d] Williams and Laumas (1981): Time series of eight Indian manufacturing sectors in 1968 with capital, labour, energy and materials using a translog function. Citation is for the non-weighted average. Originally not included in TT95. The study does not report significance of estimations.

[e] Turnovsky et al. (1982): Time series of Australian manufacturing sector 1946 – 75 with capital, labour, energy and materials. Citation is for the average. ‡ indicates that result is based on insignificant (95%) parameter.

[f] Apostolakis (1987): Time series of south European countries 1953 – 84 with capital, labour and energy using a translog function. Not included in TT95. Citation is for 1984. Significance levels can not be reconsidered.

[g] Koschel (2000): Time series of West-German sectors 1978 – 90 with capital, labour, electricity EL, non-electric energy NEl and materials. Citation is for 1990. Not included in TT95. There are 15 energy intensive sectors EIS, 19 non-energy intensive sectors $NEIS$ and 11 service sectors S. † indicates that less than half of the sectors are significant at the 5%-level; ‡ indicates one or zero sector is signinficant.

[h] s.a. means see above.

[i] Cho et al. (2004): Time series of South-Korean economy 1981Q1 – 97Q4 with capital, labour and energy. Citation is for 1990. Not included in TT95. The index *short* (*long*) is a short (long) term model. The long term model contains partial adjustment of factor shares.

Table 4.2: Overview on elasticities of substitution for nested CES production functions with $Y = f(g(K, E), L)$; i.e. the column $K - E$ contains the elasticity of substitution between capital and energy and the column $L - (KE)$ contains that between labour and the capital-energy CES composite. Source: see footnotes.

	$K - E$	$L - (KE)$
P86[a]	0.14	0.78
Ka89[b]	0.18	0.48
C94[c]	0.87	0.42
Ke98[d]	0.65	0.85

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[a] Prywes (1986): Time series of 20 US manufacturing sectors 1971 – 76 with capital, energy, labour and materials. The non-weighted averages are reported.

[b] Kahn (1989): Time series of Pakistan manufacturing 1953 – 83 with capital, energy and labour.

[c] Chang (1994): Time series of Taiwan manufacturing 1956 – 71 with capital, energy, labour and materials.

[d] Kemfert (1998): Time series of seven German manufacturing sectors 1960 – 93 with capital, energy and labour. Aggregate estimations are given.

The nested CES production function[7] is an alternative way of estimating the elasticity of substitution. Tab. 4.2 reports estimation results for a number of countries. The first CES nest combines capital and energy, which are combined with labour in the second CES nest.[8] Similar to the studies based on the translog approach the estimates do only provide a rough picture: the elasticities of substitution are between zero and one.

For this thesis two points are derived from the studies cited above. First, the discussion about separability of energy indicates that energy should be modelled explicitly, although the CES production function does imply separability. As shown in Ch. 3.6.2 this does not imply that capital stocks could be separated, which does require the explicit notion of energy in the macro-economic production function. This compromise is due to the fact that separability can only be tested for approaches like the translog approach, but integration of such functions requires additional research. Second, the elasticity of substitution for all three factors is assumed at $\sigma_A = 0.4$.

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[7] For details see Ch. 3.6.2

[8] There are studies focusing on different nesting structures that are not extended here; see e.g. Kemfert (1998).

Next, the focus is on the initial capital stock K_A^0 and the depreciation rate δ_A. We can not observe the capital stock directly, but can compute it from related data.[9] The most commonly used approach is the perpetual inventory method (PIM). This method simply uses the capital motion equation of Eq. 4.7 on p. 88 to compute the capital stock time series. The necessary information to compute the capital stock time series are an initial capital stock, a depreciation rate and a time series of investments. When the time series is sufficiently long, the effect of a badly estimated initial capital stock vanishes because of depreciation.

The computation of a global capital stock in a common currency bears the problem that investment time series are usually reported in national currencies and do not cover all countries for all years. This leads to an alternative approach applied in this thesis.

The calibration of the initial capital stock K_A^0 is done indirectly using the capital coefficient $\frac{K}{Y}$ of various countries. The task is to find a reasonable $\frac{K}{Y}$ and then to multiply it with the global Y in \$US for 1995 in order to get the global K in \$US for the same year. This method can be applied, because the capital coefficient is a dimensionless number; hence capital coefficients are comparable across countries with different currencies. Two different sources of data employing this approach are used in the following.

First, data for capital and gross domestic product (GDP) from the OECD database are used to compute the capital coefficient. The capital stock as well as the GDP given in the OECD database comprise the total economy. The method used for the computation of the capital stock is not reported. Fig. 4.6 shows $\frac{K}{Y}$ for 14 OECD countries. We can observe that the capital coefficient for different countries does not show a significant trend and there is a cluster around 2.5.

The second source of data is PWT6.1, which contains macro-economic data for 179 countries. The capital stock is constructed using PIM already described above. The depreciation rate is assumed at 5% and the initial capital coefficient is set to 1.5 in 1950. The investment and GDP data is given in constant domestic currency. For 28 countries data is not sufficient to construct a capital stock.

In Fig. 4.7 the frequency distribution of $\frac{K}{Y}$ is given. Note that the countries are not weighted with their size and that this frequency distribution should not be

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[9] For extensive discussion of the problems of capital stock measurement; see Brown (1980) and Felipe and Fisher (2003) and the literature cited there.

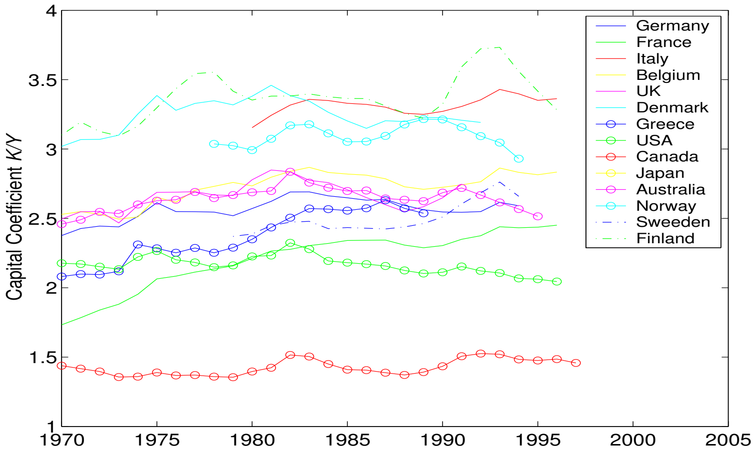

Figure 4.6: Capital coefficient $\frac{K}{Y}$ based on domestic constant currency for OECD countries 1970 – 97. Source: OECD Database 2001, #2.

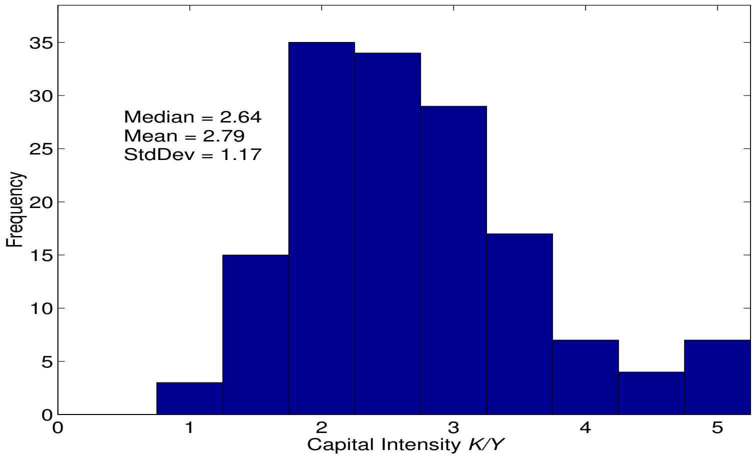

Figure 4.7: Frequency distribution of capital coefficient $\frac{K}{Y}$ in 1995 based on domestic constant currency for 151 countries. Note, that the right bin contains also countries with capital coefficients greater than 5. The frequency distribution cannot be interpreted as a probability density functions. Source: based on PWT6.1.

interpreted in terms of a probability density functions. One can observe a cluster around the median of 2.64.

For the calibration of K_A^0 a capital coefficient of 2 is assumed. The downwards deviation from the already mentioned values is due to two reasons. First, the capital stocks above do contain the energy related capital stocks. These should be excluded from K_A^0 because they are modelled separately within *MIND*. Second, the capital

Table 4.3: Factor shares in percent at the macro-economic level for several countries. Source: see footnotes

	$\tilde{\xi}_E$	$\tilde{\xi}_L$	$\tilde{\xi}_{K_A}$
M79[a]	6.6	62.2	31.2
CNP04[b]	7.3	49.1	43.5
BMWI03[c]$_{hh}$	7.3	-	-
BMWI03$_m$	1.5	-	-

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[a] Magnus (1979): Input cost shares of Dutch economy – excluding energy related sectors – in 1976.

[b] Cho et al. (2004): Means of Korean economy for quarterly data 1981Q1 – 97Q4.

[c] BMWi (2003): Value for 2001 for households hh in % of consumption expenditure p. 35 for manufacturing m in % of value added p. 34.

coefficient of developing countries with great population numbers – like China, India, Indonesia, Brazil – is lower than 2.5. These facts are taken into account by a downward deviation. The global GDP in 1995 with which the capital coefficient is multiplied is taken from SRES and equals 24.6tril.$US. As above the capital depreciation rate is assumed at 5%.

Now, the focus is on the distribution parameters ξ_i, with $i = L, K, E$. The parameters ξ_i are related to factor shares $\tilde{\xi}_i(t)$. Tab. 4.3 gives studies on factor shares for different countries. In this thesis the following parameter values are assumed for 1995: $\tilde{\xi}_E(\tau_1) = 0.04$, $\tilde{\xi}_K(\tau_1) = 0.3$ and $\tilde{\xi}_L(\tau_1) = 0.66$.

Usually, studies on factor shares focus on capital and labour, only. The shares show considerable differences depending on the concept of wage used; see e.g. Krueger (1999) for details. Most studies agree on the qualitative behaviour of the time series of the wage shares in OECD countries in the post-WWII period:[10] the labour share increased until the 1970ies to 80ies and declined afterwards; see e.g. Krueger (1999) and Serres et al. (2002). The assumption of a labour share of roughly 65% is supported by these studies.

As mentioned above, the factor shares $\tilde{\xi}_i(t)$ are related to the distribution parameters ξ_i. Both are different because the factor shares $\tilde{\xi}_i(t)$ can change, while ξ_i remain constant. For the base year 1995 it is assumed that $\tilde{\xi}_i(\tau_1) = \xi_i$, for $i = E, K, L$.

The parameters A_0 and B_0 and the constant scaling factor Φ_A have to be calibrated. Since the production function is not sufficient, we need additional in-

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[10] WWII is world are II.

formation for the determination of the three parameters. The approach is that the empirical factor shares $\tilde{\xi}_i(\tau_1)$ should be reproduced by the production function; e.g. $\tilde{\xi}_L = \frac{F_L(\tau_1)L(\tau_1)}{Y(\tau_1)}$. This implies that the information regarding two factor shares completes the set of equation to calibrate A_0, B_0 and Φ_A. The additional information required is secondary energy $E = 271$EJ, which is taken from IPCC SRES; see Nakicenovic and Swart (2000a).

4.3.3 The RD&D Sectors

For the RD&D sectors the parameters α_i and β_i, with $i = A, B$, have to be assumed. In Ch. 3.6.3 the problem to determine these parameters has been discussed in detail for the labour related RD&D sector.

Due to the problems of model validation the parameters are assumed in order to generate a scenario for the base case. The diminishing return parameters are $\beta_A = 0.05$ and $\beta_B = 0.1$. The productivity parameter $\tilde{\alpha}_A$ and $\tilde{\alpha}_B$ are calibrated according to a benchmark RD&D rate $\widehat{RD}_A$ for each sector according to the following formula:

$$\tilde{\alpha}_i = \alpha_i(\widehat{RD}_i)^{\beta_i}, \qquad \text{for } i = A, B \ . \tag{4.31}$$

The assumptions for the labour RD&D sector are $\alpha_A = 0.02$ and $\widehat{RD}_A = 0.03$. For the energy RD&D sector the assumptions are $\alpha_B = 0.015$ and $\widehat{RD}_B = 0.01$. This generates a scenario with high GWP growth and high energy demand. Since this choice exhibits some degree of arbitrariness the sensitivity of these parameters is analysed in Ch. 7.

The empirical estimates of other studies could hardly serve as a basis for assumptions of these parameters. This is due to the close relation of estimated parameters to the particular modelling approach used in each study. This is related to the specification of the function that relates productivity growth to RD&D investments as well as the production function that is affect by the productivity improvements. Although these problems are obstacles to proper model calibration, the empirical literature offers insights that are worth to mention as a basis for sensitivity analysis.

There is a broad empirical literature on RD&D and total factor productivity at the macro-economic level using regression analysis. The extensive literature study by Cameron (1996) found 20 -50% social rate of return of RD&D expenditures, while the private rate of return is about 10 – 25%. Jones and Williams (1998) assessed the private rate of return ranging from 7% to 14% and the social rate of return being at least 30%.

The relationship between research effort and improvement of the energy productivity has been explored by Popp (2001). The research effort has been operationalised by employing patent statistics. The study found that in the United States the costs of a patent related to improvement of energy productivity are 2.25mil.$US leading to economy wide long run savings of 14.6mil.$US. Moreover, the efficiency of patents is higher than average for energy intensive industries. The literature on consumer related energy efficiency improvements of equipment like cars and air-conditioning due to RD&D efforts is summarised in Jaffe et al. (2002).

The difference between social and private return rates is due to the spill-overs of technological improvements making innovations partially a public good, which drives a wedge between the private and the social rate of return. The difference of the private rate of return and the interest rate is attributed to capital market imperfections due to high uncertainties related to RD&D and asymmetric information between inventors and creditors. Both issues are usually considered as market failures that justify policy intervention.

Incorporation of the spill-over wedge in a modelling study could be established by increasing the parameters α, which is equivalent to the internalisation of the external effects into the calculation of the innovators.

4.3.4 The Fossil Resource Sector

The fossil energy extraction sector requires assumptions about three points:

1. fossil energy carrier availability χ_i and the corresponding carbon intensity $M(t)$;
2. parameters describing the learning process in the sector τ, $\kappa_{fr,max}$ and $\beta_{res,l}$;
3. initial condition K^0_{fr} and depreciation rate δ_{fr} of the capital stock.

Data about the fossil fuel availability are given in the literature. The studies contain information about coal, oil and gas at the regional scale and differences of quality. The availability of fossil energy carriers is assessed along two criteria following the classification. First, the recoverability of known deposits is subject to current and future extraction technology, which determine the costs of extraction and therefore how much of the known deposits are worth to extract. Second, the knowledge of the locations of the deposits and characteristics regarding extraction is incomplete, which limits the amount of known deposits worth for extraction.

Combining both categories allows a coarse classification of fossil energy carriers that will be used in the following. The term *reserves* comprises identified deposits that are economically recoverable with state of the art technologies and current prices. *Resources* contain hypothetical deposits that are expected to become economically recoverable or found in the future. The *resource base* is the sum of reserves and resources. Moreover, *additional occurrences* are speculative amounts, which usually contain methane gas hydrates in the deep oceans that are known to be gigantic, but there is – by now – no competitive extraction technology. For more details see Rogner (1997, p. 219 – 224) and BGR (2003, p. 42 – 43).

Tab. 4.5 and Tab. 4.4 summarise the results of the assessments.[11] Moreover, past cumulative consumption and projections for four SRES scenarios are added to assess the numbers.

Comparing the reserves and resources with historical consumption it is obvious that a multiple is not yet used, but conventional oil is the most critical energy source because the reserve to extraction ratio is the lowest. The SRES scenarios share some features. The cumulative future consumption of oil exceeds the sum of oil reserves and it exceeds the resource base of conventional oil. Except for SRES-B1 cumulative future consumption of gas exceeds gas reserves and it exceeds the resource base of conventional gas. Except for SRES-A2 cumulative coal consumption is lower than coal reserves. For all scenarios the total cumulative carbon emissions exceed the current amount of carbon in the atmosphere that has been ∼750GtC in 1998.

There are two major uncertainties with respect to fossil primary energy availability. The first uncertainty is related to coal. It is well known, where there are gigantic amounts of coal resources, but it is unclear, whether these will ever be extracted, because a considerable share is located in Siberia; i.e. bad mining conditions are combined with long transportation distances. Moreover, the coal reserves have been derated during the 1990ies for Germany, Great Britain, Poland and China due to the low economic performance of these industries in combination with the removal

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[11] Both tables are related to each other by conversion factors that are as follows: 15.3GtC/ZJ for gas, 20GtC/ZJ for oil and 26.1GtC/ZJ for coal; see Moomwa and Moreira (2001, p. 236).

Table 4.4: Carbon content in GtC of reserves and resources of fossil primary energy carriers. Source: see footnotes.

	Oil				Gas				Coal[a]		Total	
	Reserve		Resource		Reserve		Resource		Reserve	Resource	Reserve	Resource
	conv.	unc.	conv.	unc.	conv.	unc.	conv.	unc.				
NGM98[b]	126.	162.	122.	278.	90.3	122.4	179.	165.2	662.9	3053.7	1163.6	3797.9
ROGN00[c]	120.	102.	122.	304.	84.7	143.8	169.8	364.1	540.3	4671.9	990.8	5631.8
MM01[d]	118.	132.	150.	310.	82.6	122.4	179.	165.2	1096.2	2620.4	1551.2	3424.6
BGR99[e]	134.	118.	66.	504.	81.1	1.5	119.4	1712.1[f]	425.4	4671.9	760.	7073.4
BGR03[g]	128.	56.	70.	210.	78.	1.5	105.6	743.6[h]	511.6	3030.2	775.1	4159.4
1860 – 1998[i]	98.	6.			35.2	.0			156.6		295.8	
SRES-A1[j]	416				646				415		1477	
SRES-A2[k]	344				376				1221		1941	
SRES-B1[l]	392				225				345		962	
SRES-B2[m]	390				412				329		1131	

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[a] Includes hard coal and lignite.

[b] Nakicenovic et al. (1998)

[c] Rogner (2000, p. 149).

[d] Moomwa and Moreira (2001, p. 236):

[e] BGR (1999, p. X)

[f] Includes 815.5GtC of methane hydrates.

[g] BGR (2003, p. 22)

[h] Includes 238.7GtC of methane hydrates.

[i] History is given for illustrative purposes; taken from Moomwa and Moreira (2001, p. 236).

[j] Consumption 1990 – 2100 SRES-A1 marker scenario version 1.1 Nakicenovic and Swart (2000b, Scenario *AIM* A1).

[k] Consumption 1990 – 2100 SRES-A2 marker scenario version 1.1 Nakicenovic and Swart (2000b, Scenario *ASF* A2).

[l] Consumption 1990 – 2100 SRES-B1 marker scenario version 1.1 Nakicenovic and Swart (2000b, Scenario *IMAGE* B1).

[m] Consumption 1990 – 2100 SRES-B2 marker scenario version 1.1 Nakicenovic and Swart (2000b, Scenario *MESSAGE* B2).

of subsidies. This is not offset by upratings of new producer countries, which export coal like Columbia and Indonesia. Grimston (1999, p. 6) reports gross downward corrections of 95Gt coal from 1991 to 1998 to 984Gt of coal reserves.

The second major uncertainty lies in the extent to which unconventional oil and gas could be utilised. The uncertainty is mainly due to future extraction technologies, since the location of the deposits is well known. This is especially true for methane hydrates in the oceans.

Three points should be considered with respect to unconventional oil and gas production. First, the US government has introduced tax exemptions for ongoing projects since the late 1970ies, which would not be economical. Second, unconventional hydrocarbon deposits vary to a considerable extent with respect to extraction conditions. Technological progress will make available only some more deposits rather than a whole type of source because of the heterogeneity of the deposits. Third, extraction and refining of unconventional hydrocarbons increases the ow-consumption of energy as well as the capital needs relative to their conventional counterparts due to the bad natural conditions; see e.g. DTI (2001) and BGR (2003, Ch. 2 and 3).

For the model *MIND* the parameters are based on Nordhaus and Boyer (2000, p. 55): $\chi_1 = 113\frac{\$\mathrm{US}}{\mathrm{tC}}$, $\chi_2 = 800\frac{\$\mathrm{US}}{\mathrm{tC}}$, χ_3 =3500GtC and $\chi_4 = 2$. This means that the quadratic function for the scarcity effect of the capital productivity reaches about a seventh of its initial value, when the cumulative resource extraction is 3500GtC.

The parameters for the learning effect of the capital coefficient are based on *ad-hoc* assumptions. The learning potential $\kappa_{fr,l}^{max}$ is assumed twice the initial value of $\kappa_{fr,l}(t = \tau_1)$. The velocity parameter $\tau_{res,l}$ is assumed to be 100 years. The dampening parameter $\beta_{res,l}$ is assumed at 0.4.

Next, the focus is on the initial capital stock K_{fr}^0 and the depreciation rate δ_{fr}. Using the perpetual inventory method already introduced in Ch. 4.3.2 might produce misleading results, because capital installed decades ago is still in operation, which would be depreciated in the PIM approach using a reasonable depreciation rate. The point is that a reasonable depreciation rate of 5% would lead to a relatively small capital stock, since a considerable amount of capital today is assessed to be outdated and has to be replaced in the near future; see IEA (2003). This thesis aims at an analysis of future investments. This requires the replacement value of a capital stock that is derived from data on investment costs and extraction activity

Table 4.5: Energy in ZJ of reserves and resources of fossil primary energy carriers. Source: see footnotes.

	Oil				Gas				Coal[a]		Total	
	Reserve		Resource		Reserve		Resource		Reserve	Resource	Reserve	Resource
	conv.	unc.	conv.	unc.	conv.	unc.	conv.	unc.				
1860 – 1998[b]	4.9	.3	-	-	2.3	.0	-	-	6.	-	12.6	-
NGM98[c]	6.3	8.1	6.1	13.9	5.9	8.	11.7	10.8	25.4	117.	53.7	159.5
ROGN00[d]	6.	5.1	6.1	15.2	5.5	9.4	11.1	23.8	20.7	179.	46.7	235.2
MM01[e]	5.9	6.6	7.5	15.5	5.4	8.	11.7	10.8	42.	100.4	67.9	145.9
BGR99[f]	6.7	5.9	3.3	25.2	5.3	.1	7.8	111.9[g]	16.3	179.	34.3	327.2
BGR03[h]	6.4	2.8	3.5	10.5	5.1	.1	6.9	48.6[i]	19.6	116.1	34.	185.6
1860 – 1998[j]	4.9	.3			2.3	.0			6.		12.6	
SRES-A1[k]	20.8				42.2				15.9		78.9	
SRES-A2[l]	17.2				24.6				46.8		88.6	
SRES-B1[m]	19.6				14.7				13.2		47.5	
SRES-B2[n]	19.5				26.9				12.6		59.0	

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[a] Includes hard coal and lignite.

[b] History is given for illustrative purposes; taken from Moomwa and Moreira (2001, p. 236).

[c] Nakicenovic et al. (1998)

[d] Rogner (2000, p. 149).

[e] Moomwa and Moreira (2001, p. 236):

[f] BGR (1999, p. X)

[g] Includes 53.3ZJ of methane hydrates.

[h] BGR (2003, p. 22)

[i] Includes 15.9ZJ of methane hydrates.

[j] History is given for illustrative purposes; taken from Moomwa and Moreira (2001, p. 236).

[k] Consumption 1990 – 2100 SRES-A1 marker scenario version 1.1 Nakicenovic and Swart (2000b, Scenario *AIM* A1).

[l] Consumption 1990 – 2100 SRES-A2 marker scenario version 1.1 Nakicenovic and Swart (2000b, Scenario *ASF* A2).

[m] Consumption 1990 – 2100 SRES-B1 marker scenario version 1.1 Nakicenovic and Swart (2000b, Scenario *IMAGE* B1).

[n] Consumption 1990 – 2100 SRES-B2 marker scenario version 1.1 Nakicenovic and Swart (2000b, Scenario *MESSAGE* B2).

in the following.

In Eq. 4.32 fossil energy carrier extraction R^0 in units of $\frac{\mathrm{EJ}}{\mathrm{y}}$ combined with the hours of operation per year ν_R imply capacities Cap_R in GW that are necessary to achieve that extraction. In Eq. 4.33 the investment costs in units of $\frac{\$\mathrm{US}}{\mathrm{kW}}$ are multiplied with Cap_R, which results in the replacement value of K_R^0:

$$Cap_F^0 = \frac{R^0}{\nu_F}, \tag{4.32}$$

$$K_F^0 = \iota_F^0 \quad \cdot Cap^0; \tag{4.33}$$

The CO2DB database by the International Institute for Applied System Analysis (IIASA) contains investment cost data for several extraction technologies and regions in $\$\mathrm{US}_{1987}$. Tab. 4.6 summarises the relevant data for conventional oil and gas and coal. All fuels are distinguished by quality grades and the hydrocarbons are additionally distinguished by on- and offshore. For the sake of brevity the table is limited to the regions with the highest and lowest values of investment costs per technology. As can be seen, the data varies by region, fuel and deposit over a considerable range. For comparison the investment costs in terms of $\frac{\$\mathrm{US}}{\mathrm{tC}}$ are added because the investment costs for CCS technologies will be given in the same unit.

BP (2003) offers data on resource extraction by fuel and region that fit with the CO2DB regions. Tab. 4.7 gives the data on resource extraction by region and fuel. A major shortcoming is that the data does neither distinguish between on- and off-shore hydrocarbon extraction nor by the quality of a deposit.

Some ad-hoc assumptions are made. First, the shares of grade I and II fuels in each region are 60% and 40%, respectively. Second, there are no off-shore hydrocarbons. Third, the capacity utilisation is $\nu_F = 0.75 \cdot 8760\frac{h}{y}$ for all fuels and all regions. The results are given in Tab. 4.8. The capital stock computed in that way equals 2.2tril.$\$\mathrm{US}_{1987}$. If one assumes that the impact of inflation until 1995 is 25%, the effect of accounting for off-shore is about 20% and the overall infrastructure related expenditures amount to 50%, then the initial capital stock is 5tril.$US, which is chosen for K_F^0. The depreciation rate is assumed to be $\delta_R = 0.05$.

The modelling approach bears some problems related to the cost structure of coal, oil and gas extraction that are worth to add. The capital intensity is different for coal, oil and gas, which is related to the approach that labour is not modelled as a production factor in this sector. IEA (2003, p. 44) reports that it is four to five times higher for oil and gas, respectively, than for coal. Additionally, the labour share is

Table 4.6: Investment ι^0_{fr} and O&M costs of fossil energy extraction technologies in $\$US_{1987}$ by region and fuel. Source: CO2DB database.

	ι_{fr}	$O\&M_{fr,fix}$	$O\&M_{fr,var}$	ι_{fr}	$O\&M_{fr,fix}$	$O\&M_{fr,var}$
unit	$\frac{\$US}{kW}$	$\frac{\$US}{kW/y}$	$\frac{\$US}{kW/y}$	$\frac{\$US}{tC}$	$\frac{\$US}{tC/y}$	$\frac{\$US}{tC/y}$
Coal mining DC[a]	102.37	3.23	38.79	155.6	5.05	58.0
Coal mining AUS	101.29	2.16	35.69	153.96	3.28	54.25
Coal mining WE	238.15	21.55	32.33	316.0	32.76	49.14
Coal mining NA	69.	8.	34.	104.88	12.16	51.68
Coal mining LA	86.21	5.39	53.88	.	.	.
Deep mines LA	107.76	6.47	59.27	163.80	9.83	90.09
Open cast coal DC	48.49	5.89	39.87	73.70	8.95	59.08
German hard coal	377.16	34.48	75.43	573.28	52.41	114.65
Lignite NA	37.	3.75	16.9	56.24[b]	5.7	25.69
Lignite WE	329.75	8.19	16.49	501.22	12.44	25.06
Offshore Gas I[c] OP	49.15	.39	.32	127.30	1.01	.83
Offshore Gas I NA	296.6	6.	11.	768.19	15.54	28.49
Offshore Gas II OP	90.52	.39	.32	234.45	1.01	.83
Offshore Gas II NA	593.	18.	27.	1535.87	46.62	69.93
Offshore Gas III OP	109.92	.52	.39	284.69	1.35	1.01
Onshore Gas I OP	40.95	.32	.27	106.06	.83	.70
Onshore Gas I NA	130.	3.	5.	336.7	7.77	12.95
Onshore Gas II OP	75.73	.32	.27	196.14	.83	.70
Onshore Gas II NA	560.	9.	12.	1450.4	23.31	31.08
Onshore Gas III OP	91.6	.43	.32	273.24	1.11	.83
Onshore Gas III LA	775.87	21.55	16.16	2009.50	55.81	41.85
Offshore oil I OP	49.14	.39	.32	97.30	.77	.63
Offshore oil I NA	219.	12.	22.	433.62	23.76	43.56
Offshore oil II OP	135.	.59	.48	267.3	1.17	.95
Offshore oil II NA	453.	17.	30.	896.94	33.66	59.4
Offshore oil III OP	400.	2.	1.5	792.	3.96	2.97
Onshore oil I OP	40.95	.32	.27	81.08	.63	.53
Onshore oil I NA	211.	11.	20.	417.78	21.78	39.6
Onshore oil II OP	75.43	.32	.27	149.35	.63	.53
Onshore oil II DC	323.28	6.47	16.16	640.09	12.81	31.0
Onshore oil III OP	86.21	.43	.32	170.70	.85	.63

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[a] Country abbreviations are AUS ≙ Australia, DC ≙ Developing Countries, LA ≙ Latin America, NA ≙ North America, OP ≙ Organisation of Petroleum Exporting Countries, WE ≙ Western Europe.

[b] The same conversion factor as for hard coal is used.

[c] The roman numbers distinguish deposits with decreasing ease of accessibility.

Table 4.7: Global primary energy extraction R_0 in 1995 by region and fuel in EJ. Source: BP (2003).

	NA	LA	EEFSU	ME	AF	AP
Oil	27.1	12.3	28.1	41.0	14.3	14.8
Gas	27.2	2.8	34.2	5.6	3.2	8.0
Coal	25.0	1.0	20.8	0.0	5.1	42.1

different. The labour share in US coal industry is ∼40%; see Ellerman et al. (2001, p. 380). It is ∼15-20% for oil and gas. The CO2DB database confirms this, since the shares of extraction cost components – investment and operation and maintenance O&M costs – vary in a similar manner. This point is of special importance for the global fossil fuel supply curve for the 21st century, since wages are expected to increase and labour augmenting technological change in this sector might differ from the rest of the economy. These points are related to the problem regarding micro-foundation of a supply curve that puts deposits in a sequence of future extraction as mentioned in Ch. 4.2.4.

4.3.5 The Fossil Energy Sector

The fossil energy transformation sector requires assumptions on:

1. the energy input $E_{P,F}$ and output $E_{S,F}$ of the production function;
2. the parameters in the production function σ_F, ξ_F^E, ξ_F^K, ϵ_F and Φ_F;
3. the initial capital stock K_F^0 and the depreciation rate δ_F.

The differentiation of primary and secondary energy is in accordance with SRES data for 1990 – 2000. Since SRES is reported for 10-years time steps, only, but *MIND*s initial period is 1995, the average values is taken for 1990 and 2000. $E_{P,F}$ in

Table 4.8: Global primary energy extraction capital stocks K_F^0 in bil.\$US$_{1987}$ by region and fuel. Source: based on BP (2003) and CO2DB database.

	NA	LA	EEFSU	ME	AF	AP	Global
Oil	275.1	81.8	189.8	89.0	94.7	148.1	878.5
Gas	325.6	24.7	391.0	12.2	28.1	96.5	878.0
Coal	46.2	3.3	242.2	0.1	17.5	130.3	439.6
Total	646.9	109.8	822.9	101.3	140.3	374.9	2196.1

1995 consists of 141.5EJ oil, 91EJ coal and 77.5EJ gas. This sums to 310EJ primary fossil energy. The secondary energy from these sources is 271EJ.

The elasticity of substitution σ_F between primary fossil energy and capital is difficult to choose. The number of studies on that parameter is limited because most studies focus on the use, rather than the production of energy. In Koschel (2000) the corresponding parameter is estimated to be 0.3 for West-Germany's energy production sector in the period 1978 – 90. This value is assumed for σ_F. The parameters ξ_F^E and ξ_F^K are related to the factor shares $\tilde{\xi}_F^E$ and $\tilde{\xi}_F^K$. These are difficult to choose, because the changing energy prices affect the factor shares considerably. Both factor shares are assumed at 0.5 in 1995.

The initial capital stock is assumed according to the replacement principle. Constructing the initial capital stock using the perpetual inventory method PIM is related to at least two problems. First, international data sets do contain the category *electricity, water, gas*; e.g. OECD database. Obviously, the amount for water has to be subtracted, but there are no reliable information at the international level for this magnitude. The second problem is related to the investment dynamics since WWII within the energy sector in OECD countries, especially the electricity and the refinery sector. The characteristic pattern is most pronounced in the USA. The peak in electricity capacity additions has been in the 1970ies. Since then the capacity additions have been reduced to nearly zero. The last green field refinery in the US started operation in the 70ies. The capacities built up until then, are still in operation today; see EIA (2005). Using the PIM would produce a picture, with a relatively low capital stock that enters the production function. This low initial capital stock would bias the capital returns upwards and boost investment into the fossil energy sector.

The fossil energy sector capital in 1995 is chosen to be 6tril.$US. This number can be justified in the following way. The most capital intensive processes are the production of electricity generation and liquid fuels. The world electricity capacity based on fossil fuels is about 3000GW; see IEA (2003). Assuming investment costs of 1000$US per kW gives 3tril.$US. The worldwide refinery capacity is 76.5mil.b/d. Assuming investment costs of 10000$US per capacity unit, the capital stock is 0.765tril.$US. Adding a third due to other capacities and specific infrastructure justifies the assumption of 6tril.$US. The deprecation rate δ_F is assumed to be 5%.

4.3.6 The Renewable Energy Sector

In the renewable energy sector assumptions on the following exogenous model parameters are needed:

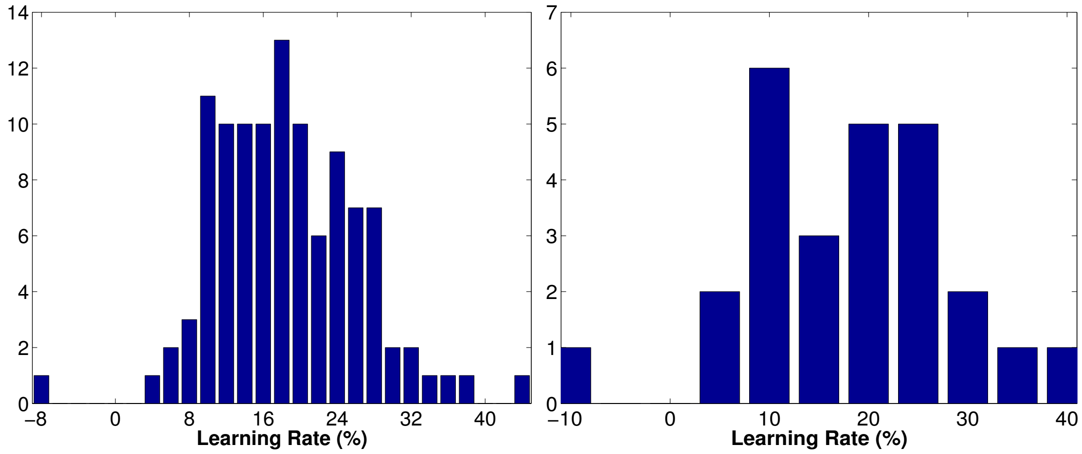
1. the learning rate λ_{ren} and the dampening parameter of learning β_{ren};
2. the initial investment costs ι^0_{ren} and the floor costs ι^{floor}_{ren};
3. the full load hours per year ν;
4. the initial condition for the cumulative capacity CK^0_{ren};
5. the initial vintage structure K^0_{ren} and the depreciation factors $\omega_{ren}(\tau)$.

The learning rate is an empirical finding that is common to several technologies and discussed in several economic disciplines. The learning rate of renewables is a highly disputed parameter in the literature about energy and climate policy. Several literature surveys and reports are available about it. Most studies deal with solar photo voltaic (PV) appliances and wind power; i.e. electricity generation technologies with large numbers of produced units. Moreover, there are some that address biomass based fuel production.

The learning rate measures the reduction of economic effort per unit of an activity for a doubling of experience. There is some dispute on the proper specification of the learning process. Junginger (2000, p. 10) identified the following two types, where the first item measures the learning success and the second item measures the experience:

1. the investment costs (e.g. in $\frac{\mathrm{\$US}}{\mathrm{kW_e}}$) per doubling cumulative installed capacity (e.g. in $\mathrm{GW_e}$);
2. the output costs (e.g. in $\frac{\mathrm{\$US}}{\mathrm{kWh_e}}$) per doubling of cumulative output (e.g. in $\mathrm{TWh_e}$);

In studies that have been published in recent years the focus has extended. Since more data is available, the focus is also on the learning rates of components of renewable energy technologies. As a rule these studies find that the learning rates of components are smaller than the learning rate of the composite. The main reason



(a) Various manufacturing sectors

(b) Energy technologies

Figure 4.8: Absolute frequency distribution of learning rates for several manufacturing sectors (left panel) and energy technologies (right panel). The frequency distribution cannot be interpreted as a probability density functions. Source: Dutton and Thomas (1984, p. 238) and McDonald and Schrattenholzer (2001, p. 258).

for this is that learning often takes place at the stage of combining components; see Neij et al. (2003).

A widely recognised literature review on learning rates is given by Dutton and Thomas (1984) that includes 108 technologies from various fields with learning rates around 19 – 20%. McDonald and Schrattenholzer (2001) summarised 26 energy technologies with learning rates centering around 16 – 17%. They found learning rate of type 1. for wind is at 4 – 8% and 18 – 32% for type 2. The type 1. learning rate is ∼20% for solar PV. Fig. 4.8 gives the corresponding frequency distributions.

Watanabe et al. (2000) study the solar PV research program in Japan. They found a type 1. learning rate of 19.3% for the Japanese PV industry for the period 1976 – 1995. The authors emphasis the significance of the government initiative to induce the process of learning that has been realised by private companies.

According to Harmon (2000, p. 10) the type 1. learning rate for PV modules at an international level has been 20.2% for the period 1968 – 98 in which thirteen doublings occurred.

Isoard and Soria (2001) study type 1. learning rates and economies of scale for solar PV and wind power using world data for the period 1976 – 94 and found 8.6%. For a different specification with the possibility for economies as well as diseconomies of scale they found a learning rate of 27.8%, but the scale elasticity has been estimated to be only 88%.

Neij et al. (2003) focused on the wind power industry in four European countries based on list prices. They found a considerable difference between type 1. and 2. learning curves; e.g. the type 1. learning rate in Denmark (Germany) is 8% (6%) and the type 2. learning rate is 14% (12%). The main reasons for the decreasing investment costs has been the upscaling of the size of wind turbines and the increased capital-labour ratio in the production process. The main reason for the difference is that the capture of wind by the power plant is improved (see below the discussion about ν) and the O&M costs are reduced. This indicates that the type 2. learning curve captures more sub-processes in which learning takes place relative to type 1. The authors claim that they are not able to distinguish between learning and economies of scale effects; see Neij et al. (2003, p. 49).

Goldemberg (1996), Moreira and Goldemberg (1999) and Goldemberg et al. (2004) study learning effects in the transportation related biofuel industry in Brazil. The type 2. learning rate increased from 7% for the period 1980 – 85 to 29% for the period 1985 – 2002. The authors claim that the biofuel is already competitive with oil based fuels in Brazil.

The present modelling approach is of type 1. and the learning rate λ_{ren} is assumed to be 15%.

There is no empirical assessment available for the dampening parameter and β_{ren} is therefore assumed at 0.4. It is justified by the observation in Neij et al. (2003) and Goldemberg et al. (2004) that the learning process is decelerated, if the capacities extension is accelerated.

Next, the assumption on the initial investment costs subject to learning ι^0_{ren} and the floor costs ι^{floor}_{ren} are laid out. In the *MIND* model the former is assumed at $700\frac{\$\mathrm{US}}{\mathrm{kW}}$ and the latter at $500\frac{\$\mathrm{US}}{\mathrm{kW}}$. The following literature study discusses the choice of these values considering especially wind energy as a representative renewable energy technology.[12]

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[12] Obviously, this is a problem that is rooted in the high level aggregation of the energy sector. Disaggregation of the sector is subject to future improvements of the model.

With respect to wind power plants the study by Neij et al. (2003) contains detailed information about the European wind industry.[13] The price data are based on list prices of manufactures. The wind turbines sold by Danish manufactures cost $750\frac{\$US}{kW_e}$ and $1000\frac{\$US}{kW_e}$ by German manufactures in 2000.

Junginger et al. (2005) emphasis that up-scaling wind turbines as a source for cost reductions is not observed generally. The study reports an increase of list price investment costs from around $0.6MW_e$ to $1.5MW_e$ with increase of investment costs from $900\frac{\$US}{kW_e}$ to $1050\frac{\$US}{kW_e}$. For greater wind turbines the up-scaling effect works, since the investment costs for $2.5MW_e$ units are reported at $800\frac{\$US}{kW_e}$. Additionally, the study reports that the number of wind turbines per order reduces the price considerably. The downwards deviation of the realised price relative to the list price per turbine is a linear decreasing function of the natural logarithm of units ordered. The study reports that order sizes of 500 wind turbines[14] lead to $500\frac{\$US}{kW_e}$ investment costs. The authors argue that the scale of production is essential for the price policy of wind turbine producers. Therefore, the scale of wind parks determine the cost of wind energy. They conclude that the view on list prices of investment costs for wind turbines or the costs of electricity from wind power are a too narrow view.

The IIASA CO2DB database contains data on wind turbines sold by several firms. The investment costs are around $900\frac{\$US}{kW_e}$.

The German Enquete-Kommission reports investment costs of $741 - 946\frac{\$US}{kW_e}$ plus $230 - 307\frac{\$US}{kW_e}$ for necessary additional charges for onshore wind turbines. For offshore wind turbines the investment costs are $895 - 1023\frac{\$US}{kW_e}$ plus $639 - 767\frac{\$US}{kW_e}$ additional charges; see Enquete-Kommision (2002, p. 535 – 37). It does not become clear in how far these additional charges are included in the numbers given above. For solar PV the investment costs are assumed to be $5000\frac{\$US}{kWh_e}$.

Zwaan and Rabl (2003) and Zwaan and Rabl (2004) summarise that the costs of grid connected solar PV installations vary between $2000 - 8000\frac{\$US}{kW_e}$. The costs of stand-alone installations are significantly higher because of auxiliary equipment for

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[13] The study reports the investment costs in domestic currencies, therefore assumptions about the exchange rate have to be done. For DM the exchange rate with the EURO is assumed. The exchange rate of $US and EURO is one to one. The Danish Krone is assumed at 7.5DKK per EURO.

[14] In that case a wind turbines capacity is $0.66MW_e$.

energy storage etc.[15]

In a report that summarises the technology characteristics of several scenarios that are developed with the energy system model *MESSAGE* Nakicenovic and Riahi (2002, p. 5 and 36) report the following figures. The investment costs for wind power in the US decreased from $2000\frac{\$\mathrm{US}}{\mathrm{kW_e}}$ in 1982 to $1000\frac{\$\mathrm{US}}{\mathrm{kW_e}}$ in 1987. For solar photovoltaic the investment costs decreased from above $15000\frac{\$\mathrm{US}}{\mathrm{kW_e}}$ in 1981 to a bit less than $5000\frac{\$\mathrm{US}}{\mathrm{kW_e}}$ in 1995.

In Bahn and Kypreos (2003, p. 344) initial investment costs for wind are $887\frac{\$\mathrm{US}}{\mathrm{kW_e}}$ and for solar PV $6075\frac{\$\mathrm{US}}{\mathrm{kW_e}}$ in 2000. In Kypreos and Bahn (2003, p. 5) the initial investment cost for wind are $1000\frac{\$\mathrm{US}}{\mathrm{kW_e}}$. For solar PV the initial investment costs are $5000\frac{\$\mathrm{US}}{\mathrm{kW_e}}$.

Next, the focus is on the floor costs ι_{ren}^{floor}. The assessment of these numbers is much more speculative because the potential for cost reduction is not realised, yet. There are two different ways to find assumptions for ι_{ren}^{floor}. Some energy system models make explicit assumptions on floor costs and other provide insight into the floor costs via the model outcome.

In Nakicenovic and Riahi (2002, p. 39) the investment costs for wind power and solar photovoltaic come into the range of $200 - 400\frac{\$\mathrm{US}}{\mathrm{kW_e}}$ in 2100 for the lowest cases. Biomass will reach $800 - 1000\frac{\$\mathrm{US}}{\mathrm{kW_e}}$ in the lowest cases. In the more pessimistic cases the investment costs will remain at higher levels. For wind power this could be $1000 - 1200\frac{\$\mathrm{US}}{\mathrm{kW_e}}$ and even above $3000\frac{\$\mathrm{US}}{\mathrm{kW_e}}$ for solar photovoltaic.

In Bahn and Kypreos (2003, p. 344) looked for the impact of different learning curve formulations. For several learning curve formulations and assumptions on climate policy the costs decrease to $520 - 564\frac{\$\mathrm{US}}{\mathrm{kW_e}}$ for wind and to $1755 - 6075\frac{\$\mathrm{US}}{\mathrm{kW_e}}$ in 2050. Kypreos and Bahn (2003, p. 5) explicitly assumes floor costs. For wind they are $400\frac{\$\mathrm{US}}{\mathrm{kW_e}}$ and for solar PV $1000\frac{\$\mathrm{US}}{\mathrm{kW_e}}$.

Next the full load hours per year ν_{ren} are assessed that determine the output generated with a unit of capacity. The task is to find a single number for ν_{ren}. In *MIND* the same number is applied as in *MARKAL*, which is $2190\frac{\mathrm{h}}{\mathrm{y}}$ for wind and solar PV; see Kypreos and Bahn (2003, p. 5).

Hoogwijk (2004) assesses ν_{ren} ranging from 500 to 3400 full load hours per year for onshore wind power production based on a global 0.5°×0.5° grid. The German

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[15] They assess the break-even investment costs at $1000\frac{\$\mathrm{US}}{\mathrm{kW_e}}$, which would imply costs of electricity of $4\frac{\mathrm{centUS}}{\mathrm{kWh_e}}$.

Enquete-Kommission reports full load hours ranging from 1580 – 2700$\frac{\mathrm{h}}{\mathrm{y}}$ for onshore and 2500 – 4200$\frac{\mathrm{h}}{\mathrm{y}}$ for offshore wind power for Germany.

There are highly productive regions with up to 6000$\frac{\mathrm{h}}{\mathrm{y}}$ for wind power like the West-African coast line; see Kabariti et al. (2003, p. 3).

The use of a single number for ν_{ren} is highly problematic because the assumption of an average value for a heterogenous distribution of ν_{ren}. The relevant characteristic for the problem at hand is expressed by a specific ν_{ren} for each place.

Moreover, the parameter ν is not only a matter of location and natural conditions. Neij et al. (2003, p. 44) cite an increase of ν_{ren} in Denmark for wind power from 1750$\frac{\mathrm{h}}{\mathrm{y}}$ in 1980 by 43% to 2500$\frac{\mathrm{h}}{\mathrm{y}}$ in 2000. The authors address this to higher towers and improved aerodynamic designs of turbine blades. These technical improvements are not captured in the investment cost as it is modelled in this thesis as well as in other energy systems models.[16]

In order to estimate the initial vintage structure of capital in the renewable energy sector, we assume a total cumulative amount of modern renewable energy production until 1995 of 40EJ and a growth rate of 20% p.a. for renewable energy production from 1960 to 1995. This leads to renewable energy production of 8EJ in 1995. In order to calculate the capacity that has to be installed in each period to achieve 8EJ in 1995, we assume a depreciation scheme for capital[17] and constant full load hours of 2190h per year.

4.3.7 The Climate System

The climate model is tuned to reproduce the short-term (100-years) behaviour of the climate model *MAGICC* that was used an an emulator of complex atmosphere-ocean general circulation models as well as a scenario generator in the Third Assessment Report (TAR) of the IPCC; see Cubasch and Mehl (2001).

The climate sensitivity of the model is set to 2.8°C. The coupling factor between carbon and sulphur emissions $C2SO_2$ decreases by 1% p.a. The land-use change

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[16] The authors support this argument by finding that the learning rate of wind power of type 2. based on electricity production costs in $\frac{\$\mathrm{US}}{\mathrm{kWh_e}}$ and cumulative production in kWh is higher than the type 1. that is based on investment costs in $\frac{\$\mathrm{US}}{\mathrm{kW_e}}$ and cumulative capacity in GW. This is due to the fact that type 2. subsumes the increase of ν.

[17] $\omega_{ren}(1) = 1$, $\omega_{ren}(2) = 0.9$, $\omega_{ren}(3) = 0.8$, $\omega_{ren}(4) = 0.7$, $\omega_{ren}(5) = 0.5$, $\omega_{ren}(6) = 0.15$ and $\omega_{ren}(7) = 0.05$.

scenario is according to SRES B2 scenario; see Nakicenovic and Swart (2000b). The scenario for the radiative forcing of other than CO_2 GHG F_{OGHG} assumes constant emissions of the corresponding other GHGes. More detailed information can be found in Edenhofer et al. (2002, Appendix B).

4.4 Computational Issues

The use of numerical methods has been justified already and some remarks have been made on the interpretation of the results in Ch. 3.4. This section focuses on computational issues of employing numerical methods. There are two major fields that will be addressed in this section. First, the computation time required for one single optimsation run and the corresponding numerical stability and accuracy of solution are discussed (Ch. 4.4.1). Second, since *MIND* integrates technologies with learning effects the problem of multiple optima and the uniqueness of the optimal solution are addressed (Ch. 4.4.2).

4.4.1 The Goodness of Approximation

Optimisation algorithms approximate the optimal solution with respect to the control variables. This is done by iterating a search method that moves towards the location of the solution in the multi-dimensional space. An iteration step starts with the computation of a search direction by determining the direction of the steepest ascent with respect to the objective guaranteing that all constraints are obeyed; this is called the reduced gradient. The step length is determined by moving into that direction as long as the objective is increasing. Otherwise the iteration step is stopped and a new search direction is computed.

In order to receive a solution in finite time one has to choose stopping criteria for the iteration; see Judd (1999, p. 39 – 41). These include minimum progress rates of the control variables between iteration steps and the slope of the reduced gradient. If an iteration does not lead to sufficient change of the control variables and the reduced gradient is sufficiently flat, the algorithm judges that an additional iteration step does not lead to noteworthy changes of the objective function; i.e. the optimal result is found.

It is the task of a good algorithm to approximate the solution sufficiently without

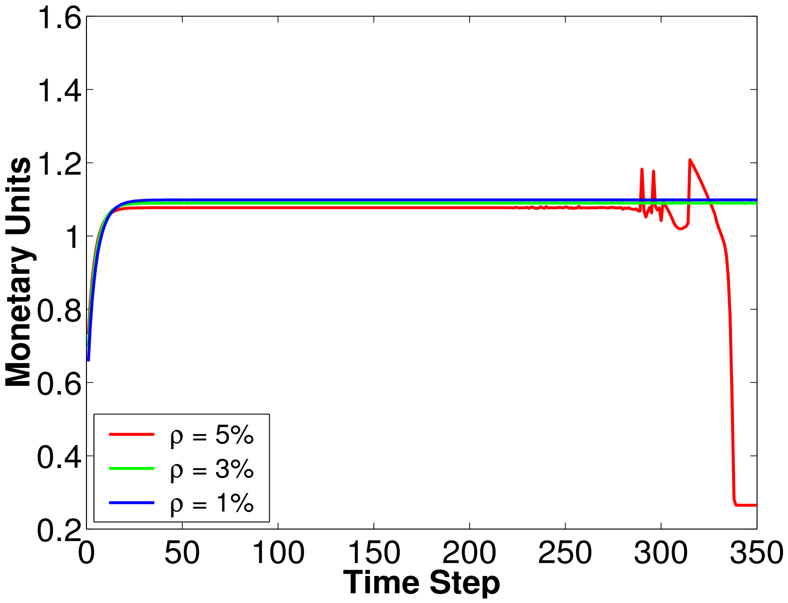

Figure 4.9: Sensitivity of the discounting on the goodness of approximation of the optimal solution in the Ramsey model.

requiring excessive computing time. Low stopping criteria imply a closer approximation to the real optimum, but require additional computing time. Therefore, the appropriate choice of stopping criteria is a compromise. With respect to dynamic models that maximise a discounted objective function one has to pay attention to the discounting rate and the time step that is chosen for the implementation in time discrete form.

The problem is that for small time steps or for high discounting rates changes in control variables in the distant future do not affect the discounted objective value very much. This implies that the approximation to the optimal solution is not as good for late time periods. Fig. 4.9 illustrates this problem for the basic Ramsey model with different discounting rates. For a discounting rate of 5% the approximate solution becomes non-smooth after about 200 time steps. After 250 time steps the solution becomes virtually chaotic. Obviously, it is desirable to have short time steps, but shortening the time step has the same effect on the approximation as increasing the discounting rate. The approximation could be improved by decreasing the stopping criteria of the solution algorithm, which would increase the computation time.

With respect to *MIND* the problem becomes more important for control variables that affect the energy sector. This is due to the fact that changes of the energy sector investments do affect the welfare function indirectly through the channels of the production function.

For the *MIND* model the time steps are 5 years, which is short relative to other models, which assume time steps of 10 years usually. Some even assume 20 years starting in 2000 (see Gerlagh and Zwaan (2003)) or 25 years after 2050 (see Manne et al. (1995)).

It is well known from the numerical computations of physically motivated systems of differential equations that the time step has a significant influence in determining the result. It is an outstanding issue whether there are similar effects in numerical models of economic growth.

4.4.2 Multiple Optima

The issue of multiple optima is an often discussed problem of models that suggests the presence of so called non-convexities. A unique optimum can be proofed, if the task is to maximise a monotonous increasing function over a compact set that is convex.[18]

Fig. 4.10 illustrates the problem. A household has a fix amount of a resource x that can be allocated to two purposes $x = x_1 + x_2$ as is shown in sector I. The amount x_1 is used to produce a good g_1 with a neo-classical production function (sector IV). The amount x_2 is used to produce the second good g_2 with a production function that is not neo-classical since it exhibits changes of the sign of the second partial derivative (sector II). Both production functions in combination with the resource constraint imply a non-convex production possibility set $\mathcal{P}_{nc}$. The utility function is neo-classical in g_1 and g_2. The optimality conditions are fulfilled at $(g_1^{\#}, g_2^{\#})$ as well as (g_1^*, g_2^*), but the isocline U_0^* represents a higher utility than $U_0^{\#}$ and is therefore the global optimum.

The essential point, if a numerical solution algorithm is used, is given in the lower part of Fig. 4.10. Here the optimisation problem is transformed into an optimisation problem with one variable g_2. It can be seen that the function has two maxima and one minimum. If the numerical algorithm starts the search right from the minimum,

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[18] A set is compact, if the set is a subset of a sufficiently large ball and the edge of the set belongs to the set. A set is convex if the straight line connecting two arbitrary points within the set lies completely within the set.

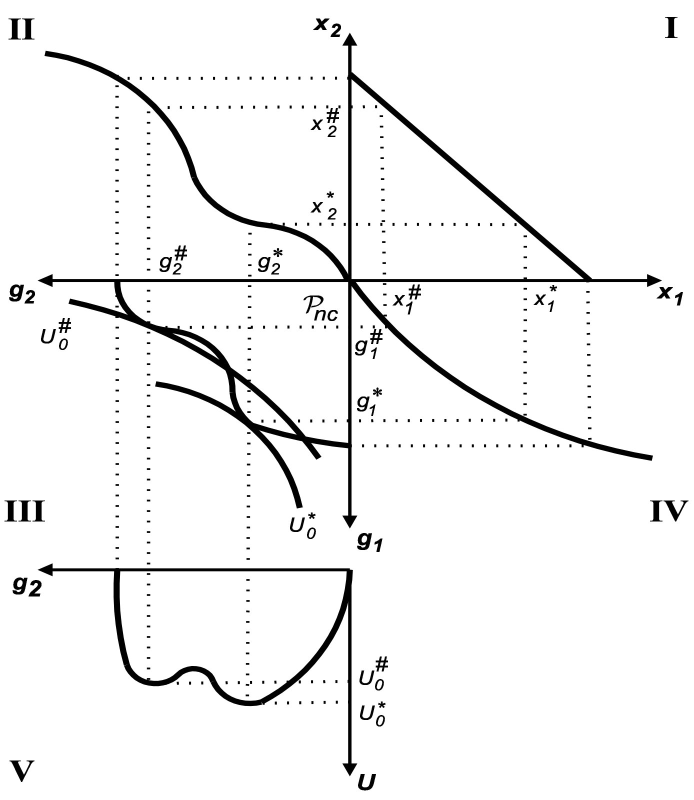

Figure 4.10: Multiple optima in an optimisation problem of a household producing two goods for own-consumption with one resource.

it will find the global maximum. If it starts left from the minimum it will find the lower local maximum. If we rely on the result the algorithm is giving back only, we cannot conclude that the global optimum has been found.

There are several real world phenomena implying non-convexities, if they are represented in a model. Non-convexities could lead to the existence of multiple local optima of which one is the global optimum. The learning effects modelled in *MIND* could imply such non-convexities, which in turn could imply multiple optima. The problem in numerical optimisation problems is that search algorithms as described above find the optimum according to local criteria, only. It could be that a solution that is found is not the *optimum optimorum* and that there is a superior optimum that is located at a different location of the space of control variables.

MIND is solved using the non-linear optimisation algorithm *Conopt3*. This solver relies on local search procedures and is therefore not able to decide, whether an optimum is the global. Therefore, it can not be rigorously guaranteed that the solution found is indeed the global optimum.

To address this problem some search strategies have been performed – not discussed in detail here – that are reasonable to find different local optima, if they are present. The result has been that the same solution has been found for several points from where the algorithm starts to search for the optimum. To the best of my knowledge, the *MIND* model as it is introduced in this thesis does not give rise to multiple optima.[19]

4.5 Results with *MIND1.0*

In this section the results computed with *MIND1.0* are presented with respect to the business-as-usual BAU and two climate protection (CPP) scenarios:

1. ***BAU*** The climate problem is not considered to constrain the economic development.
2. ***CPP***^{0} The climate guardrails of the WBGU window constrain the economic development. CCS is not an available option for climate policy.
3. ***CPP***$^+$ The same as CPP^0 but now CCS is available through the exogenous paths of the amount and costs of CCS.

The introduction of two different CPP scenarios serves for the assessment of CCS for climate protection strategies within the model framework. The analyses of each issue will be done in two steps. First, the BAU scenario is introduced and compared with both CPP scenarios. Second, the significance of CCS will be assessed by comparing the CPP^0 scenario without CCS with the CPP$^+$ scenario with CCS.

The presentation of the results is distinguished into five subsections. In the first subsection the optimal emission paths and the implied climate change of the three scenarios are introduced; see Ch. 4.5.1. Then the changes of the total energy

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[19] The economic discussion on optimal control problems with non-convexities is summarised in Haunschmied et al. (2003). A numerical algorithm devoted to solve problems of multiple optima is developed by Tawarmalani and Sahinidis (2002). The problem of multiple equilibria is treated by Krugman (1991). Up to my knowledge the relationship between multiple optima and equilibria in dynamic economic systems with capital stocks is not addressed in the literature, already.

production and the energy mix as well as the required changes in energy related investments are presented; see Ch. 4.5.2. Third, the macro-economic impacts of the CPP scenario are shown; see Ch. 4.5.3. In the final subsection these results are compared with those found in the related scientific literature; see Ch. 4.5.6. The second purpose is to analyse the overall macro-economic dynamics of the model with respect to the stylised facts of economic growth introduced in Ch. 2.6.3.

4.5.1 Emissions and Climate System

In this part the results for the CO_2 emissions and the implied climate change is presented.

The time path of the total CO_2 emissions – sum of fossil fuel combustion and land-use change – are shown in Fig. 4.11(a). The CO_2 emissions start at 7.7GtC in the year 2000. In the BAU case the emissions increase approximately linearly to more than 32GtC in 2100, which is a high emission scenario relative to the IPCC SRES scenarios; see Nakicenovic and Swart (2000a). The little decline around 2020 is due to the exogenous scenario of land-use change.

In the CPP scenarios we observe a sharp deviation from the BAU scenario already in the near-term. The emissions are constant until 2030 and decrease thereafter. The initial reductions in the CPP scenarios of the CO_2 emissions is due to the flexibility of substitution in the macro-economic production function. The emissions in the CPP^+ scenario are mildly higher than in the CPP^0 scenario until 2020 and lower thereafter; see Ch. 4.5.2 below for details.

The essential observation is that for both CPP cases the CO_2 emission paths are nearly the same. The only small difference between CPP^0 and CPP^+ emerges because confronting the economy with this climate constraint leads to an intertemporal optimal emission time path that is as strong as a constraint on the emissions. The inclusion of CCS does not lead to considerable intertemporal arbitrage of emissions that are permissible. Since the economy is on a macro-economic transition path – as will be explicated below – the near-term emissions are more valuable than emissions in the distant future because the economy starts at a relatively low capital stock. This finding is in accordance with the theoretical discussion in Ch. 3.6.1.[20]

The implications on climate change are shown in Fig. 4.11(b) as a phase dia-

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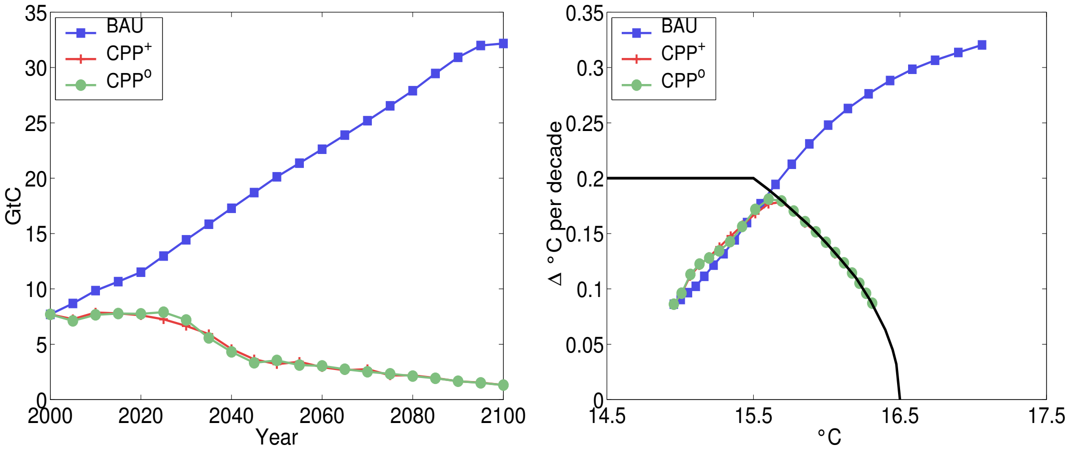
[20] This argument is not considered in Wigley et al. (1996).



(a) Total global carbon emissions

(b) Dynamics of the GMT

Figure 4.11: Total global carbon emissions and the dynamics of the GMT for the three scenarios.

gram, where the climate window delimited by the guardrails is added. The abscissa represents the global mean temperature GMT, where the origin is the pre-industrial GMT. The ordinate represents the rate of change of GMT per decade. The markers indicate time steps of 5 years. For all model runs the GMT shows an initial anomaly of about 0.5°C that is a consequence of climate change that has been realised by historic CO_2 emissions until 2000.

The figure shows that in the BAU case the climate window will be left around the year 2050. The GMT increases by 2.6°C above the pre-industrial level until 2100 and will increase thereafter, which is indicated by the positive rate of change. In the CPP cases the climate window will not be left by definition. The edge of the climate window will be approached around the year 2050, then the system moves along the edge towards a stable climate. The GMT will increase over the course of the 21^{st} century and thereafter.

The phase diagram for the GMT exhibits a different short-term behaviour for the BAU scenario and the CPP scenarios: the rate of GMT increase is higher for the CPP than for the BAU scenario. This is due to the combined reduction of CO_2 and sulphate aerosol emissions, which leads to the accelerated draw back of the aerosol mask and its cooling effect. The effect is moderate, but it should be noted that this is the global effect and there could be more drastic effects at the regional level. The same effect distinguishes the CPP scenarios. A close look at the path of the CPP scenarios shows that the CPP$^+$ case exhibits a mildly higher rate of temperature increase. This is due to the combined removal of CO_2 and sulphate aerosol emissions by CCS and the different CO_2 emission scenario in the CPP$^+$ scenario.

Although the climate window is obeyed in the CPP scenarios, climate change until 2050 will be approximately the same as in the BAU scenario. Note that this statement depends heavily on the very simple climate model integrated into the framework! A similar result is computed taking into account CO_2 and aerosols emission by West et al. (1997, p. 931).

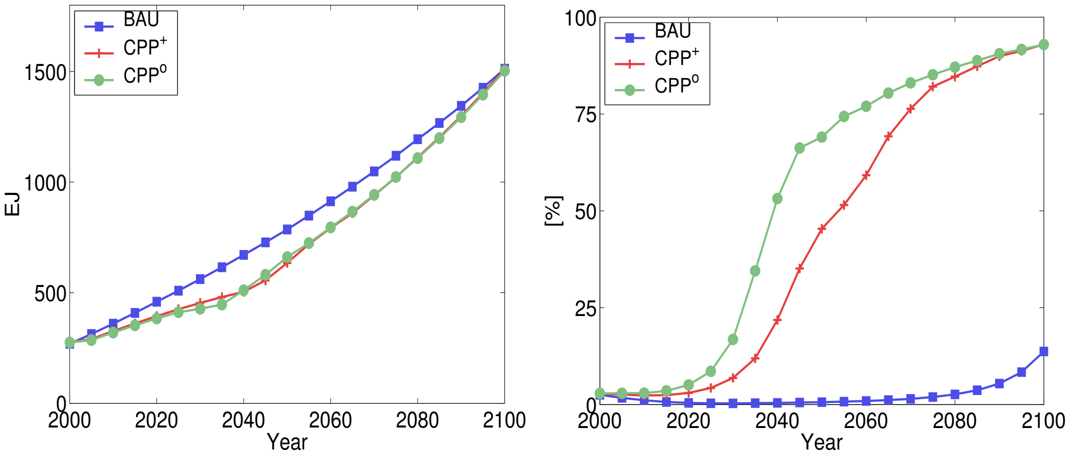
The integration of all climate relevant emissions of fossil fuel combustion and the climate system within an IAM is important for the assessment of climate stabilisation scenarios. In WBGU (2003, p. 119) the climate protection constraint has been imposed on the atmospheric CO_2 concentration, which is limited to 450ppmv. The implied – but not integrated – time path of the GMT leaves the climate window and enters back after some time due to the accelerated removal of sulphate aerosols. The maximum rate of GMT increase reaches 0.24°C per decade, which violates the corresponding guardrail; the path does not violate the 2°C GMT guardrail until 2100.

4.5.2 The Energy Sector

In the following the changes of the total energy production, the energy mix and changes of the energy related investments are analysed. The imposition of the climate window requires considerable changes in the overall level of energy related investments as well as in the energy mix. This in turn implies changes in the level and structure of energy production.

Fig. 4.12(a) shows the time path of the overall energy production that is available for the growing economy. In the BAU scenario the energy production reaches about 1.5ZJ in 2100, which is six times the energy production of the year 2000. The CO_2 emissions growth is nearly linear in time. This is a high energy scenario relative to the IPCC SRES scenario; see Nakicenovic and Swart (2000a).

The time paths of energy production in the two CPP scenarios are characterised by gaps to the BAU scenario that are increasing until 2040. The difference is remarkable: in 2035 the energy production in the CPP$^+$ scenario is 25.8% lower than in the BAU scenario; in the CPP^0 scenario this reduction is even 31.1%. This gap



(a) Total global energy production

(b) Market share of renewable energy

Figure 4.12: Energy production and market share of renewable energy for the three scenarios.

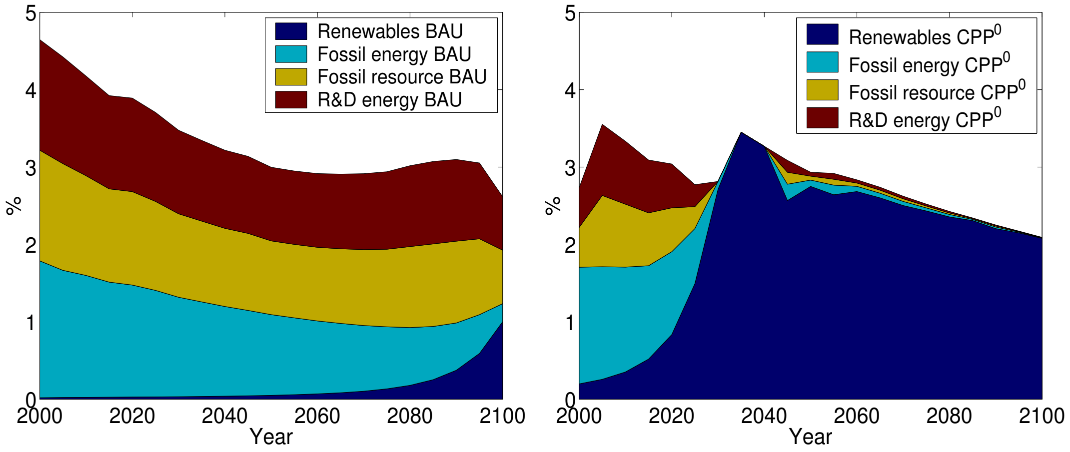
is the result of substitution effects within the macro-economic production function. The improvement of energy efficiency plays a different role as will be shown below.

From 2050 on the gap between the CPP scenarios and the BAU scenario becomes smaller. This is mainly due to the increase of renewable energy production, which does not lead to CO_2 emissions.

The difference between the two CPP scenarios is less remarkable. In the CPP^0 scenario the energy production is higher until 2040, but becomes a bit smaller thereafter. Both paths exhibit approximately the same behaviour from 2060 on.

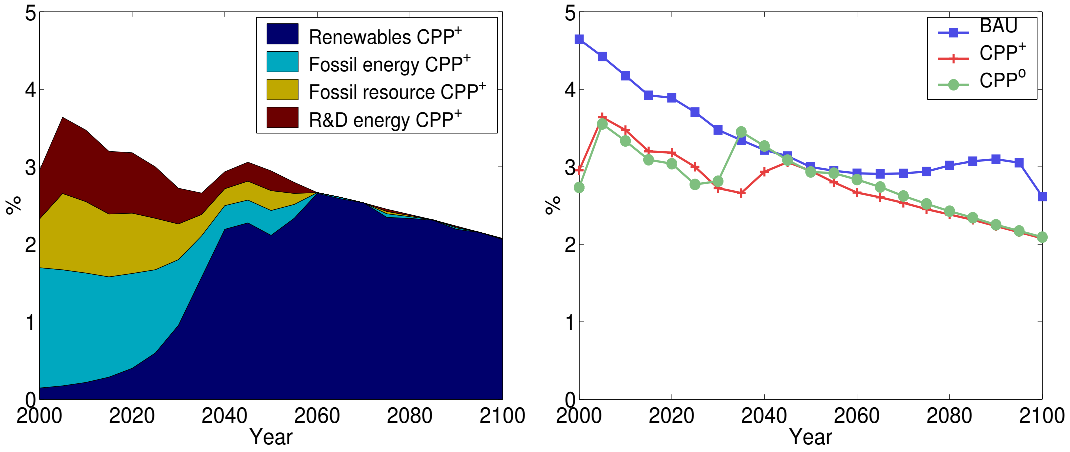
Fig. 4.12(b) shows the market share of renewable energy production for the three scenarios. In the BAU scenario renewable energy technologies are not present over the course of the 21st century and will gain a market share of 6.4% in the year 2100. In the CPP scenarios the market share of renewable energy technologies has to increase drastically by the middle of the 21st century. In the CPP^0 scenario the increase is most drastically and reaches 69.2% until 2050. In the CPP^+ scenario with CCS the increase is delayed and not as sharp, although the climate window will be obeyed. The renewable energy technologies have to reach a market share of 46% until 2050, which still implies major changes to the energy system.

The total energy production and the structural change of the energy mix require considerable changes of the investments related to the energy sector, which are



(a) BAU scenario

(b) CPP^0 scenario



(c) CPP$^+$ scenario

(d) Comparison

Figure 4.13: Disaggregated energy related investment shares for the three scenarios and comparison of aggregate energy related investment shares.

given in Fig. 4.13 and described next. The investments related to energy comprise the investments in renewable energy technologies, the fossil energy sector, the fossil resource extraction sector and the energy related RD&D sector. The results will be presented in terms of investment shares, which are the investments divided by the GWP of a year.

The BAU scenario in Fig. 4.13(a) is characterised by steady decline from high initial level of energy related investment shares in total and in each component until 2070. At this time the fossil energy carriers become scarce and the investment share for extraction increases, while the share for the fossil energy sector keeps on decreasing. The scarcity is partly reduced by production of energy from renewable sources and acceleration of energy productivity growth. In the course of the 22nd century the energy system will be transformed to renewable energy sources because of the increasing scarcity of fossil energy carriers.

The imposition of the climate guardrails reduces the fossil energy related investment shares and requires to bring forward the transition of the energy system; see Fig. 4.13(b). Both issues are related to the reduced energy production shown in Fig. 4.12(a). Moreover, the RD&D share is reduced in the CPP scenarios. This is due to the modelling approach that renewable energy sources are not subject to constraints that limit the potential of renewable energy production. In the BAU scenario the economic system has to deal with the increasing scarcity of fossil fuels by decelerating the growth of energy demand.

In the scenario with CCS shown in Fig. 4.13(c) the investments into the fossil energy sector are prolonged. Moreover, if the renewable energy technologies have become competitive, the RD&D is considerably reduced, because renewable energy sources represent a production factor that can be used unlimited.

The comparison of the total energy related investment shares is given in Fig. 4.13(d). The overall observation is that the model computes – *grosso modo* – decreasing energy related investment shares. The transition to the renewable based energy system implies temporary increasing investment shares. A comparison of the scenarios reveals that investment shares in the BAU scenario are considerably higher (around 1%) than in the CPP scenarios until 2030, which is due to the lower energy supply and the reduction in RD&D investments. When the transition starts in the CPP scenarios, the investment shares increase. A comparison of the CPP cases shows that the increase is more pronounced in the CPP^0 scenario than in the

CPP^+ scenario. By the year 2100 the two CPP scenarios converge towards the same path of investment shares.

The overall amount of investments and their allocation to sectors and the resulting energy production shows that CCS leads to higher energy production until 2040 due to prolonged use of fossil energy carriers. The transition towards renewable energy sources is deferred and the peak of investments around 2040 is cut. The consequences on aggregate economic variables is analysed next.

4.5.3 The Macro-Economic Consequences

In this part the macro-economic consequences due to the reallocation of energy investments and energy production are analysed. For this purpose the differences between the BAU scenario and the CPP scenarios are computed with respect to time paths of GWP and consumption as well as the expenditure shares of the macroeconomic production function.

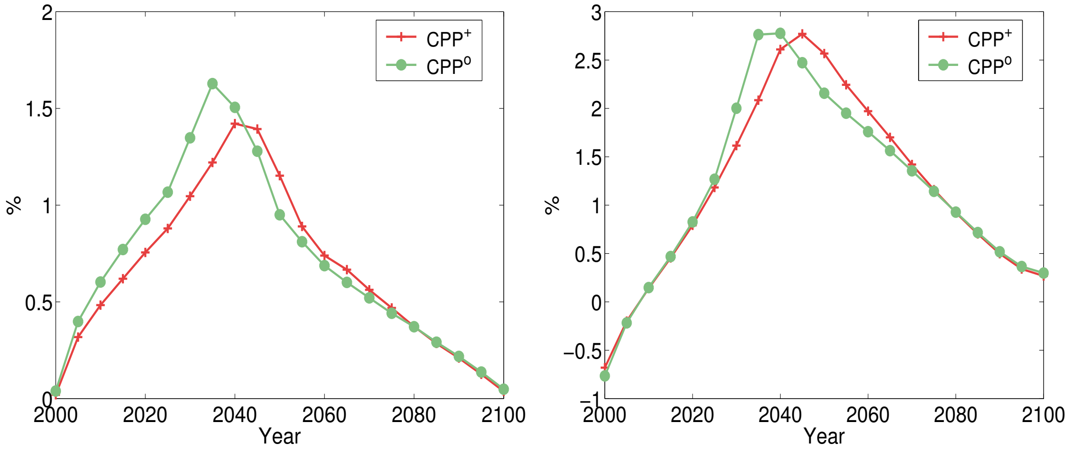
In Fig. 4.14 the time paths of the differences of GWP and consumption of the CPP scenario compared to the BAU scenario are given. These indicators provide an insight into the dynamics of the reduction of economic activity – indicated by the GWP – and reduction of welfare improving consumption. Hence, the indicators provide insights into the welfare implications of the mitigation measures.

Fig. 4.14(a) shows the relative differences of GWP relative to the BAU scenario. The CPP^0 scenario (CPP^+ scenario) is characterised by an increase of the relative GWP difference to 1.7% in 2035 (1.4% in 2040) and a decline thereafter to about 0.1% in 2100 in both scenarios. Fig. 4.14(b) shows the relative differences of consumption compared to the BAU scenario. The differences start at -0.7% and reach 2.8% in 2035 in the CPP^0 scenario and in 2040 in the CPP^+ scenario.

Computing the relative differences of cumulative discounted GWP and consumption is needed to assess the net effect of CCS. Using a 5% discounting rate and the time horizon 2000 to 2100 leads to the following result. The relative cumulative losses in the CPP^+ case are 0.75% for GWP and 1.25% for consumption. For the CPP^0 scenario the results is 0.85% and 1.29%, respectively.

From this figure we can draw the following six conclusions in relation to the findings reported above:

1. During the first decade of the 21st century the decreased energy related invest-



(a) Relative GWP differences (b) Relative consumption differences

Figure 4.14: Relative differences of GWP and consumption for the two CPP scenarios compared to the BAU scenario.

ments finance increased consumption.

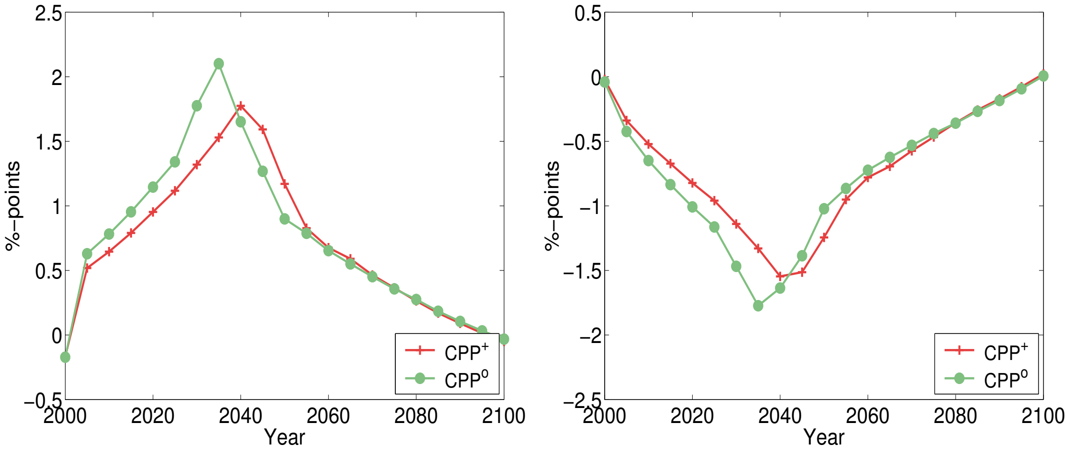
2. Increasing energy scarcity in the CPP scenarios becomes pressing and the lower energy supply outweighs reduced investments.

3. When this scarcity effect becomes too pressing, the production of energy by renewables is increased. In order to reduce these costs learning investments are undertaken prior to the remarkable increase.

4. The decline in economic losses in both scenarios is due to the endogenous improvement of renewable energy production due to learning by doing LBD.

5. In the course of the transition of the energy system the difference between the two indicators shows that the reductions in consumption are more remarkable than those of the GWP.

6. Both indicators show that the inclusion of CCS reduces the economic burden of the climate guardrails due to prolonged use of relatively cheaper fossil fuels. This is the *benefiting effect* of CCS. After 2040 both indicators exhibit the reverse behaviour, which indicates a long-term negative economic effect of CCS. This effect is due to the postponed LBD in the CPP$^+$ scenario. This is



(a) Difference of energy share (b) Difference of labour share

Figure 4.15: Differences of expenditure shares of energy and labour for the two CPP scenarios compared to the BAU scenario. Positive differences mean that the expenditure share is higher than in the BAU scenario.

the *crowding out effect* of CCS on renewables. The benefiting effect outweighs the crowding out effect with respect to cumulative discoutned consumption and GWP losses.

The lower supply of energy suggests to put the focus on the consequences for the distribution of income. This is done by computing the expenditure shares of the macro-economic production function. Fig. 4.15(a) gives the time path of the differences of the expenditure shares of energy of the CPP scenarios compared to the BAU scenario. This effect is related to the reduced energy production and to the assumption that the elasticity of substitution of the macro-economic production function is less than one. The figure shows that the expenditure share of energy is higher in the two CPP scenarios than in the BAU scenario. In the CPP^0 scenario (CPP^+ scenario) the difference reaches 2.2%-points in 2035 (1.8%-points in 2040).

Fig. 4.15(b) shows the corresponding differences of the expenditure shares of labour. The time path for both scenarios is a bit less than for the expenditure share of energy, but the sign is negative. The differences of the expenditure shares of capital are much smaller and therefore not shown.

This indicates that the increase of the expenditure share of energy is mainly financed by the reduction of the expenditure share of labour. This implies that the temporary scarcity of the production factor energy imposes differing burdens for the production factors labour and capital. The difference has to be accounted to the different degree at which the two production factors react to emerging scarcities. The more flexible production factor capital has a higher ability to deal with a temporary scarcity of energy than labour has.

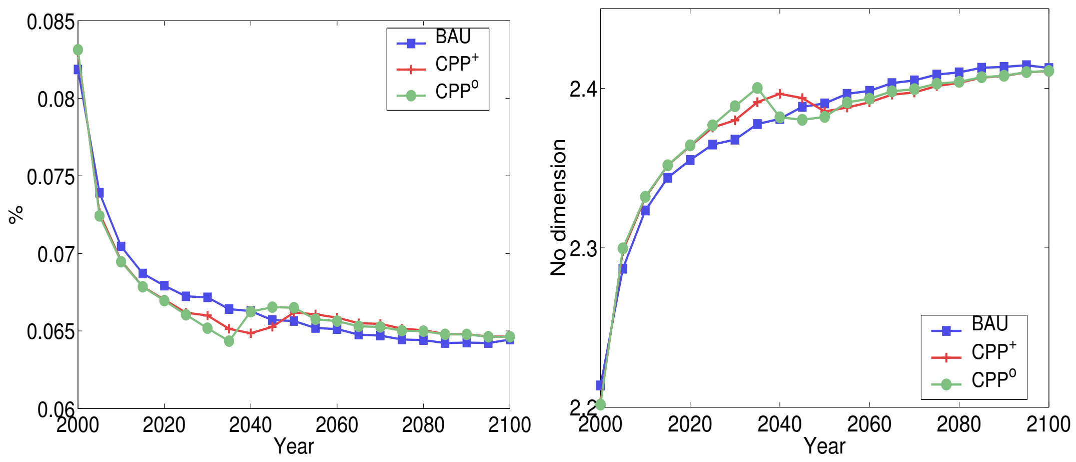
The reason to relate the argument to the different degree of flexibility of the production factors stems from the fact that the observed model behaviour is not in accordance with the static properties of the CES production function. In a comparative static analyses of a CES production function the burden of the increased expenditure share of energy would be distributed evenly on labour and capital; see Ch. 4.2.2 and Klepper et al. (2003, p. 27 and 35). In the static framework there is no possibility to circumvent the temporary scarcity by forward looking investment behaviour. The ability to react flexibly through investments is relatively more in favour of capital instead of labour. The possibility of endogenous improvement of the labour productivity is not sufficient to balance the distributional conflict.

The availability of CCS reduces this distributional conflict as is indicated by the less emphasised time paths of the differences of the expenditure shares in the CPP^+ scenario. This implies that CCS is not only a technological option that reduces the overall economic burden but also one that reduces the distributional conflicts implied by climate protection.

The results show that the explicit consideration of multiple capital stocks leads to temporary reallocation of investments and distribution of income; see Ch. 3.6.2. Moreover, it shows that the availability of an additional CO_2 emission mitigation option reduces the temporary burdens and macro-economic disruptions of climate protection.

4.5.4 The Stylised Facts of Economic Growth

The results so far suggest considerable macro-economic consequences of the transition of the energy system either due to climate protection or resource scarcity. In the following the overall macro-economic behaviour is analysed in order to show that the model reproduces the stylised facts of economic growth that have been introduced in Ch. 2.6.3. Moreover, the macro-economic consequences of CO_2 emission mitigation will be analysed.



(a) Interest rate (b) Capital coefficient

Figure 4.16: Interest rate and capital coefficient in the three scenarios.

The stylised facts of economic growth are a concept for developed countries, which are sufficiently near to their steady state. The global economy modelled in *MIND* comprises the global economy and therefore the developing countries, too. The implicit assumption in *MIND* is that all economies will converge to the same steady state, which implies high growth of the developing countries. This convergence process is contained in *MIND* by a global transition phase over the next decades. Therefore, the properties of constant time paths of stylised facts will be approached after this transition period, which will be around 2040.

Fig. 4.16(a) shows the time path of the interest rate for the three scenarios. It is derived from the shadow price of capital, which is the relative extra value of income invested today expressed in units of the aggregate good today. It is the willingness to accept the reduction of one unit of consumption in a period through compensation by a stream of additional consumption in the future generated by this investment that is discounted to that particular period. This ratio can therefore be expressed in percentage and serves as an indicator for the long-term interest rate of the economy; see Ch. 3 for details.

The overall behaviour in all scenarios is the exponential decline starting at about 8.3% and the long-term asymptotic approximation of about 6.5%. This behaviour indicates that the economies initial capital stock is relatively scarce and therefore the interest rate is high, which leads to a high and decreasing share of GWP that is devoted to investments. This shows that the *MIND* model is in accordance with the stylised fact of constant long-term interest rates and the transition behaviour can be explained with reference to the Ramsey model; see Ch. 3. This macro-economic transition behaviour is due to the relative low capital coefficient implied by the developing countries that is analysed next.

Fig. 4.16(b) shows the time paths of the capital coefficient for the three scenarios. Capital, here, refers to the capital stock that enters the macro-economic production function and excludes energy related capital. The capital intensity is an indicator without dimension of the production structure of an economy and is a mirror of the interest rate.

In all three scenarios the long run capital coefficient of about 2.4 is approached asymptotically. The pronounced increase until 2040 is due to the initial capital scarcity that is decreased rapidly, but at a decelerating pace.[21]

The optimal climate protection policy inducing the transition towards renewable energy sources generates a complex pattern of these macro-variables. The CPP scenarios exhibit a lower interest rate then the BAU scenario until the middle of the 21st century and a higher afterwards. The main reason is the lower energy supply.[22] The minor reason is that the economy accumulates more capital prior to the energy transition. This implies a higher capital coefficient in the CPP than the BAU scenario in the first half of the 21st century.

The increasing interest rate in the CPP scenarios comes with a reduction of investments in the macro-economic capital stock, which is used to finance the renewable energy capital; this is about 0.4% investment rate difference in the CPP^0 compared to the BAU scenario. The macro-economic sector reduces the capital coefficient, which implies that it has to catch up with the reduced investments after 2040. This requires a higher interest rate compared to the BAU scenario; the investment rate is about 0.1% higher in the CPP^0 compared to the BAU scenario.

The availability of CCS reduces and defers the deviation from the BAU scenario during the transition towards renewable energy sources. The macro-economic transition towards a higher capital-coefficient is a major reason for the low initial

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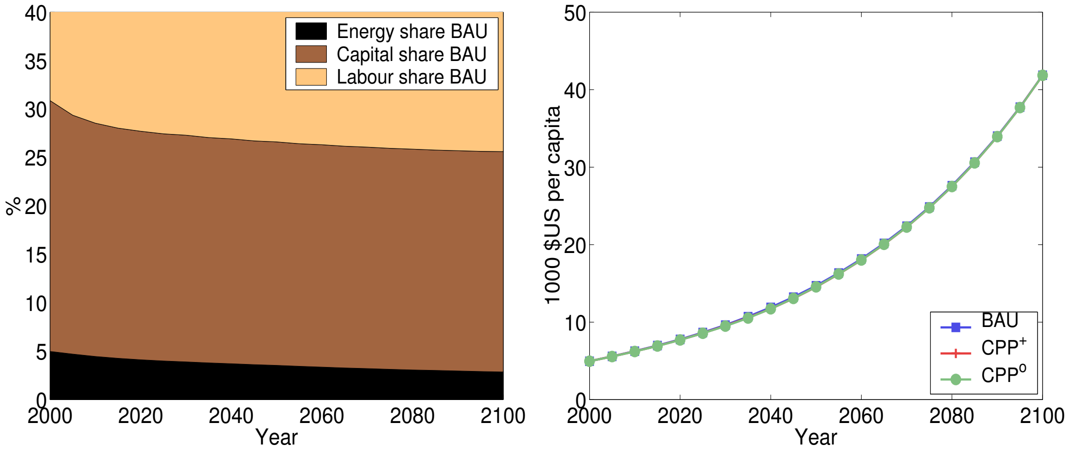
[21] In comparison with the empirical findings of a constant value of about 2.5 (Including energy capital stocks) for developed countries in Ch. 4.3.2 this is a roughly good matching.

[22] Due Wicksell's law the reduction of a production factor decreases the marginal productivity of all other factors; see Simon and Blume (1994, p. 493). The CES function captures this feature.



(a) Expenditure shares in BAU

(b) Per-capita income

Figure 4.17: Expenditure share in the BAU scenario and per-capita income for the three scenarios.

learning investments in renewable energy technologies. In a situation of low per-capita income, society addresses only a low value on cost reductions of technologies that will be used in the future.

Next, the focus is on the time path of the distribution of income in the BAU scenario as it is expressed by the expenditure shares of the macro-economic production function. Fig. 4.17(a) shows the expenditure shares in the BAU scenario. Everything above the 40% mark is distributed to labour. The overall behaviour is that labour gains income shares from capital and energy over the whole 21$^{\text{st}}$ century at a decelerating pace. The share of energy reaches 3% in 2100.

The differences of the expenditure shares of the CPP scenarios have been discussed, already. The time path for the BAU implies that ∼2%-points difference in the CPP scenarios shown above are considerable, if it is compared with this reference path.

Finally, the long run dynamics of per-capita income is analysed. Fig. 4.17(a) shows the time path of the logarithm of per capita income for the three scenarios. It starts at 5000$US and reaches 42000$US in 2100 in all three scenarios. The growth rate is approximately constant and the differences between the BAU scenario and the CPP scenarios seem negligible. Due to the inflexible labour supply, the per-capita income equals the wage rate.

Therefore, it can be concluded that the model *MIND* reproduces the stylised facts of economic growth. Moreover, the numeric values that are reached in the steady state are within the range of the empirical findings. Nonetheless, more research will be necessary to enhance the empirical behaviour of intertemporal growth models and therefore to improve the reliability of policy advice that is drawn from these models.

4.5.5 Assessing the Options

In the following the several options of CO_2 emission mitigation are compared. For this purpose the availability of the options in the CPP scenario are restricted to the BAU scenario; i.e. the endogenous paths of control variables of the BAU scenario are the boundary condition for the CPP scenario. The following scenarios are distinguished, where factor substitution is always an available option:

1. ***ALL*** All options are available, which coincides with the CPP^+ scenario.
2. ***EE*** Energy efficiency improvement is available. CCS and renewable energy utilisation are taken from the BAU scenario.
3. ***REN*** Renewable energy utilisation is available. CCS and energy efficiency improvement are taken from the BAU scenario.
4. ***CCS*** CCS is available according the exogenous path. Renewable energy utilisation and energy efficiency improvement are taken from the BAU scenario.
5. ***NONE*** Only factor substitution is available. Energy efficiency improvement, renewable energy utilisation and CCS are taken from the BAU scenario.

Fig. 4.18 summarises the results by comparing the relative cumulative discounted GWP and consumption losses for the 21st century. As expected the availability of all options leads to the lowest possible losses compared to all other scenarios. The second lowest losses are achieved in the REN scenario, which implies that the availability of renewable energy is the single most important option. In the scenarios ALL and REN the consumption losses are higher than the GWP losses.

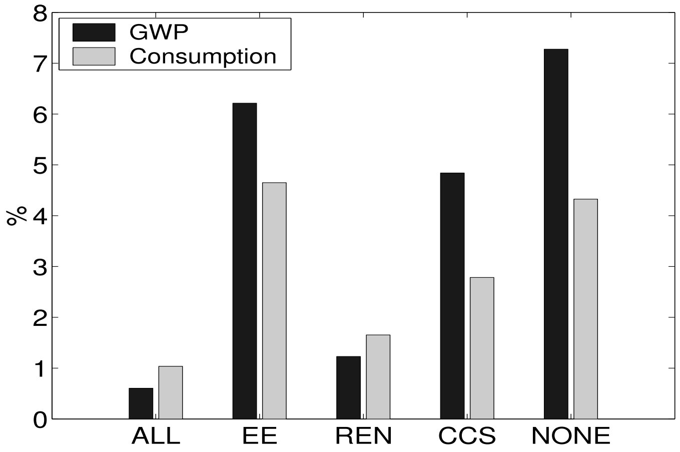


Figure 4.18: Comparison of the effects of CO_2 emission mitigation options on relative cumulative discounted losses of GWP and consumption. The discounting rate is 5%.

The third lowest losses are achieved in the CCS scenario making CCS the third most important option. In this scenario, as in the next two, the GWP losses are higher than the consumption losses. This is related to the consumption financing effect of reduced investments and discounting. The later point means that the effect on GWP and consumption losses depends on the discounting rate – here 5% – that tends to values the near-term financing effect higher than the long-term GWP effect.

With respect to GWP the EE scenario leads to lower losses than the NONE scenario, the effect on consumption is a bit higher in the EE scenario, which is due to the particular time paths of consumption. The GWP (consumption) losses exceed the 5% (4%) mark, which appears to be beyond the acceptable range. This means that the reduction of economic growth is only accepted as an optimal solution, when energy supply options leading to lower CO_2 emissions are not available. These results confirm the findings of Nordhaus (2002) and Popp (2003).

The analysis of the options reveals that the availability of carbon-free energy supply technologies is essential to achieve ambitious climate protection goals. This is espec. the case for the availability of renewable energy sources and to CCS technologies. This analysis also reveals that the appropriate assessment of economic effects of CO_2 emission mitigation requires an integrated model of energy supply and demand technologies. Focusing on single technologies or options would exaggerate the economic losses because CO_2 emission mitigation requires an optimal intertemporal strategy considering all options.

4.5.6 Comparison with other Studies

In this section the results of *MIND1.0* are compared with other studies. The focus is on studies that mainly differ in the representation of technological change. The in-depth comparison of results with focus on CCS will be deferred to Ch. 7 because CCS is assumed exogenous in *MIND1.0*.

The comparison focuses on the costs of CO_2 emission mitigation costs. The studies differ from the analyses above in at least five respects:

1. Different types of models are used in the studies, which are introduced in Ch. 2.7.
2. The degree of endogenous technological change and the availability of mitigation options is different.
3. The BAU scenario with respect to CO_2 emissions, energy production and GWP are different.
4. The climate protection goal is integrated differently.
5. The indicator of mitigation costs differs.

In the following the differences are explicated with respect to the first four issues. For the sake of comparison the several mitigation cost indicators for the *MIND1.0* CPP$^+$ scenario are computed. Tab. 4.9 summarises the comparison.

The studies contained in the table share as a common feature that the economic consequences of deep emission reductions are computed. The collection of studies is not exhaustive. In the following the details of the entries of the table are given.

The model types that are employed in the reviewed studies have been introduced in Ch. 2.7, already. These model types differ in the ability to take account of the CO_2 emission mitigation options. The studies differ with respect to the time horizon over which the model computes results as well as the time horizon over which the indicator of the mitigation costs is computed; see Ch. 2.5.3 for details.

The studies impose different constraints, which represent the climate goal. Some studies restrict the atmospheric CO_2 concentration, one employs a constraint on the GMT and a third study restricts the emissions, which are consistent with the WBGU climate window.

Table 4.9: Comparison of *MIND1.0* results with other studies.

	RR00[a]	GZ03	KS03	KB03	MR04
Model type	ESM	Hybrid	CGE	Hybrid	Hybrid
Model horizon	2100	2200	2030	2100	2100
Indicator horizon	2100	2100	2030	2100	2100
Climate goal	Conc.	GMT	Emis.	Conc.	Conc.
Climate constraint	450	2°C	Window[b]	500	450
BAU GWP (tril.$US)	550.			284.	
BAU Energy (EJ)	1750.			2211.[c]	
BAU CO_2 (GtC)	33.	14.8	12.8[d]	31.7	27.
Options[e]	CFR	RS	FS	FRS	FRS
Indicator	Invest.	Cons.	GWP	GWP	GWP
Measure	abs.	rel. dis.	HEV	rel. dis.	abs. dis.
Unit	tril.$US	%	%	%	tril.$US
Study	149.	.06	16.0	.22	11.4
MIND1.0 CPP$^+$	104.1	.75	.6[f]	.6	10.6

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[a] The studies are RR00 $\hat{=}$ Roehrl and Riahi (2000); GZ03 $\hat{=}$ Gerlagh and Zwaan (2003); KS03 $\hat{=}$ Klepper and Springer (2003); K03 $\hat{=}$ Kypreos (2003); MR04 $\hat{=}$ Manne and Richels (2004).

[b] This means that the emission constraint obeys the climate window.

[c] This is primary energy.

[d] Does not include CO_2 emissions from land use change.

[e] If an option is available, it is indicated by a letter. The letters indicate C $\hat{=}$ carbon capture and sequestration; F $\hat{=}$ fossil fuel substitution; R $\hat{=}$ renewable energy technologies; S $\hat{=}$ factor substitution.

[f] If the *MIND1.0* model is restricted to the factor substitution option, the corresponding number is 4.1%.

The BAU scenarios of the studies differ in several variables. Tab. 4.9 refers to the key variables GWP, energy production and CO_2 emissions at the end of the indicator time horizon. The studies differ with respect to the CO_2 emission mitigation options that are available, which is to some extent related to the model type that is used in the studies.

The studies computed different indicators for the assessment of the mitigation costs. All indicators refer to cumulative costs until the end of the indicator time horizon. The entry *abs.* refers to the absolute cumulative costs. The entry *abs. dis.* denotes the cumulative discounted costs. For computing *rel. dis.*, the absolute discounted costs are divided by the net present value of GWP of the BAU scenario. The discounting rate in the studies has been assumed at 5%.

The entry *HEV* is special and denotes the Hick-equivalent variation, which is a concept to compute the welfare losses according to the theory of Hicks compensated demand function. This welfare measure does not only take into account the reduction of GWP, but adds to this the monetary compensation that is necessary to maintain the welfare level of the households due to changes of relative prices. The households welfare position is worse, if the price of a good increases,[23] which justifies an income compensation; see Mas-Colell et al. (1995, Ch. 3). Therefore, this measure only makes sense in models with multiple consumption goods, like CGE models. Regarding *MIND* it is best compared with the consumption losses.

The row denoted with *study* refers to the welfare indicator as it is reported in the study. The row denoted *MIND1.0* contains the result of the CPP$^+$ scenario and the indicator has been computed as that of the corresponding study.

The general observation of the indicators are that the results of *MIND1.0* are in quite good agreement with Manne and Richels (2004) ***MR04***. The study by Roehrl and Riahi (2000) ***RR00*** shows a moderate agreement, but the study by Gerlagh and Zwaan (2003) ***GZ03*** and Kypreos (2003) ***K03*** are considerably lower and Klepper and Springer (2003) ***KS03*** is considerably higher than *MIND1.0*. In the following the explanations given in the reviewed studies are used.

RR00 do not provide detailed insights into the determination of the mitigation costs. The focus of the study is on the comparison of several scenarios. For the scenario cited above it is worth to note that the amount of CCS is 1555GtC until 2100.

GZ03 use a hybrid type model with a fossil and a non-fossil energy technology and assess the mitigation costs of a maximum 2°C GMT increase. The mitigation costs are measured by the relative discounted differences of consumption. The study provides insights into the determination of the mitigation costs by differentiating four scenarios. The study distinguishes the scenarios by switching endogenous LBD on and off as well as by either allow for energy production flexibility or by determining the energy demand to the BAU scenario.

In the two cases with flexible energy demand the energy production is reduced by about 25% compared to the BAU scenario in 2060. Leaving the option of energy demand at the BAU scenarios level would increase the mitigation costs from 0.06% to 0.08%. If the energy demand is flexible and the costs of the carbon free technology is taken from the BAU scenario the mitigation costs increase to 0.11%. If both

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[23] In economics it is known that there are several cases, in which the opposite happens that are not important here.

mitigation options are determined on their BAU scenario levels the mitigation costs are 0.19%.

The difference to *MIND1.0* can be attributed to the much lower CO_2 emission in the BAU scenario and that the study does not constrain the rate of increase of the GMT. A common feature of both models is that there is a financing effect through increased consumption in the initial periods, which is generated through the reduced energy production. This is about 0.05%; see Gerlagh and Zwaan (2003, p. 52) and compare Fig. 4.14(b) on p. 136.

The study by KS03 uses a CGE model that does not contain renewable energy technologies. It does take account of the production factor and fossil interfuel substitution. The mitigations per period are increasing over time, since the emission reduction relative to the BAU becomes stricter with time. If the model *MIND1.0* is reduced to factor substitution, only, the corresponding mitigation costs are 4.1%, which is still much lower than the 16% computed in KS03.

K03 also uses a hybrid type model that models the capital stocks of energy technologies explicitly and integrates LBD for several energy technologies based on fossil and renewable sources. The model assesses the mitigation costs of an atmospheric CO_2 concentration constraint of 500ppmv.

The much lower mitigation costs compared to *MIND1.0* are due to the less ambitious climate protection goal, which implies an deferring effect on CO_2 mitigation action. The effect of LBD is considerable in this study. The mitigation costs are 1.42% without LBD, which is a 1.2%-points difference to the case with LBD. If the concentration constraint is relaxed to 550ppmv the mitigation costs are 0.1% and 0.52% without LBD. This implies that the effect of LBD on mitigation costs becomes more important for stricter climate constraints. The study by MR04, which also computes 550ppmv constraints, does not confirm this result; see Manne and Richels (2004, p. 616).

The time path of the relative GWP losses exhibits also an U-shaped form; compare Fig. 4.14(a) on p. 136. In 2010 the difference is 0.05% and increases until it reaches a maximum of 1.9% in 2070. Afterwards this relative difference decreases to 1.5% at which it stabilises. This behaviour is different at the end of the 21^{st} century since in *MIND1.0* relative differences decrease to much lower level (0.1%).

MR04 focus on the economic significance of learning by doing LBD assessing the importance of a 450ppmv CO_2 concentration limit. The model is a hybrid type model without energy capital stocks. The inertia of the capital stocks is modelled through constraints on introduction and fade out of energy technologies.

The authors distinguish two phases. In the first phase until 2060 learning by doing has to be induced, since the carbon free technology is yet not competitive. This will be changed in the second phase that covers the last decades of the 21^{st} century. The authors note that LBD allows higher emissions in the short-term because when the carbon free technologies have become competitive, the CO_2 emissions will decline through market dynamics. Therefore, the energy production is higher in the short-term and the economic impact is lower. The LBD effect reduces the cumulative discounted mitigation costs by about 3.6tril.$US.

4.6 Conclusions from *MIND1.0*

The model *MIND1.0* allows a first assessment of several CO_2 emission mitigation options within a hybrid type model that selects the optimal climate protection strategy based on a welfare criterion. The assessment of particular mitigation options is weighted against the significance of other options. The model is able to reproduce the stylised facts of economic growth qualitatively and quantitatively with respect to key macro-economic variables.

The results of *MIND1.0* indicate that the availability of a broad portfolio of mitigation options is essential to achieve ambitious climate protection goals at low mitigation costs. This result confirms the findings of several studies with which *MIND1.0* has been compared, if a broad portfolio of mitigation options is considered.

The availability of CCS – although modelled exogenously at this stage of the analysis – has turned out to defer and to reduce the macro-economic consequences due to the reallocation of investments and the corresponding changes of energy supply. This means that CCS indeed is an option to buy time. The reason is that the relatively cheaper fossil energy carriers can be used at a larger extent and over a longer time horizon. This short-term benefiting effect is partly offset, since the LBD is crowded out and renewable energy carriers are latter introduced into the market. Moreover, CCS helps reducing the macro-economic consequences of a pre-mature transition of the energy system.

The inclusion of renewable energy technologies has turned out to be the single most important option. The major obstacle of renewable energy technologies are the high costs, which could be reduced through learning by doing. Bringing the costs down requires learning investments that come with a reduction of energy supply at the same time. Although the transition is inevitable for the global economy in the long run due to the scarcity of fossil energy carriers, climate protection requires to bring the introduction of renewable energy technologies forward and at a faster rate. This implies considerable macro-economic consequences on the amount, distribution and utilisation of income compared to the BAU scenario. CCS reduces the burdens of this transition.

The modelling approach of each sub-module is subject to considerable critique. The model is not able to take into account the various technical details of the mitigation options. The technical details imply obstacles as well as opportunities for CO_2 emission mitigation. In the field of renewable energy technologies the obstacles might arise from the integration of new technologies into existing energy infrastructures and limits on the overall utilisation of renewable energy sources. The opportunities are related to the heterogeneity of locations with respect to utilisation rates of capital and the economies of scales due to increased and stable demand for these capital goods. This could imply interesting – but not modelled – dynamics: investing at highly profitable locations could induce investment cost reductions through learning that make less favourable locations profitable. The assumption of an average value is highly problematic from an economic point of view since the option is used up to the marginal value and not at the average value; see also Ch. 6.5.

In the sub-modules of fossil energy extraction and production two main problems are present. First, the assumption of an aggregate fossil energy carrier is problematic because it neglects the different technical and economic characteristics like different production functions, different carbon intensity and reserve/resource assumptions. The second problem is related to the assumption of an aggregate secondary energy carrier. The different forms of energy like electricity and heat are also different with respect to production functions. Moreover, the potential for substitution by renewable energy technologies is different; e.g. high temperature process heat for industrial processes is difficult to produce from renewable energy sources.

The modelling approach of the macroeconomic production function is questionable for two reasons. First, the empirical literature on substitution elasticity indicates that energy cannot be separated from capital and labour as is implied by the CES production function. This suggests to improve the model by introducing a translog production function. The second issue is related to technical progress that is induced through RD&D expenditures is problematic on empirical grounds as has been shown in Ch. 3.6.3. The study indicates that the source of technological change is related to investment externalities into capital rather than RD&D expenditures. Although the study focuses on labour productivity, only, it seems reasonable that energy productivity growth is related to investments, too. It is worth to note that the learning by doing effect with respect to energy supply technologies follows a similar approach, since investments trigger reductions of investment costs.

It is a modelling task for the future to relate the endogenous productivity growth in the macro-economic production function to investments in capital, too. The main problem then is to model the bias in technological change, since the productivity growth of energy and labour have to be determined through one variable. A first model approach is provided in Edenhofer et al. (2004b). It is then open in how far RD&D effects should be incorporated into endogenous growth models to assess the significance for CO_2 emission mitigation.

The assumption of an exogenous path of CCS is questionable and addressed in the following: The literature on CCS is reviewed in detail and a modelling approach is developed and integrated into *MIND*. The review of the literature on CCS is also done to assess the technology on a more techno-economic and geologic basis. This augments the assessment using the model *MIND1.1*.

Chapter 5

The Techno-Economics and Geology of Carbon Capture and Sequestration

In this chapter the characteristics of CCS are introduced with respect to technical and geological details as well as cost assessments. The detailed overview serves as a basis to discuss the CCS option on a broad basis without use of a model. It prepares the discussion of modelling approaches that are integrated into IAMs, and it is the basis for the modelling approach pursued in this thesis.

The idea of carbon capture and sequestration CCS is to utilise the abundant amounts of valuable fossil fuels without emitting the CO_2 into the atmosphere in order to mitigate climate change. CCS is a chain of sequential process steps containing capture, compression, transportation and injection of CO_2. Since none of these process steps is for free, the extra efforts for doing so have to be assessed. Additionally, the geological sequestration capacity and the geological integrity of sequestration sites have to be assessed. The information will then be used in the modelling approach developed in this thesis.

The idea of extra effort of CCS is related to the modelling approach developed in this thesis. The modelling approach is not based on the explicit representation of fossil energy conversion technologies with carbon capture, but on the extra effort of capturing CO_2. The modelling approach distinguishes several categories of extra effort that lead to a reduction of CO_2 emissions into the atmosphere:

1. the extra capital effort;
2. the extra energy effort;
3. the extra operation and maintenance O&M.

The extra effort is a feature of capture, compression, transportation and injection of CCS. The sequestration part of CCS is mainly related to the features of geological sequestration capacities and the integrity of the sequestration sites. In this section these features of CCS are assessed from an economical point of view that is derived from the engineering and geological sciences. This assessment is then used to develop an approach that is then integrated into the model *MIND* and to discuss alternative modelling approaches found in the literature.

The structure of describing CCS is usually along the lines of the technical process; i.e. along the chain of process steps. Structuring the text in accordance with this chain implies a serious problem, when it comes to reasoning and justification of the features of a particular process step: process step A is designed in order to meet the requirements of the down-stream process step B. In describing A it would lengthen the text considerably, if one would justify this step by all the features required in B that has not already been introduced.

From this point of view it appears reasonable to structure the text reverse to the technical sequence and to start with sequestration first. But this is in conflict with the human habit to reconstruct the flow of steps – frankly speaking – as "a journey of a ton of carbon from cradle to grave". The text sticks to the *natural* flow of process steps. The note above should prepare the reader to pay attention to the following: the flow of process steps is converse to the direction of reasoning why this process step is designed in that specific way. The reader will see this problem gleam through at several points in this chapter.

A particular problem with this way of structuring the text is related to the scope of most techno-economic studies of carbon capture, which contain the compression step. It would be necessary to introduce compression prior to the capture part in order to provide the basis for the techno-economic studies. However, the text is organised along the natural sequence of process steps.

The chapter is organised as follows. Ch. 5.1 introduces the technology of carbon capture. Ch. 5.2 treats compression. In Ch. 199 the transportation and in Ch. 5.4

the injection are introduced. Sequestration is treated in Ch. 5.5. Ch. 5.6 summarises the chapter and discusses the findings.

5.1 The Technology of Carbon Capture

5.1.1 Introduction

The problem of carbon capture is mainly a problem of gas separation in order to produce concentrated CO_2. It is well known in thermodynamics that the separation of gases is an energy intensive process. This energy need is due to the reversal of the mixing process and problems of implementation. The energy requirement for separation of a mass unit of a gas gets higher the lower the concentration of the gas is; see Göttlicher (1999, p. 135) and Baehr (2002, Ch. 5).

The utilisation of fossil energy carriers today results in flue gas streams that are mixtures of gases that are usually vented into the atmosphere. The flue gases that contain CO_2 are only by-products of production activities, where the primary energy contained in the fossil fuel is needed; e.g. heat.

Fossil fuels are usually combusted in air. Air is a mixture of gases that mainly consists of nitrogen (∼78%) and oxygen (∼21%). The fuel reacts with the oxygen and generates heat that is used for several production activities; e.g. combustion of coal for the production of electricity. The carbon in the fuel ends up as CO_2 in the flue gas stream, which – still – mainly consists of nitrogen.[1] Although nitrogen is not important for the combustion process, its fraction in the flue gas is an important boundary condition for the gas separation because it determines the extra effort of carbon capture. Tab. 5.1 contains the shares by volume of ambient air and the most important flue gases of industrial plants considered in this chapter.

The aim of carbon capture is to produce a pure[2] stream of a considerable share of CO_2 that previously has been contained as carbon in the fossil fuel instead of venting into the atmosphere along with the flue gas. Gas separation processes need energy. The required energy is has the form of heat, pressure or electricity, which have be to produced by using capital and energy carriers. The smaller the CO_2

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[1] Technically, it is possible to capture and sequester the total flue gas stream, but the effort for compression, transportation and injection is beyond any reasonable scale. Moreover, the sequestration capacity would be exhausted at a much higher rate due to the larger gas volumes.

[2] The pureness of CO_2 is a prerequisite for pipeline transportation.

Table 5.1: Share of gases in ambient air and flue gases of industrial production processes by volume in percent. Source: see footnotes.

	Nitrogen	Oxygen	CO_2	Other
Air[a]	78.	21.	.03	.97
Coal power station	80.	5.	>10.	.
Gas power station	.	.	.	.
Cement kiln[b]	-	-	~20.	-
Basic oxygen furnace[c]	52.	2.	42.	4.
Steam methane reforming[d]	67.8	0.9	8.1	23.[e]

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[a] See Bates and Jackson (1980, p. 40).

[b] Hendriks et al. (1998) reports 14 – 33% and Hendriks et al. (2002, p. 11) reports 15 – 25%.

[c] Farla et al. (1995, p. 447); Hendriks et al. (2002, p. 11) reports 15 -20%.

[d] Mimura (2001); Hendriks et al. (2002, p. 11) reports 8%.

[e] Contains 22% water vapor.

concentration in the flue gas the higher the energy requirement to capture it and the larger the separation device that is needed to treat the gas mixture because of the larger flue gas volume. The annual amount of flue gas of a large scale industrial plant is of a magnitude that makes the scale of equipment a serious cost driver, which could be reduced by increasing the CO_2 concentration in the flue gas stream. Fig. 5.1 illustrates the qualitative relationship between the CO_2 concentration and the extra effort of carbon capture. It delimits three regions that will be described next.

1. There are some industrial processes – like hydrogen production for ammonia synthesis – that produce a stream of nearly pure CO_2 by default. The CO_2 emissions from such sources is only ~6% of the global CO_2 emissions; see Ch. 2.3.2. Some of the CO_2 is demanded for industrial processes or beverage production; the rest is emitted to the atmosphere. Gas separation plays a role for the production of hydrogen in these processes, but only a small extra effort is needed for dehydration and collection to produce pure CO_2.

2. At most large scale point sources of CO_2 the conditions are not so favourable to carbon capture because the CO_2 is vented in a flue gas stream at low concentrations. The most obvious approach of carbon capture is to simply

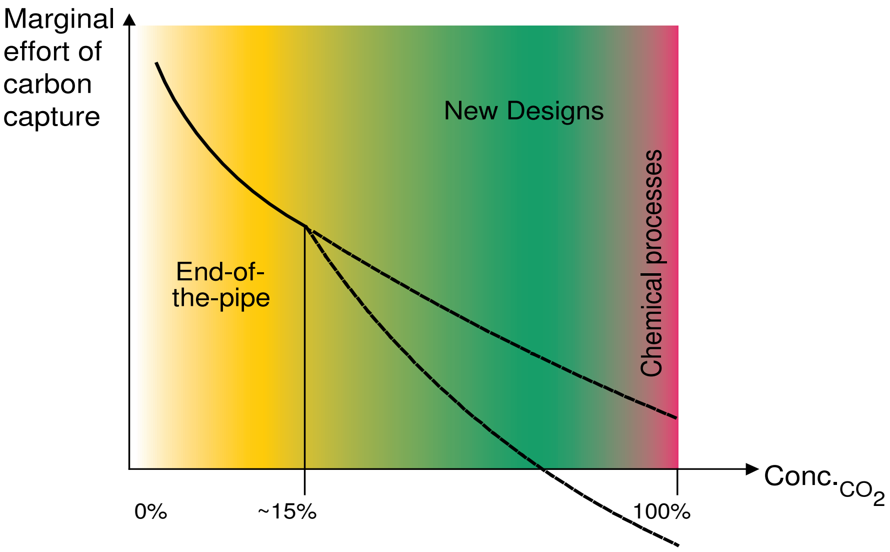

Figure 5.1: Energy and equipment need for CO_2 capture, depending on CO_2 concentration.

separate the CO_2 from the other gases. This approach works and there is operational experience on a large scale commercial basis. The technical design of a plant remains unchanged and it is possible to retrofit existing plants. Therefore, it is called the end-of-the-pipe (EP) approach. The major problem of the EP approach is that it requires a large extra effort for carbon capture.

3. The major concern of engineers in carbon capture is how to change the design of a plant in order to reduce the extra efforts for the capture of CO_2. The task can also be formulated like this: how can the fuel be brought in contact with oxygen in order to use the energy efficiently and thereby produce a stream of highly concentrated CO_2 with as small as possible extra effort in order to reduce the marginal effort of carbon capture. There are several proposals at different levels of technological maturity and each of them changes the industrial plant to a lesser or greater extend. These changes are new arrangements of well-known components, and yet not operational on a large scale, commercial basis. They are therefore called new design (ND) approaches.[3]

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[3] The term ND has an obvious relation to the term new combinations (NC) introduced by Alois J. Schumpeter that is widely used in the economics of innovation. Although both terms describe the invention as new arrangements of known components, there is a difference between both terms.

There are two different types of ND approaches that are distinguished by the feature whether the products sold at the market require changes of consumer behaviour. The first type leaves the product unchanged, but alters the design of the production process; e.g. carbon capture at power plants, where the electricity is the same as without carbon capture. This is called the *process* ND approach. The second type is related to new products that require changes of the consumer behaviour. For example, hydrogen that is produced from natural gas with carbon capture require end-use facilities like fuel cell cars. This is called the *product* ND approach. Johnson and Keith (2004) note that process NDs have the advantage not to require changes of consumer behaviour and particularly of consumer related infrastructures.

Up to now, a large number of realisations according to the EP and ND approach have been proposed, especially in the electricity sector. Most of these proposals are based on computer programming studies. This feature of the studies, which will be presented in the following, is worth a more extensive discussion.

Historians of economy and science inter alia focus on the question whether science is a precondition for successful technological change. Science here means the generation of proposals of improved or completely changed production processes and end products. In energy related technological change this question is important because of the large investment needs, long lead times in building plants and plant related infrastructure investments. The energy sector can be seen as conservative and risk averse with respect to new technologies: working technologies are of high value; the technical concepts that are in operation are improved incrementally; the switch to new technical concepts is seen sceptical. For this, see e.g. Radkau (1983), Ellerman and Dubroeucq (2004) and Nordhaus (2004).

The increasing number of proposals of NDs in all fields of energy transformation and use stands in contrast to this claim. The growth of this number increased considerably during the last two decades due to the introduction and broad availability of specific computer programs like *Aspen plus*. These computer programs offer the possibility to plug together components of industrial plants and to analyse the efficiency of a steadily operating plant. The components are available in libraries and

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NCs are introduced in order to generate a benefit to consumers directly; e.g. fuel driven cars are better than horse coaches. The distinguishing feature of ND is that it does not generate direct benefits, but offers the possibility for firms to lower the costs of policy induced emission caps or taxes.

delivered with the program. This offers cheap and immediate exploration of new production concepts.

The large amount of newly available concepts stands in contrast to the latest investments in the electricity sector. For example, the latest coal power plants connected to the grid – like Niederaussem, Germany and Iskenderun, Turkey – are based on conventional steam cycles; so called pulverised coal (PC) plants. For several years the alternative concept of IGCC[4] has been proposed, but up to now only five pilot plants do exist. No order for such a power plant has been made by an electricity company. Additionally, the development of natural gas combined cycles plants took several decades and it is the technology of choice today.

The studies in the following – espec. for ND approaches – bear the problem that they are speculative. They rely on complex system designs without commercial experience. It is not clear whether such a system works steadily, although each component in isolation is well known to do so. Therefore, the studies should be treated with care. Although the numbers are impressive and suggest good prospects, they can turn out to be fundamentally wrong, when it comes to the realisation of a project, simply because the system does not work as promised.

Fig. 5.2 gives an overview of the approaches discussed in this section. The green items represent several types of *industrial plants* which are large point sources of CO_2 at which carbon capture is applicable. The capture of carbon at a plant follows either an EP or an ND approach, indicated by the grey boxes. Such plants belong to a *capture concept* (indicated by the blue boxes), if an additional effort – apart from compression – is required to capture the CO_2. Iron blast open furnace (BOF) is a special case of industrial plants that will be treated below.

The three capture concepts distinguish fundamentally different ways of capturing carbon:

1. The post-combustion approach separates the CO_2 from the flue gas stream of an otherwise unchanged power plant. It is therefore a typical EP approach.

2. In the oxy-fuel concept the plants remain basically unchanged, but instead of air the fossil fuel is combusted in oxygen that has to be separated from

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[4] This refers to IGCC without carbon capture. The IGCC concept with and without carbon capture will be introduced below; see Ch. 5.1.5.3.

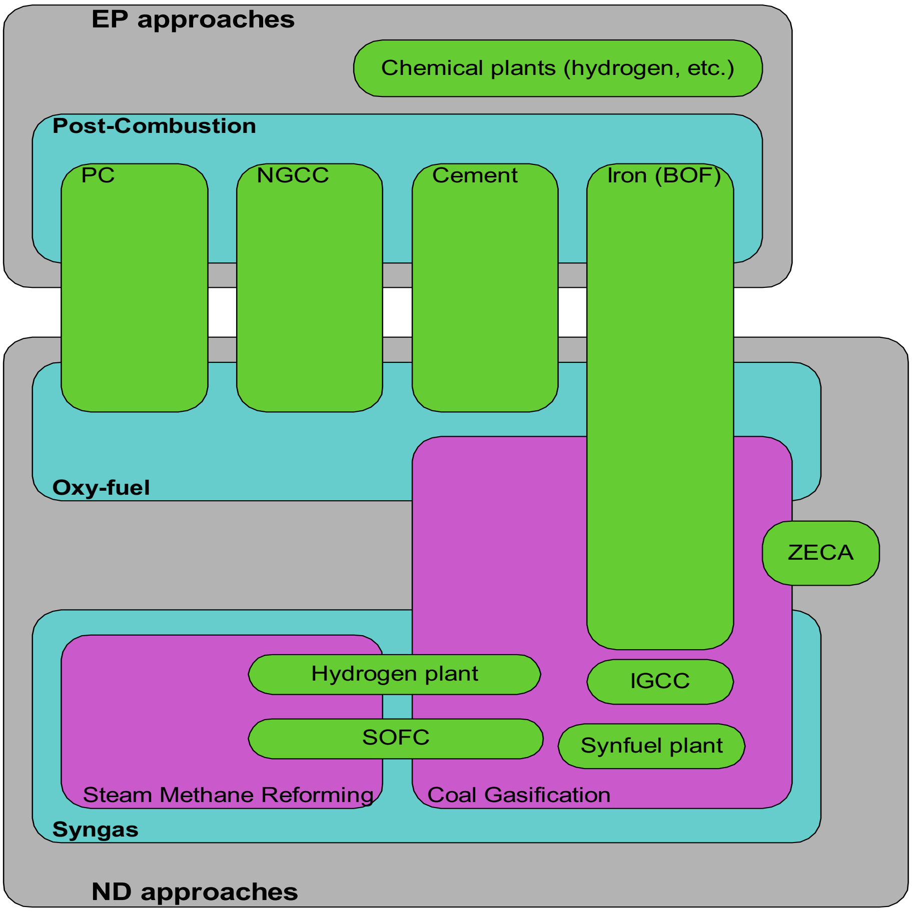

Figure 5.2: Overview of carbon capture. Approaches are grey, industrial plants are green, capture concepts are blue and technical processes are red. The size of any box does not correspond with the significance of any of these items.

air. This constitutes an ND approach, because the oxygen production and integration is a major change to the process design.

3. In the syngas concept the first step is to transform the fossil fuel into syngas by a *technical process*; indicated with the red boxes. Coal gasification has an overlap with the oxy-fuel concept because the gasification process requires oxygen.

A basic oxygen furnace BOF for iron production is a special case because a BOF is essentially an oxygen-blown gasifier. The exhaust gas is a syngas that could be used in any of the industrial processes. Alternatively, the exhaust gas could be treated by post-combustion type carbon capture methods. An exception within an ND is the Zero Emission Coal Alliance (ZECA) type plant because it is designed to produce a concentrated CO_2 stream inherently. It is a coal gasification based ND that does not need oxygen and does not produce syngas and if it is in operation, it requires no extra effort for carbon capture.

The remaining part of this section is organised as follows. This section is devoted to the introduction of the techno-economics of carbon capture with respect to the industrial plant types. The industrial plants are grouped according to the carbon capture concepts, but this does not catch all industrial plant types as can be seen in Fig. 5.2. The two exceptions of chemical plants and ZECA will therefore be treated separately. The exception of chemical plants are treated first in Ch. 5.1.2, because these plants are ready for carbon capture today. Ch. 5.1.3 deals with the post-combustion capture concept and its application on the several industrial plants. Ch. 5.1.4 treats the oxy-fuel capture concept in the same way. Carbon capture according to the syngas concepts requires the introduction of syngas production, which is then applied at the several industrial plant types in Ch. 5.1.5. The second exception – the ZECA type plant – will be treated separately in Ch. 5.1.6. In the final Ch. 5.1.7 summarises and discusses the results. An Appendix to this section provides a short overview of the gas separation processes that are applied in the several capture approaches.

5.1.2 Chemical Plants

Industrial plants treated in this subsection are mostly chemical plants that produce hydrogen from fossil fuels as an intermediate product and natural gas extraction facilities that separate the naturally occurring CO_2 from the hydrocarbons. Both categories are important for the overall issue of CCS because they represent the low cost options that are already available today.

The common characteristic of these plants is that without intention a concentrated stream of CO_2 is produced that is not intended. This is simply due to the fact that the CO_2 is the waste product of a gas separation process. From a technical point of view several of the technical approaches discussed in this thesis are applied to produce – for example – hydrogen, but the carbon capture process as an conscious production activity starts at the concentrated CO_2 gas stream.

The main technical issue – except compression – is that the CO_2 has to be dehydrated, which simply means condensing the water vapour that comes with the CO_2. The extra effort due to investments, energy and O&M are quite low.

Farla et al. (1995) report data for a particular plant of the fertiliser industry in The Netherlands. The investment is 10mil.\$US for capturing 177.3MtC per year; i.e. the investment costs are $56.41\frac{\$US}{tC/y}$. The energy consumption is $0.03\frac{MJ_t}{kgC}$ and the electricity consumption is $1.47\frac{MJ_e}{kgC}$. The O&M costs are $1.69\frac{\$US}{tC}$.

Hendriks et al. (2002) report numbers without compression. The study estimates the investment costs at $23.25\frac{\$US}{tC/y}$ without compression.

With respect to CCS in natural gas extraction the Sleipner West project in the Norwegian sector of the North Sea is the best known. The Kvaerner membrane contactor[5] has been introduced in the course of the introduction of the Norwegian CO_2 tax in 1991 that aimed at avoiding CO_2 emissions from methane production. The major technical problem was to decrease the size of the capture plant for the requirements of an off-shore operation at Sleipner-field; a case study of development stages is provided by Herzog and Falk-Pedersen (2001) and technical details of the plant can be obtained from Falk-Pedersen et al. (2001). The extra investment costs have been 80 – 96mil.\$US in order to capture, compress and inject 0.27MtC per year; see Karstad (2002, p. 59) and Holt et al. (2003). Specific numbers on extra needs of natural gas and O&M are not available.

5.1.3 The Post-Combustion Concept

In the following the main features of the post-combustion concept (Ch. 5.1.3.1) are presented. Then an overview of the related techno-economic assessments (Ch. 5.1.3.2) is provided.

5.1.3.1 The Technology

At industrial plants following the post-combustion capture concept chemical absorption for carbon capture is the best understood process. The first related patent dates back to 1930. According to Strazisar et al. (2002) a similar process has been used the first time for the removal of acid gases from natural gas streams 60 years ago. The chemical absorption process is in operation for CO_2 capture today, be-

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[5] The term "Kvaerner" is due to the company. The characteristics of the membrane contactor will be explained in detail below.

cause the removal of CO_2 from flue gas is a competitive source of CO_2 for use in urea production, enhanced oil recovery etc.; see Aboudheir et al. (2001). A list of twelve commercial CO_2 recovery plants – of which three already shut down – is given by Herzog (1999). Chapel and Mariz (2001) give a list of 21 plants using the absorber of the company Fluor, while the competitor Kerr-McGee/ABB-Lummus Crest has integrated the process in four plants worldwide. Moreover, the gas separation concept of a membrane contactor is applied at the Norwegian Sleipner West platform in order to separate CO_2 from the extracted natural gas in order to inject it in a geological formation. In the following the chemical absorption method for EP carbon capture is discussed and then some remarks on the membrane contactor concept are added.

The chemical absorption process of flue gas CO_2 capture is based on an absorption-regeneration approach. The key role is played the so called absorber, which contains a highly reactive substance called the absorbent. Alkanol amines are particular suitable as absorbents. The most widely considered amines for CO_2 capture are mono-ethanol amine (MEA), di-ethanol amine (DEA) and methyl di-ethanol amine (MDEA). Since the absorbents are highly reactive, which could lead to damage of the equipment, they are solved in water. This mixture is the absorber.

The principle idea is that the absorbent catches the CO_2 from the flue gas at low temperatures and releases the CO_2, when the absorber is heated. In order to separate the CO_2 from the flue gas the absorption takes place in one column and the release of the CO_2 in a second column. Fig. 5.3 illustrates the implementation within a technical process that shall be explained in more detail next.

The CO_2 rich flue gas with a temperature <50°C is pumped into the absorber column at slightly higher than atmospheric pressure, where the alkanol amine at 40 – 60°C absorbs the CO_2. The CO_2 lean flue gas – containing about 10% of the original CO_2 – is released into the atmosphere.

The CO_2 rich absorber is pumped into the regenerator column. The absorber is heated in the heat exchanger to temperatures up to 110 – 120°C with low pressure steam. The absorber releases the CO_2, which is saturated with water vapour. The water vapour is condensed to liquid in the flasher. The CO_2 leaving the flasher has a concentration of >98%. The CO_2 lean absorber is cooled and pumped back into the absorber, where the cycle can start again.

Since the CO_2 rich absorber has to be heated and the CO_2 lean absorber has to

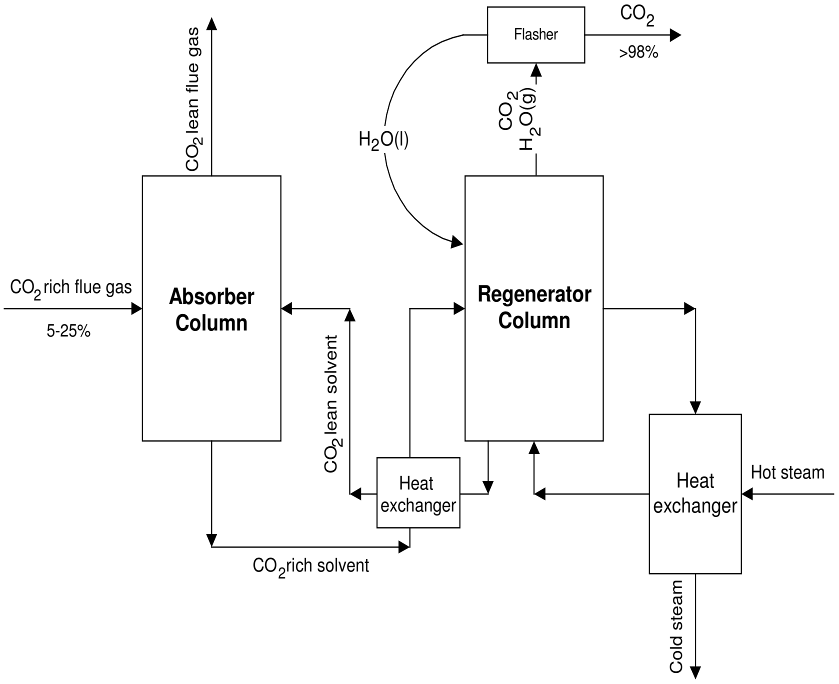


Figure 5.3: Technical principle of the pure end-of-the-pipe approach. Source: based on Chakma (1997).

be cooled both processes are linked together by the heat exchanger in the middle. This is important to reduce the overall energy consumption of the process. The CO_2 rich absorber is pre-heated here to ~105°C.

The effort to capture the CO_2 with this process needs energy: low pressure steam for absorber regeneration, electricity to operate the blowers and pumps to move the masses. Capital need is due to the absorber, regenerator and other equipment. Moreover the extracted steam has to be produced previously, which implies an additional extra effort for capital and energy. The amine, the additives and the work-force are summarised in the O&M costs.

The energy required to regenerate the absorber in the regenerator column is called reboiler heat duty (RHD) and will be discussed at some detail in the following. The RHD is measured in $\mathrm{kWh_t}$ heat that is required to capture one kgC. The literature provides a range for the RHD of MEA of $3.8 - 4.4\frac{\mathrm{kWh_t}}{\mathrm{kgC}}$; see Mimura et al. (1997), Desideri and Paolucci (1999), Chapel and Mariz (2001) and Geuzebroek et al. (2002). Göttlicher (1999, p. 45) notes that about two thirds of the total low pressure steam in a coal power plant with carbon capture are needed for RHD.

The RHD is the most important source of energy need in the overall process. About 85% of the overall energy consumption of the carbon capture process is due to the RHD. The other extra consumption is due to pumps, blowers and others; see Hendriks (1994), Mimura et al. (1997), Chapel and Mariz (2001) and Geuzebroek et al. (2002).

To assess the RHD a good benchmark for comparison are the CO_2 emissions per unit electricity produced in units of $\frac{\mathrm{kgC}}{\mathrm{kWh_e}}$ using a conventional coal power plant. If the overall efficiency of energy conversion is 45% the emissions are about $0.2\frac{\mathrm{kgC}}{\mathrm{kWh_e}}$, which requires $2.2\mathrm{kWh_t}$ of primary energy. Following from the laws of thermodynamics the efficiency of low pressure steam is low: $\sim$15%. Therefore, $4\mathrm{kWh_t}$ of low pressure steam could produce $0.15\frac{\mathrm{kWh_e}}{\mathrm{kWh_t}}\cdot 4\mathrm{kWh_t}=0.6\mathrm{kWh_e}$. This implies that the RHD needed to capture 1kgC could alternatively produce electricity that is equivalent to $0.6\mathrm{kWh}_e\cdot 0.2\frac{\mathrm{kgC}}{\mathrm{kWh_e}}=0.12\mathrm{kgC}$ emissions.

The RHD is not only important because of the fuel costs, but the low pressure steam has to be produced and is not available for electricity production any more. The steam for RHD is either extracted from the steam cycle of a power plant or produced in an extra process. In the former case the capital of an industrial plant without capture does not produce the same output. This is the major part of *capital derating* effect of carbon capture applying the post-combustion concept.

Efforts aimed at incremental improvement of the chemical absorption process focus on the reduction of the RHD. There are seven measures in order to achieve this aim that are being discussed next.

The first measure is to increase the CO_2 concentration in the flue gas. The shape of the curve in Fig. 5.4 indicates diminishing productivity of the CO_2 concentration on the RHD as has been suggested in Fig. 5.1.

Since the CO_2 concentration of the flue gas of natural gas plants is only $\sim$5%, the RHD can be reduced by recycling some of the flue gas into the combustion process to increase the CO_2 concentration. The maximum flue gas recycling is limited to 50%, which doubles the CO_2 concentration and therefore reduces the RHD. Moreover, this reduces the amount of flue gas to be treated in the absorber by 50%. This leads to a proportional decrease for the equipment need of the absorber and regenerator column; see Audus (2001).

The second measure to reduce the RHD is to increase the concentration of the

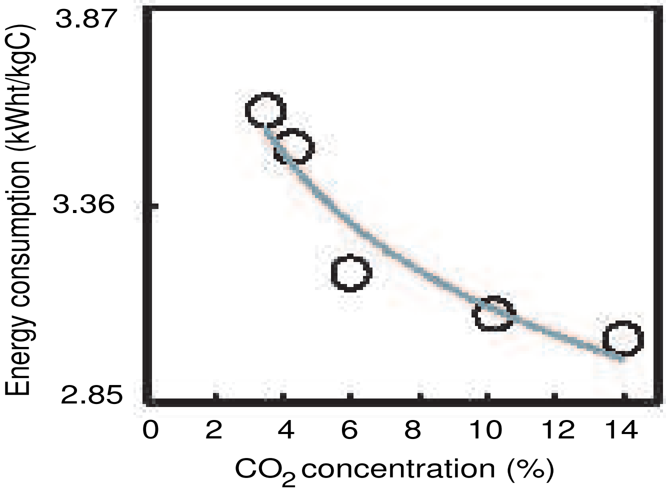
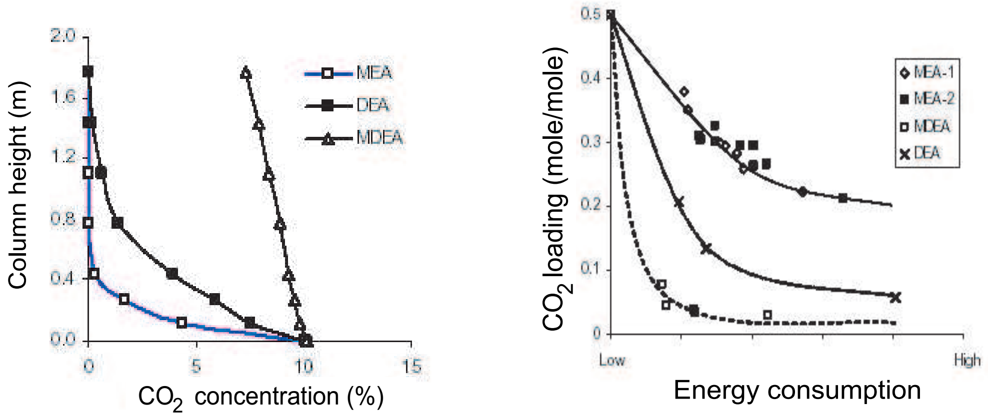


Figure 5.4: Reboiler heat duty for CO_2 capture depending on CO_2 flue gas concentration using the absorber KS-1. The data is taken from a plant in Malaysia. Source: Mimura (2001).

absorbent. This implies additional benefits from reducing the size of the capture plant and therefore decreasing the capital effort. Usually, the MEA concentration is assumed to be 30%. Based on simulation studies Hendriks (1994), Leci (1996) and Aboudheir et al. (2001) proposed a remarkable reduction of the extra effort of carbon capture, if the concentration of MEA is increased from 30% to 70%. This proposition has to be contrasted with the experience from long run large-scale operation. Strazisar et al. (2002) and Chapel and Mariz (2001) report that the MEA concentration in commercially operating capture plants have been decreased to <20%. The reason is corrosion of the equipment, which is decreased by lowering the reactivity of the water-absorber mixture.

The third measure is related to the choice of the amine used as absorber, because the amines show different properties concerning chemical reactivity. It turns out that the aim of reducing the RHD by using an optimal absorber has a trade-off relationship with the absorber size. The best candidate amines are compared in an experimental study by Veawab et al. (2002) shown in Fig. 5.5.

Fig. 5.5(a) shows the CO_2 concentration of a flue gas at different heights that moves through an absorber column. On the way upwards CO_2 is absorbed from the flue gas indicated by the decreasing CO_2 concentration. It turns out that MEA, which is the absorbent with the highest reactivity, has removed nearly all CO_2 at



(a) CO_2 concentration and column height (b) Energy consumption and CO_2 loading

Figure 5.5: Experimental results for several chemical absorbents. Source: Veawab et al. (2002)

a height of 0.4m. MDEA has not removed a significant portion at 2m. Fig. 5.5(b) shows the energy requirements for the absorber regeneration for different CO_2 loadings in the absorbent. The loading is measured in terms of the number amine molecules (in mole) that are chemically connected with CO_2 molecules (in mole). The shape of the figure indicates diminishing productivity of CO_2 release with respect to additional energy input.

The results in Fig. 5.5 show the trade-off: the higher reactivity of an absorber, the smaller is the height of the absorber column (Fig. 5.5(a)), but the higher is the RHD (Fig. 5.5(b)). The selection of an appropriate absorbent reduces the RHD at the expense of higher capital costs for the absorber column and the mass that has to be moved.

The fourth measure is to mix the amines in order to utilise the best features of each. This is suggested by different characteristics of the absorbents in Fig. 5.5. Chakma (1997, p. S55) proposes the potential for reducing the RHD through an optimised absorbent mix to 30% relative to the case with MEA absorbent concentration of 30%.

The fifth measure is to develop new absorbent substances. The commercial plant for the combined production of ammonia and urea in Gurun Kedah, Malaysia, uses a newly developed absorbent named KS-1. A steam methane reforming plant[6], at which the CO_2 is captured delivers pure hydrogen for ammonia production. The CO_2 is delivered to an urea production plant.

The RHD bas been reported to be constant at $2.95\frac{\mathrm{kWh_t}}{\mathrm{kgC}}$ over several days of operation. The corrosive behaviour is less aggressive compared to MEA and the amine loss is $1.3\frac{\mathrm{kgMEA}}{\mathrm{tC}}$. These low values are not comparable with plants fuelled with coal, since the impurities contribute to the amine loss, which are higher in coal than in natural gas. Additional improvements are proposed by Veawab et al. (2001) and Idem et al. (2001).

The sixth measure is related to the choice of the fraction of CO_2 that shall be captured from the flue gas. This parameter has to be chosen prior to the installation of the plant. Due to technical properties the process is limited to 90% CO_2 to be captured from the flue gas. The question is whether the RHD is decreasing at decreasing share of captured CO_2. In a simulation based study Dave et al. (2001) focused on implications of the share of CO_2 captured from the flue gas of coal fired power plants. This share has effects on the plant efficiency and the investment costs for the CO_2 capture plant. Dave et al. (2001) and Mimura (2001) found linear decreasing relationships between RHD and the share of CO_2 that is captured from the flue gas. This means that there is no diminishing productivity of RHD with respect to the share of captured carbon.

Finally, the energy requirement of the chemical absorption process might be decreased by appropriate integration of the capture process into the plant. This issue is related to the performance of possible retrofitting of existing plants. In the retrofitting case the arrangement of the components is inflexible. Therefore, several measures to reduce the energy requirements can not be applied; see David (1999, p. 34), Desideri and Paolucci (1999), Desideri and Corbello (1998), Desideri and Paolucci (1999), Simbeck (2001a) and Simmonds et al. (2002).[7]

Apart from energy efficiency improvements additional issues that affect the extra effort of carbon capture are worth to consider. The high reactivity of the absorbers is the main reason from which several problems follow. The absorber does not only

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[6] See Ch. 5.1.5 for details.

[7] Due to the space requirements of the equipment, even the location can be a serious problem. The absorbers (regenerators) of a carbon capture plant at a 237$\mathrm{MW_e}$ power plant coal power plant are 47m (40m) in height and 8.45m (5.24m) in diameter. The space at premises can be a scarce factor, since the capture plant requires considerable space.

react with CO_2 , but it reacts with impurities of the flue gas and it reacts with the equipment material (corrosion). The former problem mainly implies the waste of the absorber, which is an operation cost. The latter problem could imply downtimes, production losses, need for maintenance of equipment and even injury and death of personnel; see Veawab et al. (2001).

The O&M extra effort of absorber degradation depends on the amount of carbon capture. This is an extra effort of O&M that will be discussed next. The degradation is higher, the higher the oxygen (O_2) concentration and the more impurities are contained in the flue gas. O_2 in the flue gas reacts with amines to form heat resistant salts; i.e. the absorber cannot be regenerated again; see Chakravarti et al. (2001) and Strazisar et al. (2002).

The absorber degradation due to impurities is especially a problem with respect to the use of coal. The problem of absorber degradation due to flue gas impurities increases for decreasing coal quality. Impurities are SO_2, NO_x, flying ashes and inorganic oxides[8] The problem is most considerable with respect to SO_2, because the absorbers prefer to react with this rather than with CO_2.

The alternative is to pre-condition with a the flue gas because SO_2 in the flue gas would reduce the absorptive capacity of MEA; see Meisen and Shuai (1997), David (1999), Simmonds et al. (2002), Wilson et al. (2002). Most significantly, the SO_2 content has to be reduced, because MEA prefers to absorb this relative to CO_2.

The loss of the absorber is an important extra effort for the operation of a chemical absorption based carbon capture plant. Chapel and Mariz (2001), Mimura (2001) and Singh et al. (2003) found that 5.9 − 7.3kg MEA are lost per tC captured. According to Singh et al. (2003) the costs of MEA are $0.97\frac{\$\mathrm{US}}{\mathrm{kg}}$. Chapel and Mariz (2001) noted that the costs of absorber losses are 10.7$US per tC, while the modelling study by Hendriks (1994) found 7.3$US per tC. The US company Fluor Daniel developed a proprietary MEA based absorbent called Econamine FG, which contains inhibitors to avoid problems arising from impurities in the flue gas. The costs of the inhibitors are 20% of the absorber costs; see Chapel and Mariz (2001).

Desideri and Paolucci (1999) found that a 237MW_e coal power plant needs 2740t MEA per year of which some is emitted into the atmosphere. Audus (2001) reports for a 500MW_e gas fired plant 2000t MEA sludge per year and 10t MEA per year

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[8] Examples are SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O and P_2O_5; see Wilson et al. (2002).

are emitted into the atmosphere. The environmental and health impacts of these emissions are not studied, yet.

The operational problem of SO_2 impurities could also increase the extra effort of capital, since carbon capture presupposes flue gas de-sulpherisation FGD. Leci (1997) reports an increase of the total investment costs for a coal power plant of 11% for the SO_2 and 46.5% for the CO_2 removal plant. Chapel and Mariz (2001) note that the costs of de-sulphurisation are 9% of the total CO_2 capture costs. The costs of de-sulphurisation is significant in the USA because coal power plants usually use low sulphur coal instead of FGD to reduce sulphur emissions, but these emission levels are sufficiently low for carbon capture with chemical absorption; see Simbeck (2001b) and Ellerman and Dubroeucq (2004).[9]

An alternative to the chemical absorption process in the post-combustion concept is the use of selective membranes that will be introduced next. There are two different approaches: gas separation membranes (GSM) and gas absorption membranes (GAM).[10] Fig. 5.6 illustrates the two concepts.

Fig. 5.6(a) shows the GSM concept. It is based on the idea of semi-permeability of a porous structure with high selectivity and permeability for CO_2, which separates two gas streams. On the left of the membrane is the pressurised flue gas mixture. CO_2 permeates through the membrane because of the pressure gradient and the selectivity of the membrane; see Feron and Jansen (1997). An important problem is that the pressure of the flue gas has to be increased. This is an important cost driver; see Meisen and Shuai (1997). The overall process is more expensive than chemical absorption. Riemer and Omerod (1995) reports high costs relative to other EP designs.

Fig. 5.6(b) illustrates the gas absorption membrane acting as a contactor. On the left hand of the membrane is the flue gas mixture and right hand is the absorber liquid. The streams of flue gas and the absorber are countercurrent. The membrane

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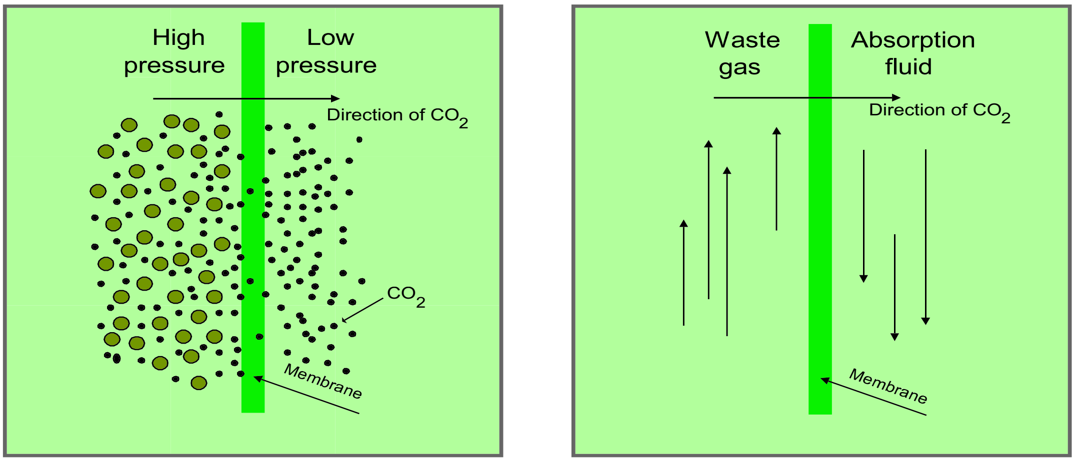
[9] Some engineering based studies focus exclusively on the details and inherent problems using MEA based absorbent under real world conditions; see Chakma (1997), Aboudheir et al. (2001), Chakravarti et al. (2001), Supap et al. (2001), Geuzebroek et al. (2002), Strazisar et al. (2002) and Wilson et al. (2002).

[10] Recently, a new approach has been proposed using facilitated transport membranes are used. This approach is based on the idea that the flue gas and the absorber are in contact. Only, the CO_2 saturated absorbent permeates to the other side of the membrane. The approach is at an early stage; see Teramoto et al. (2002).



(a) Gas separation membrane (b) Gas absorption membrane

Figure 5.6: Two approaches for selective membranes. Source Riemer et al. (1993)

acts as a contactor between the flue gas and the absorber.

GAM are based on the idea that the flue gas stream at atmospheric pressure is separated from a liquid absorbent by a microporous solid membrane. The liquid can be MEA, again. CO_2 diffuses through the membrane and is solved in the absorption liquid. The difference is that the membrane in GSM is not required to be selective for CO_2. There has to be a contact area of flue gas and absorbent, which selects CO_2. The result is that the flue gas stream and the absorber liquid do not contact. The rest of the process and the corresponding problems are *cum granusalis* the same as for the chemical absorption approach, but operating problems are reduced and the overall size of the equipment is smaller.

5.1.3.2 The Economics

In the following studies are reviewed that focus on the economics of the integration of carbon capture following the post-combustion concept into industrial plants. A remarkable number of studies focus on power plants, which are treated first. Information available on cement and iron plants is not as detailed and will be treated in the end.

The studies cited here follow the same method. First, a reference plant is described that does not incorporate carbon capture. Second, several variants of carbon capture are implemented via technical computing routines. Third, the variants are assessed using cost data for equipment. Fourth, the best variant is selected due to a specific criterion; e.g. lowest costs of avoiding a ton of carbon relative to the reference plant. In the following the reference plant is compared with the best available capture process. The aim is not to select the best capture plant, but to provide an overview of the economics of EP carbon capture.

Two different types of power plants are reviewed in detail that are quite different in the reference case. The first type is the pulverised coal power plant PC. Here the coal is fed into a combustion chamber and the heat produces pressurised steam that is expanded in a steam turbine (ST). The flue gas is vented to the atmosphere. The second type is the natural gas fueld combined cycle (NGCC) power plant. Here two different types of turbines produce power. The natural gas is compressed and introduced into the gas turbine (GT), where it is combusted and thereby the pressure is further increased. The expansion of the gas powers the GT. The GT off-gas has a high temperature that is used to generate steam, which in turn powers a ST. The GT produces about 60% of the power of an NGCC.

Natural gas is of higher quality than coal. This leads to three differences for studies of carbon capture with respect to the type of the reference plant. First, the carbon intensity of natural gas is lower than that of coal. Second, the efficiency – the ratio of electricity output to fuel input – is about 55% for NGCC and up to 45% for PC. These two differences imply that the CO_2 emissions per kWh_e of NGCC are lower than of PC plants. Third, the cost shares of cost of electricity (COE) are different. A NGCC has low capital, but high fuel costs and *vice versa* for PC plants.

The reviews are summarised in Tab. 5.2 and 5.3. In the following some considerations are provided that are useful for a better assessment of the EP capture technology.

The Electric Power Research Institute (EPRI), California, initiated a study by Booras and Smelser (1991) on capture at coal power plants, named ***B&S91*** in the following. The focus is on the retrofit of an existing power plant using high sulphur coal that is removed by flue gas desulpherisation FGD.[11] A similar study at Univer-

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[11] Based on the numbers they, additionally, calculated the costs of retrofitting the existing PC plants in the US. Retrofitting the most favourable plants emitting 20% of CO_2 would cost 34bil.$US. Retrofitting all plants would increase the cost to 450 – 750bil.$US; i.e. the cost increase is more than proportional with respect to the amount of carbon capture.

sity Utrecht, The Netherlands, by Hendriks (1994, Ch. 2) (***H94*** in the following) looked at three different designs. The study is based on the technical data of the existing plant Amer-8 in The Netherlands.

A comparison between B&S91 and H94 with respect to changes in investment (\$US per kW_e) and changes in plant efficiency (%-points of the original plant) is given in Fig. 5.7. The investments for the equipment of carbon capture are approximately the same. The differences of the total investment costs arise from the remaining cost components. B&S91 see a considerable effort for retrofitting an existing plant, H94 does not even consider any costs with respect to that. On the other hand, H94 accounts for interest to be payed during 3 years of construction, which is ignored by B&S91. There are also differences in the investment costs of the compression plant. The derating of the original plant capital is about twice in the B&S91 study because of the higher energy penalty; see Tab. 5.2.

The higher energy penalty of B&S91 is caused especially by the difference in the compression plant and the energy need for running the absorber-regenerator plant. The compression related reduction of efficiency is 3.6%-points in B&S91 and 2.3%-points in H94. As will be pointed out below (Ch. 5.2), the electricity consumption of H94 is low relative to other studies. Göttlicher (1999, p. 149) concludes that the reduction of efficiency of the power plant due to compression is about 3%-points. The RHD is approximately the same in both studies.[12]

The retrofit option is interesting especially for old power plants that have already paid off their capital costs. These power plants are characterised by low efficiencies and low cost of electricity COE. The addition of carbon capture only requires the investments related to the carbon capture equipment. Two studies primarily focus on this issue: Simbeck (2001a) ***S01*** and Singh et al. (2003) ***S03*** that are treated in more detail next.

For S01 the numbers for the reference case in brackets in Tab. 5.1.7 refer to the rebuilding costs of a PC plant with the same capacity. S03 do not refer to such a reference plant. Both studies use as a starting point a capacity of the reference plant and a flue gas stream. The overall carbon capture equipment is added and the heat and electricity are produced by separate gas fuelled equipment. The S01 plant has to be augmented by a FGD because of high SO_2 concentration in the flue gas.

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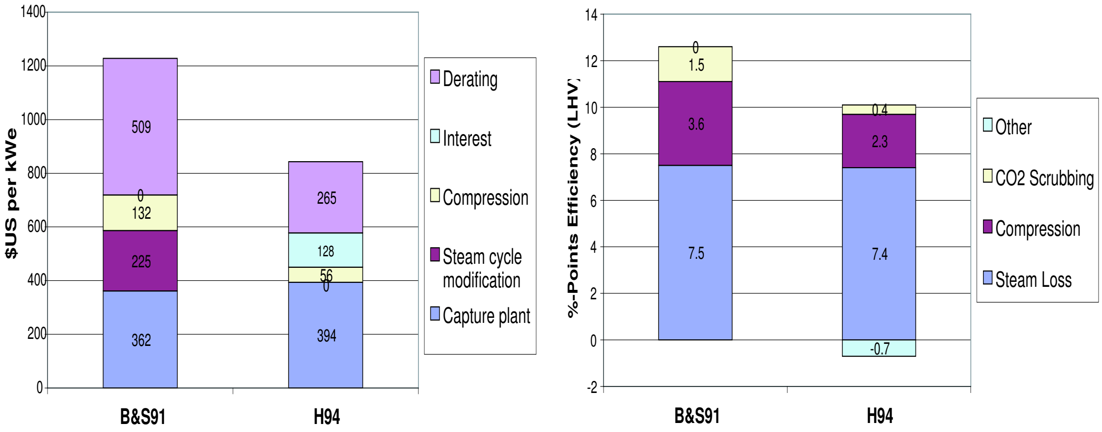
[12] The theoretical minimum without compression is 1.5%-points reduction of the power plant efficiency; see Göttlicher (1999, p. 135).



(a) Investment costs

(b) Energy penalty

Figure 5.7: Comparison of investment costs and energy requirements by component between B&S91 and H94.

Fig. 5.8 shows the breakdown of the investment costs by component. The capture plant components are quite comparable and lower than the derating of the two studies reviewed above (Fig. 5.7). The reason is the lower investment costs of natural gas equipment, which is offset by the higher costs of natural gas. The investments for extra heat requirement and compression are considerable in size and differ remarkably. The *other* component is approximately equal and accounts for fees, assurance, site costs etc.

Fig. 5.7 and 5.8 show that the crucial component in magnitude and difference across studies is not so much the capture plant in a narrow sense, but the components that are necessary consequences of the capture plant. The compression plant is a disputable component in terms of investment costs and electricity consumption. The category *other* is not defined compared with the technical components, but at least as important to get the machine into operation. The *other* cost component usually is computed as a percentage up-scaling of the physical investment; costs and the percentage rates differ between the studies. Most often, it is not clear whether this component is considered and what it represents. Therefore, the comparison of the assumptions of the techno-economic assessments should be treated with care.

To summarise the studies it is referred to the range that is in the numbers leaving

Table 5.2: Techno-economic assessments on PC plants without (Ref.) and with (Cap.) CO_2 capture using the post-combustion concept. Source: based on David (1999) and David and Herzog (2001).

	B&S91[a]	H94	R&O95	L96	S98	D&P98	H00	A01	S01	S03[b]
Fuel cost (millsUS/kWh$_t$)[c]	4.38	4.38	7.2	9.	4.38	N.A.	4.38	5.3	4.9	15.19[d]
Load factor[e] (%)	0.75	0.75	N.A.	N.A.	0.75	0.98	0.75	N.A.	0.85	91.
Capital charge per year (%)	15.	15.	N.A.	10.	15.	10.	15.	10.	15.	15.
CO_2 Captured (%)	90.	90.	80.	90.	N.A.	90.	90.	N.A.	N.A.	90.
Base Case FGD[f]	Yes	Yes	Yes	Yes	N.A.	Yes	Yes	Yes	No	Yes
CO_2 Compression (bar)	152.	80.0	52.6	N.A.	137.	140.	Yes	N.A.	Yes	150.
Ref. efficiency (%LHV)[g]	36.1	41.0	39.9	39.9	44.4	44.3	40.3	46.	36.2	N.A.
Cap. efficiency (%LHV)	23.8	31.5	26.7	28.5	37.4	32.7	32.2	33.	25.4	N.A.
Energy penalty (%)	34.1	23.0	33.1	28.5	15.8	26.2	20.	28.3	29.8	N.A.
Δ efficiency (%-points)	12.3	9.5	13.2	11.4	7.0	11.6	8.1	13.	10.8	N.A.
Ref. emission (gC/kWh$_e$)	247.9	218.2	226.	N.A.	195.5	N.A.	210.0	196.9	264.8	252.3
Cap. emission (gC/kWh$_e$)	37.6	27.3	62.	N.A.	36.9	N.A.	27.3	40.4	33.0	88.3
Δ emissions (%)	84.8	87.5	73.6	N.A.	82.1	86.5	87.	79.5	87.5	65.
Ref. COE K.[h] (millsUS/kWh$_e$)	25.8	26.3	N.A.	21.0	29.7	N.A.	26.	N.A.	(19.6)	N.A.
Cap. COE K. (millsUS/kWh$_e$)	56.7	47.3	N.A.	32.2	46.2	23.4	45.	N.A.	18.7	13.8
Ref. COE Fu.[i] (millsUS/kWh$_e$)	11.7	10.3	18.1	22.6	9.5	N.A.	10.	11.5	(13.5)	N.A.
Cap. COE Fu. (millsUS/kWh$_e$)	17.8	13.3	24.7	28.7	11.3	N.A.	13.	16.1	19.3	15.7
Ref. COE O&M[j] (millsUS/kWh$_e$)	10.3	5.9	N.A.	9.8	7.9	N.A.	6.	N.A.	(5.2)	N.A.
Cap. COE O&M (millsUS/kWh$_e$)	29.9	12.9	N.A.	19.5	12.3	N.A.	11.	N.A.	9.5	8.8
Ref. COE Tot.[k] (millsUS/kWh$_e$)	47.8	42.5	49.	53.4	47.1	68.6	43.	37.	(38.3)	N.A.
Cap. COE Tot. (millsUS/kWh$_e$)	104.4	73.7	77.	80.4	69.8	130.9	69.	64.	47.5	38.3
Δ COE[l] (%)	118.4	73.4	57.1	50.6	48.2	90.8	60.5	73.0	23.0	N.A.
Ref. investment (US/kW_e$)	1129.	1150.	N.A.	1058.	1300.	N.A.	1150.	1020.	(974.)	N.A.
Cap. investment (US/kW_e$)	2484.	2073.	N.A.	2578.	2022.	2011.	1967.	1860.	824.	737.
Δ Investment (%)	120.0	80.3	N.A.	143.6	55.5	N.M	71.0	82.4	N.M.	N.A.
Mitigation cost[m] ($US/tC)	267.7	165.0	170.	N.A.	143.0	N.A.	146.7	172.3	121.00	233.5

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[a] The studies are B&S91 ≙ Booras and Smelser (1991); H94 ≙ Hendriks (1994, Ch. 2); R95 ≙ Riemer and Omerod (1995); L96 ≙ Leci (1996); S98 ≙ Simbeck (1998); D&P98 ≙ Desideri and Corbello (1998); H00 ≙ Herzog (2000); A01 ≙ Audus (2001); S01 ≙ Simbeck (2001a); S03 ≙ Singh et al. (2003).

[b] This study focuses on a carbon capture plant. The extra heat and electricity is delivered by a gas power plant.

[c] millsUS is 0.001·$US.

[d] This is the assumed price for gas.

[e] Fraction of hours of a year ($8760\frac{\mathrm{h}}{\mathrm{y}}$) the plant is running.

[f] FGD is flue gas desulphurisation.

[g] LHV is the lower heating value, which measures the fuel input.

[h] COE K. are the costs of electricity due to capital.

[i] COE Fu. are the costs of electricity due to fuel.

[j] COE O&M are the costs of electricity due to operation and maintenance.

[k] COE Tot. are the total costs of electricity.

[l] COE is the costs of electricity.

[m] The mitigation costs are computed as follows: (Cap. COE Tot. − Ref. COE Tot.) · (Ref. emissions − Cap. emissions)$^{-1}$.

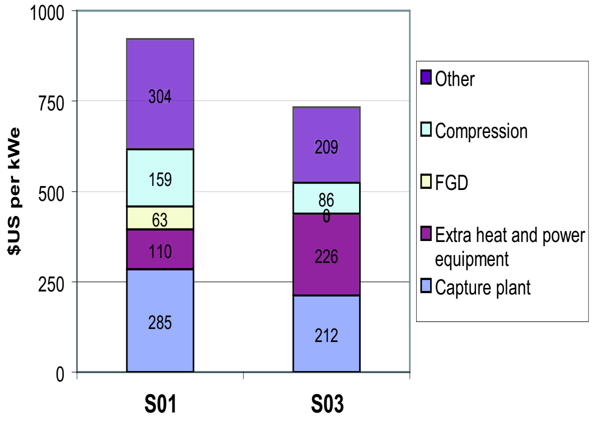

Figure 5.8: Comparison of carbon capture by retrofit of paid-off PC plants according to the chemical absorption concept. Source: based on Simbeck (2001a) and Singh et al. (2003).

the highest and lowest number of each characteristic out. The overall picture reveals that the CO_2 emissions could be reduced by more than 80%, but not more than 87.5%. The reduction of the efficiency is 7 – 13%-points, which implies an energy penalty of 19 – 33%. The literature review by Göttlicher (1999, p. 149) concludes that the reduction of efficiency for coal power plants is between 11 – 14%-points. Therefore, the results with less than 9%-points reduction should be treated with care.

The additional effort of carbon capture implies considerable impact on economic variables. The investment costs for the reference plant are in the range of 1000 – $1150\frac{\$US}{kW_e}$. The extra investments vary over a broad range: the lowest assessment is 70% while the highest is 120%. The costs of producing electricity increase by 57 – 91%. Note that the increase of operation and maintenance O&M costs is more than proportional to this increase: 83 – 119%.

The CO_2 mitigation costs are an useful first order indicator of the EP concept. The studies imply that the CO_2 mitigation costs are well above $100\frac{\$US}{tC}$ and could even reach $200\frac{\$US}{tC}$.

In studies treating NGCC power plants the authors do not mention whether the study focuses on retrofitting of existing plants or not. Since NGCC plants have been built mostly in the last 10 – 15 years, it can be assumed that the studies assume only new installations. The studies are based – as far as notes are given - on conventional MEA based absorption processes. Since natural gas contains no sulfur, problems related to degradation and the need for additives are reduced.

The studies on NGCC plants are presented that are summarised in Tab. 5.3. The studies show that the potential for CO_2 reductions is again clearly above 80%, but will not exceed 89%. The investment costs could increase by about 93 – 134%. The energy penalty ranges from 14 – 20%. The costs of producing electricity will increase by 48 – 58%. Although this increase in unit costs is lower than for carbon capturing at PC plants, the CO_2 mitigation costs are higher: 193 – $240\frac{\$US}{tC}$. This is because the CO_2 emissions per kWh_e are lower for the NGCC base case plants due to the use of natural gas and its higher efficiency.

Next, the focus is on studies that are devoted to carbon capture at cement and iron BOF plants. Cement and iron BOF production are high temperature processes that are usually fuelled with coal. Both types of industrial plants produce a flue gas stream with relatively high CO_2 concentration.

Farla et al. (1995) studies MEA based chemical absorption carbon capture at a particular iron BOF plant in The Netherlands. The study found that 373mil.$US are needed for the capture of 0.557MtC per year. This implies investment costs of $669.77\frac{\$US}{tC/y}$. The electricity consumption is $0.32\frac{kWh_t}{kgC}$ and there is an additional reduction of electricity production of $0.03\frac{kWh_e}{kgC}$. The steam consumption is $3.5\frac{kWh_e}{kgC}$. The O&M costs are $14.37\frac{\$US}{tC}$.

Hendriks et al. (2002) report numbers on investment and O&M costs for two different iron BOF plant sizes without compression costs in order to account for economies of scale. The investment costs for small plants with yearly carbon emissions between 0.55 and $1.09\frac{MtC}{y}$ are $255.79\frac{\$US}{tC/y}$ and O&M costs are $15.11\frac{\$US}{tC}$. For smaller plants up to $0.55\frac{MtC}{y}$ the corresponding numbers are $348.81\frac{\$US}{tC/y}$ and $20.93\frac{\$US}{tC}$, respectively. These figures do not contain compression costs, which are computed according to Ch. 5.2. This study does not report numbers on energy needs for the carbon capture process.

The two studies provide quite different data on extra efforts for capital as the investment costs of the former study are about twice that of the latter. Hendriks et al. (2002) do not give reasons for the differences and the studies are not sufficiently detailed in order to reconcile these differences. Based on the investment costs of compression from Hendriks et al. (2002) it is not possible to attribute the difference to this factor; see also Fig. 5.22(a) on p. 221.

The other large scale industrial plants emitting CO_2 are cement plants. Cement

Table 5.3: Techno-economic assessments on NGCC plants without (Ref.) and with (Cap.) CO_2 capture using the post-combustion concept. Source: based on David (1999) and David and Herzog (2001)

	B&S92[a]	R&O95	L96	S98	D&C98	H00	A01	UBA01
Fuel cost (millsUS/kWh$_t$)[b]	10.35	10.8	10.35	10.35	23.45	10.35	6.63	N.A.
Load factor[c] (%)	0.75	N.A.	N.A.	0.75	0.5	0.75	N.A.	N.A.
Capital charge per year (%)	15.	N.A.	10.	15.	8.	15.	10.	15.
CO_2 Captured (%)	90.	N.A.	85.	90.	90.	N.A.	N.A.	N.A.
CO_2 Compression	Yes	52.6	N.A.	135atm	Yes	Yes	N.A.	150.
Ref. efficiency (%LHV)	52.2	52.0	52.0	60.0	35.5	54.1	56.	58.
Cap. efficiency (%LHV)	44.5	42.0	41.7	53.0	25.4	46.8	47.	49.
Energy penalty (%)	14.7	19.2	19.8	11.6	28.6	13.6	16.1	15.5
Δ efficiency (%-points)	7.7	10.0	10.3	7.0	10.1	7.3	9.	9.
Ref. emissions (gC/kWh$_e$)	109.1	N.A.	N.A.	90.	N.A.	100.9	100.9	99.0
Cap. emissions (gC/kWh$_e$)	12.5	N.A.	N.A.	15.3	N.A.	10.9	16.6	16.4
Δ emissions (%)	88.5	N.A.	N.A.	83.	90.	89.2	83.5	83.4
Ref. COE K.[d] (millsUS/kWh$_e$)	17.2	N.A.	10.5	11.1	(30.0)	12.	7.	N.A.
Cap. COE K. (millsUS/kWh$_e$)	30.1	N.A.	19.5	25.9	(66.7)	26.	13.	N.A.
Ref. COE Fu.[e] (millsUS/kWh$_e$)	19.2	N.A.	17.4	16.7	(28.2)	18.	13.	N.A.
Cap. COE Fu. (millsUS/kWh$_e$)	22.5	N.A.	21.4	18.8	(92.3)	21.	15.	N.A.
Ref. COE O&M[f] (millsUS/kWh$_e$)	2.7	N.A.	4.1	3.0	5.9	2.	2.	N.A.
Cap. COE O&M (millsUS/kWh$_e$)	5.2	N.A.	6.0	6.9	12.3	6.	4.	N.A.
Ref. COE Tot.[g] (millsUS/kWh$_e$)	39.1	35.	32.0	30.7	90.4	33.	22.	N.A.
Cap. COE Tot. (millsUS/kWh$_e$)	57.7	55.	50.2	51.7	139.0	52.	32.	N.A.
Δ COE[h] (%)	47.6	57.1	56.9	68.4	53.8	57.6	31.3	N.A.
Ref. investment (US/kW_e$)	754.	N.A.	702.	485.	1514.	525.	410.	600.
Cap. investment (US/kW_e$)	1317.	N.A.	1367.	1135.	3455.	1120.	790.	1598.
Δ investment (%)	74.7	N.A.	94.7	134.0	128.2	113.3	92.7	166.3
Mitigation cost[i] ($US/tC) ($US/tC)	192.5	240.0	N.A.	281.1	N.A.	211.1	118.3	N.A.

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[a] The studies are B&S92 ≙ Bolland and Saether (1992); R95 ≙ Riemer and Omerod (1995); L96 ≙ Leci (1996); S98 ≙ Simbeck (1998); D&C98 ≙ Desideri and Corbello (1998); H00 ≙ Herzog (2000); A01 ≙ Audus (2001); UBA01 ≙ Undrum et al. (2001).

[b] millsUS is 0.001·$US.

[c] Fraction of hours of a year ($8760\frac{\mathrm{h}}{\mathrm{y}}$) the plant is running.

[d] COE K. are the costs of electricity due to capital.

[e] COE Fu. are the costs of electricity due to fuel.

[f] COE O&M are the costs of electricity due to operation and maintenance.

[g] COE Tot. are the total costs of electricity.

[h] COE is the costs of electricity.

[i] The mitigation costs are computed as follows: (Cap. COE Tot. − Ref. COE Tot.) · (Ref. emissions − Cap. emissions)$^{-1}$.

production has two major sources of CO_2 emissions. First, the calcination process, which transforms the raw material limestone ($CaCO_3$) into calcium oxide (CaO) and CO_2. This reaction requires high process temperatures (about 900°C). The second source of CO_2 emissions is the combustion of fossil energy carriers (usually coal) in order to provide the process energy. At the global level 52% of the CO_2 emissions from cement industry is related to the calcination process; see Hendriks et al. (1998). This explains the higher CO_2 concentration in the flue gas stream of cement plants of about 20% compared with PC coal power plants <15%.

The only study focusing on carbon capture at cement plants is Hendriks et al. (2002). This study found the same numbers for cement plants as it does for iron BOF plants and hence the same critique applies.

5.1.4 The Oxy-Fuel Concept

In the oxy-fuel approach the flue gas of an industrial plant contains despite vapour nearly 100% CO_2, because the nitrogen of air is completely excluded from the combustion process. This is achieved by combusting the fuel in an O_2/CO_2 environment. The oxy-fuel approach moves the gas separation process to the separation of oxygen from nitrogen in ambient air. The oxy-fuel concept of carbon capture shifts the focus from the out-going gas to the in-going gas.

Therefore, the oxy-fuel approach is an ND that leaves the fundamental design of an industrial plant unchanged. The major difference is the use of pure oxygen that is not common in industrial production sectors. This novelty is a reason of concern, because it is not clear whether the physical depreciation rate of capital could increase. Despite the notion of the oxy-fuel as an ND, existing plants can be retrofitted.

Fig. 5.9 shows the scheme of an oxy-fuel capture power plant. The O_2-N_2 separation of ambient air requires an air separation unit (ASU). Installation of the ASU needs capital and the operation requires energy and delivers O_2, which is introduced into the combustion chamber. The O_2 concentration in the combustion chamber is about 20%; the rest is CO_2 and water vapor. About 80% of the gas stream leaving the combustion chamber is recycled into the combustion chamber. The reason for this flue gas recycling is that it limits the combustion temperature in order to prevent damage of the equipment. The CO_2 rich off-gas that is not recycled has to be cleaned by condensing the water vapor and removing other impurities. The cleaned

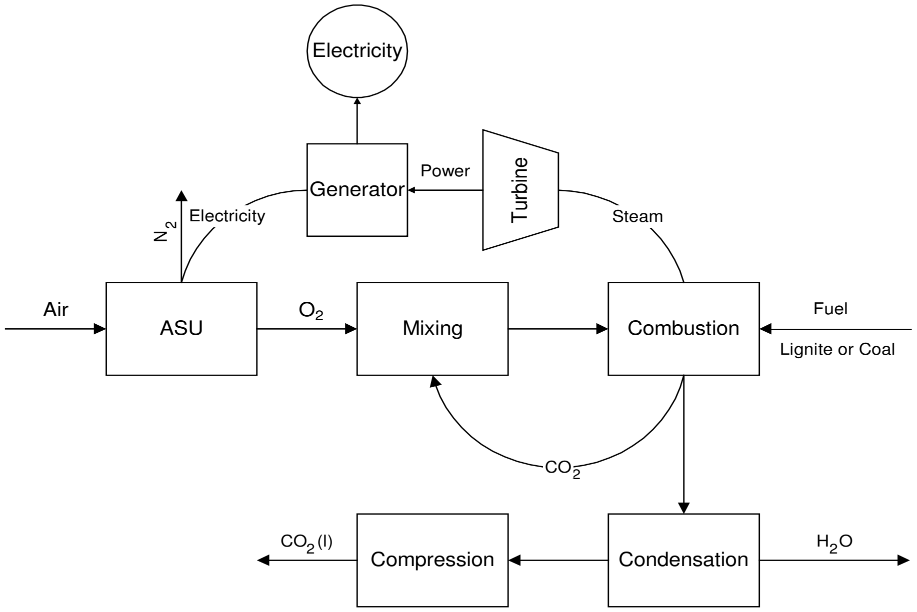

Figure 5.9: Scheme of an oxy-fuel lignite or coal power plant. In comparison with the base-case plant this plant does not require a FGD. All pollutants and the CO_2 are captured and are compressed. Source: Andersson and Maksinen (2002, p. 2).

CO_2 is then ready for compression. The rest of the plant is a typical PC power plant. The combustion of the fossil fuel produces heat that is used to produce the steam that is used to produce electricity via a steam turbine and a generator.

The main problem of this approach is that O_2 production requires a considerable extra effort of capital and energy. This point will be treated in more detail below. At first some minor important problems are discussed. Technical problems could arise from the change of the gas composition in the combustion chamber and the in-leakage of N_2. The former problem could lead to accelerated depreciation of equipment. The latter is a problem especially for the case of retrofitting old plants because it obviously counteracts the primary intention of the capture concept.

For the separation of air there are two different processes. The cryogenic process is widely applied; see e.g. Marion et al. (2001). The gas separation membrane process is more speculative. Both approaches are analysed in some detail next.

The cryogenic process requires electricity. The purity of O_2 can be increased to 97%. At that point the separation of O_2-N_2 becomes one of separating O_2-Argon, which is much more expensive; see Wilkinson et al. (2001).

Jody et al. (1997, p. 136) note that the cryogenic based production of 1 kg of O_2

requires 0.220 – 0.275kWh$_e$; Göttlicher (1999, p. 40) reports a range from 0.221 to 0.228$\frac{\text{kWh}_\text{e}}{\text{kgO}_2}$.[13] This would consume 25 – 30% of the *electricity* output. This implies that the investment costs of the power plant would increase by that factor because the plant without capture would be derated. Moreover, the ASU investment costs have to be added.

The gas separation process of oxygen benefits from general technological progress, especially from ceramic based materials for membranes with improved performance at high temperatures; see Ch. 5.1.3.1 for the working principle of gas separation membranes. Stiegel and Maxwell (2001) compared conventional cryogenic and advanced ceramic membrane based processes for oxygen production in a simulation study. The membrane-based system requires thermal energy at high temperatures, which is obtained from the thermal processes of a plant. The study concludes that membrane-methods lower investment costs by 7.3% and decrease the energy own-consumption by 2.9% compared to cryogenic methods.[14]

The oxy-fuel approach offers ancillary benefits that reduce the net extra effort. Regional air pollution problems are solved automatically: the formation of NO_x is reduced; ash and SO_2 is highly concentrated in the flue gas stream that is not vented to the atmosphere anymore. This reduces efforts to decrease air pollution. Additionally, Jody et al. (1997) point out that CO_2 has a higher heat capacity than N_2, which is a favourable feature in industrial plants. This could increase the overall thermal efficiency of a power plant by 2%-points. The combined mitigation of regional air pollutants and CO_2 emission mitigation as well as the gain of efficiency reduce the extra effort of carbon capture.

Next, the focus is on techno-economic assessments of the oxy-fuel approach. There are by far not as many studies available as for the post-combustion approach, and all are limited to power production.

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[13] The theoretical minimum is 0.034$\frac{\text{kWh}}{\text{kgO}_2}$; see Göttlicher (1999, p. 135).

[14] Wilkinson et al. (2001) illustrates another another example: the heat recovery of the compression for O_2 production. A promising option is the integration of liquified natural gas (LNG) transported by ship, because the exergy being freed by expansion of LNG can be used for an ASU based on cooling, which could be 2%-points of the thermal efficiency of a gas fired power station. Additionally, the ASU can be coupled with the CO_2 liquefaction unit (if ship transportation is assumed), which separates the CO_2 from the rest of oxygen and water vapour and liquifies CO_2 for transport; see Shao et al. (1995) and Shao and Golomb (1996).

A Swedish research team at Chalmers University in Gothenburg (see Andersson et al. (2002), Andersson and Maksinen (2002) and Birkestad (2002)) have undertaken simulation studies for a lignite fired power plant. They took operating data from a lignite fired 865MW$_e$ power plant in Lippendorf (near Leipzig), Germany,[15] which exhibits 42.6% efficiency and a 115MW district heating unit. The authors added a cryogenic ASU and a CO_2 capture plant to that plant using a computer simulation.

The ASU produces 451000m^3 oxygen per hour. The oxygen purity is 95% and the oxygen share in the combustion process is 20%. The power requirement for the ASU[16] is equivalent to 137MW$_e$. This is equivalent to 6.7% of the thermal power of the plant, which is much lower than the numbers reported by Jody et al. (1997); see above. The own-consumption for CO_2 compression is equivalent to 71MW$_e$.

The total output of the capture plant is 696MW$_e$. Hence, the efficiency is reduced to 34.3%. This is a reduction of 8.3%-points relative to the reference plant.

The investment costs of the 865MW$_e$ plant are given in Tab. 5.4. The reference case investment costs of $1272\frac{\$US}{kW_e}$ are within the usual range compared to the numbers given in Enquete-Kommision (2002), where current costs are assumed to be $1300\frac{\$US}{kW_e}$.[17] The flue gas de-sulpherisation FGD investment costs of the reference plant are $191\frac{\$US}{kW_e}$.

The output is reduced by 169MW$_e$ due to carbon capture; i.e. the energy penalty is 19.5%. CO_2 emissions are reduced by 99.5%, the SO_2 emissions by 99% and the NO_x emissions by about 64%. The investment for the ASU are $144\frac{\$US}{kW_e}$. The investment costs for compression are $17\frac{\$US}{kW_e}$. Additional investments are assumed to be $12\frac{\$US}{kW_e}$, which are due to the treatment of the flue gas to make the CO_2 ready for pipeline transportation; see Birkestad (2002). The capture plant does not require FGD. Although the total investment costs of the power plant with carbon capture are 4% lower, the investment costs per unit output increase by 19%. The decrease of the total investment costs of the power plant is due to the lower investment costs of the carbon capture equipment relative to the FGD. The increase of the investment costs per output are due to the electricity own-consumption of the ASU.

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[15] The operator of the plant is Vattenfall Europe. There is a second plant in Lippendorf of the same size operated by EnBW and Bayernwerke.

[16] With respect to the ASU the authors refuted the use of membrane techniques, because of high energy requirements.

[17] They are expected to decrease to 1200$US per kW$_e$ until 2020.

Table 5.4: Techno-economic assessment of newly built PC power plants without (Ref.) and with carbon capture (Cap.) using the oxy-fuel concept. Source: Andersson and Maksinen (2002) and Andersson et al. (2002).

	AM02[a]				D04[b]			
	Ref. 865MW$_e$		Cap. 696MW$_e$		Ref. 677MW$_e$		Cap. 532MW$_e$	
	mil.$US	$\frac{\$US}{kW_e}$[c]	mil.$US	$\frac{\$US}{kW_e}$	mil.$US	$\frac{\$US}{kW_e}$	mil.$US	$\frac{\$US}{kW_e}$
Power plant	935.	1080.9	935.	1342.0	732.	1081.1	732.	1375.9
FGD	165.	190.8	-	-	100.	178.7	-	-
ASU	-	-	100.	143.5	-	-	180.	338.3
Compression	-	-	20.	28.7	-	-	71.	133.5
Total	1100.	1271.7	1055.	1514.3	853.	1260.0	988.	1857.1
COE (millsUS/kWh$_e$)[d]	26.7[e]		32.2		44.0[f]		61.2	
Mitigation costs[g]	-		29.3		-		207.0	

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[a] AM02 is Andersson and Maksinen (2002) and Andersson et al. (2002)

[b] D04 is Dillon et al. (2004)

[c] This calculation excludes district heating.

[d] COE is cost of electricity and millsUS are 1000·$US.

[e] Assumptions 4. $\frac{\text{millsUS}}{\text{kWh}_t}$ price of lignite and 7% discounting rate p.a.; the load factor is not given.

[f] Assumptions are 5.4$\frac{\text{millsUS}}{\text{kWh}_t}$, 10% discounting rate and the load factor is assumed to be 85%.

[g] The mitigation costs ($US/tC) are computed as follows: (Cap. COE Tot. – Ref. COE Tot.) · (Ref. emissions – Cap. emissions)$^{-1}$.

The study makes the additional assumptions that the price of lignite is 4.2$\frac{\text{millsUS}}{\text{kWh}_t}$ and the discounting rate is 7% p.a. The increase of the cost of electricity is only 20.6%. The authors conclude that the carbon mitigation costs are 29.3$\frac{\$\text{US}}{\text{tC}}$; see Stroemberg (2002). This is very low compared to other approaches; see Tab. 5.2 and 5.3.

The three major points of critique are the low discounting rate (relative to other studies), the low investment costs for the compression plant and the low own-consumption of the ASU.

With respect to the investment costs it is worth to compare the investment costs with the equation provided by Hendriks et al. (2002) that results in an extra capital effort of 36mil.$US; see Ch. 5.2. This is considerably higher than the 20mil.$US given in Tab. 5.4. Moreover, the electricity own consumption would require 79MW$_e$ of the power plant capacity compared to 71MW$_e$ that is reported in Andersson and Maksinen (2002).

The electricity need for the ASU are reported at 137MW$_e$. The productivity of the ASU must hence be 0.21$\frac{\text{kWh}_e}{\text{kgO}_2}$ to meet the oxygen production with the proposed power capacity. This is a bit lower than the lowest number (0.22$\frac{\text{kWh}_e}{\text{kgO}_2}$) cited in the

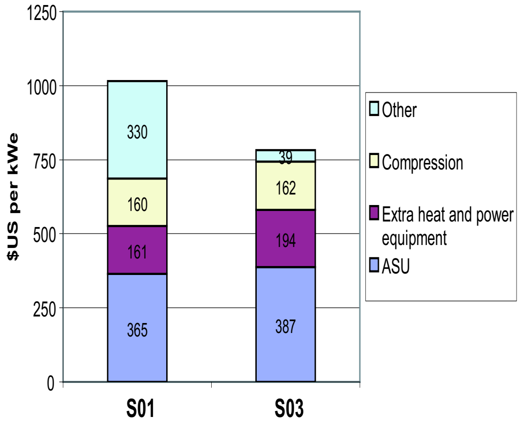

Figure 5.10: Comparison of carbon capture with retrofit of paid-off PC plants according to the oxy-fuel concept. Source: Simbeck (2001a) and Singh et al. (2003).

literature.

The results can be compared with the study by Dillon et al. (2004) ***D04*** that investigates a coal fired power plant of comparable size that is also augmented by carbon capture following the oxy-fuel concept. The comparison in Tab. 5.4 reveals that the investment for components for the compression and ASU equipment are 174% higher. Moreover, the energy penalty is 1.9% higher. These technical assumptions in combination with the differences of discount rate (10% in D04) result in the much higher plant specific mitigation costs for the AM02 case.

The studies Simbeck (2001a) ***S01*** and Singh et al. (2003) ***S03*** study the retrofitting of existing paid-off PC plants following with the oxy-fuel approach. The studies are mainly equivalent to those reviewed in Ch. 5.1.3.2 on p. 171. The study S03 explicitly assumes the problem of air in-leakage into the combustion chamber. The flue gas therefore contains a considerable share of nitrogen, which has to be removed.

Fig. 5.10 shows the break down of the investment costs. The component compression and cleaning contains the removal of nitrogen through in-leakage in S03. Obviously, S01 assumes slightly lower costs in the three physical investment components, but much higher expenditures in the *other* component. The reason is that S03 do only take into account the percentage mark-up for the compression and cleaning component, while S01 marks-up the overall physical investments.

A comparison with the numbers by Andersson and Maksinen (2002) and

Stroemberg (2002) shows considerable differences with respect to the ASU and the compression component. Reasons for these difference are the optimistic assumptions about low extra energy and investment effort.

5.1.5 The Syngas Concept

The syngas concept of carbon capture aims at reducing the extra effort by changes of the processes or products of the energy system and, hence, is an ND approach. The idea is to transform the primary energy carrier, which contains the carbon, into a secondary energy carrier in such a way that the carbon fuel is transformed into a higher quality energy carrier (e.g. hydrogen) and the resulting CO_2 is captured before the fuel is combusted. For this concept the production of syngas is the essential preparatory step in order to capture carbon. The syngas concept is seen as a promising technology to reduce the extra effort of carbon capture.

The syngas approach is characterised by a high degree of flexibility with respect to inputs, types of industrial plants and outputs. Fig. 5.11 illustrates this flexibility, which are outlined next.

Syngas – or synthesis gas – describes a gas mixture that is produced from carbon containing feedstock. This can be coal, biomass, waste, natural gas or other solid energy carriers. Syngas consists mainly of O_2, carbon monoxide (CO), CO_2 and hydrogen (H_2); the shares can be controlled by setting the operational parameters. The production of syngas needs process high temperature heat.

The syngas can be used in several ways. First, it could be used in the chemical industry or as town gas for heating and lighting purposes as done in the nineteenth and twentieth century in Europe and Northern America. For these purposes syngas derived from coal has subsequently been replaced by oil, natural gas and electricity, but China and India are currently increasing coal based town-gas production, because of the large amounts of coal and the lack of domestic natural gas reserves to deliver clean energy for the cities; see Grimston (1999, p. 49). Second, the syngas can be combusted for the production of electricity within a combined cycle. Both alternatives of using syngas are not intended for the capture of CO_2.

The third alternative is to produce pure hydrogen, which could be used for several purposes. Fourth, the syngas can be used as the essential input for the so

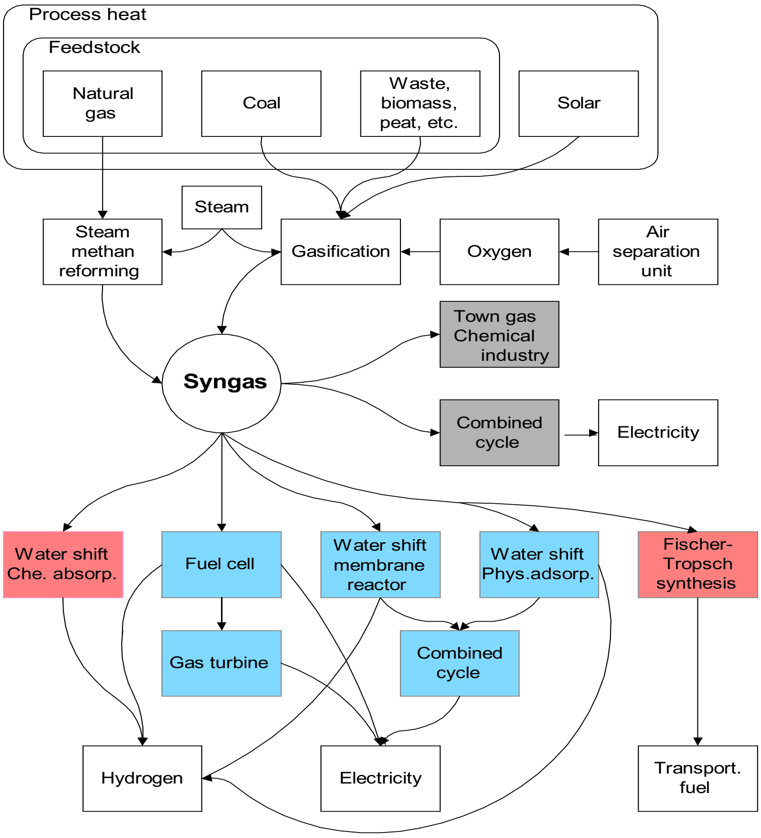

Figure 5.11: The production of syngas from various feedstocks, heat sources, processes and utilisation. Grey indicates that carbon capture is not possible for these routes, red denotes alternatives where carbon capture is optional and blue indicates that the development and utilisation of these processes is motivated by the ease of carbon capture. Source: based on Yamashita and Barreto (2003, p. 4).

called Fischer-Tropsch synthesis to produce liquid transportation fuels.[18] In these two approaches the capture of CO_2 is optional, but not intended.

The fifth alternative is to produce hydrogen using a shift reaction, where the CO_2 can be captured using either physical adsorption or gas separation membranes. The hydrogen is then either directly used for electricity production in a combined cycle or other purposes. Sixth, a related route is to use a fuel cell for electricity production, which produces a gas stream of concentrated CO_2 by default, but still contains

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[18] Two alternative processes to produce methanol out of syngas within a biomass gasification and hydrogen/methanol production plant are outlined in Hamelinck and Faaij (2002). The authors suggest these processes to become economical options in the future.

energy rich gas shares. The remaining energy content in these off-gases can be used either for further electricity or hydrogen production; see e.g. Göttlicher (1999, p. 48 – 53), Jansen and Dijkstra (2003) and Maurstad et al. (2004). Both types of industrial plants are motivated by the integration of carbon capture, because of the relatively low – but still considerable – extra effort.

The application of the first two alternatives is not motivated by carbon capture. The next two alternatives could be augmented by carbon capture, while the last two alternatives are primarily motivated by it. The production of transportation fuels and hydrogen for utilisation in the household sector are product NDs. The production of electricity or hydrogen for other industrial processes belong to the process NDs.

In the following the production of syngas is described (Ch. 5.1.5.1). Then the capture of CO_2 and simultaneous production of hydrogen is introduced (Ch. 5.1.5.2). After that the integration of syngas production into coal power plants with and without carbon capture is presented (Ch. 5.1.5.3). The use of syngas with fuel cells is introduced in Ch. 5.1.5.4. Then the use of syngas from an iron BOF combined with carbon capture is analysed in Ch. 5.1.5.5. After that the production of transportation fuels from syngas with integrated carbon capture is discussed; see Ch. 5.1.5.6. Finally, the results are summarised and discussed in Ch. 5.1.7.

5.1.5.1 Production of Syngas

There are mainly two processes for the production of syngas. First, steam methane reforming (SMR) and second the gasification of solids, which are both in operation today. There are alternatives that are at a more speculative level, but the following is limited to SMR and then gasification.

Producing syngas by steam methane reforming SMR is a well known process. There are about $8GW_t$ SMR capacity world wide. Methane and steam react to CO and H_2 under high temperature of 800 – 900°C.[19] There are no considerable technical problems with SMR, since natural gas is comfortable to handle. This is different in coal gasification, which is treated at some length next.

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[19] In Ch. 5.1.3.1 a SMR plant with CO_2 capture by chemical absorption has been described. Göttlicher (1999, p. 25) and Yamashita and Barreto (2003) also consider the water shift reaction, physical adsorption of CO_2 and subsequent physical pressure swing adsorption (PSA) (see Appendix to the Chapter below) for the purification of hydrogen.

The term gasification means that a solid or highly viscous feedstock is transformed into syngas. The input to gasification could be any carbon based energy carrier: biomass, waste, sewage sludge, refinery residuals, peat and coal. Combinations of these feedstock are possible. Fossil energy carriers dominate the gasification as input with $\sim$90% for the cumulative existing gasification plants of 32GW_t in 2000; see Stiegel and Maxwell (2001, p. 81).

Gasification is by no means a novel process. It has been used for the production of town gas. Moreover, gasification processes are integrated in petroleum refineries. Gasification has been used to produce synthetic transportation fuels from coal in Germany, South-Africa and other countries. Five pilot power plants based on coal gasification have been built. Additionally, the blast furnace for iron production is essentially a gasifier. DTI (1998) lists 125 gasification plants primarily applied in refineries in order to utilise the heavy residuals that would otherwise be waste. Stiegel and Maxwell (2001, p. 80) note that there are 366 gasifier in 128 industrial plants.

If carbon capture shall be introduced in these processes, additional process steps are necessary that will be described in Ch. 5.1.5.2. The extra effort of carbon capture is related to the characteristics of the gasification process: the feedstock, the syngas mixture resulting from the gasifier, the energy efficiency, the investment costs and the steadiness of operation. Therefore the focus is on this issue in the following.

There are several variants of gasification; overviews are given in Diekmann and Heinloth (1997, Ch. 4), DTI (1998) and Tsatsaronis (2003, Ch. 9). Existing gasification technologies, which are deployed commercially, are not suitable for using low-grade coal or even biomass at small scales; see Stiegel (2002).

Technically, gasification denotes a set of chemical reactions that require energy and can be controlled by variation of temperature and inputs. Gasification reactions require high temperatures of 500 – 1400°C. The higher the temperature, the higher are the shares of the preferred gases H_2 and CO. Above 1200°C the syngas mainly consists of H_2 and CO; see Göttlicher (1999, p. 69 – 71).

The main characteristic distinguishing gasifiers is related to the source of the process heat. If gasification is based on feedstock combustion, it is called direct internal combustion (DIC), where $\sim$10% of the feedstock have to be combusted and the resulting CO_2 is contained in the syngas. Alternatively, in the indirect external heat (IEH) approach the process heat stems from an external source; e.g. solar.[20]

Second, DIC gasifiers can be distinguished whether the combustion process within the gasifier is air or oxygen-blown. The choice between these two variants depends on the valuation of the higher efficiency of the oxygen-blown gasifier that trades off with the requirements of an air separation unit ASU; see Sec. 5.1.4 for details on ASU. The reason for the higher efficiency of oxygen-blown gasifiers is that nitrogen in the air has not to be heated, thereby reducing the energy own-consumption of the process. Oxygen blown gasifiers are attractive for carbon capture because the nitrogen is also excluded in subsequent process steps, which reduces the extra effort of carbon capture. The amount of air or oxygen blown into the gasifier regulates the reactor temperature and the amount of feedstock that is combusted.

Studies that deal with carbon capture assume DIC oxygen blown gasifiers. Tab. 5.5 gives an overview of the main processes of that type that are reviewed next.

An important approach employed in existing gasification plants is the Lurgi-process – also known as moving-bed gasification – producing syngas consisting of a one to one (or one to two) mixture of hydrogen and carbon monoxide.[21] Fig. 5.12 illustrates the process. The composition and temperature of the syngas depends on the properties of the coal and on selected operation conditions, like coal feed-rate, feed temperature and pressure; see Diekmann and Heinloth (1997, Ch. 4), Coetzer and Keyser (2003).

Fig. 5.12 illustrates the scheme of a Lurgi gasifier. Pulverised coal is fed from above into the coal lock. From there it is distributed into the gasifier and moves downward. On its way down it is first dried and then gasified. Particles moving down further are combusted and deliver process heat for the gasification and drying process. A mixture of steam and oxygen is fed from the bottom (green arrows)

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[20] Another source of process heat could be the high temperature reactor; see e.g. Häfele (1976) and Häfele (1990). However, the development of this technology has been cancelled because it has not been successful.

[21] This approach has been used in Sasolburg and Secunda, South Africa, during the apartheid era, when the country was faced with an embargo and utilised local coal to produce 230000 tons of liquids per year or 60% of the transportation fuels; see Diekmann and Heinloth (1997, p. 88) and DTI (1999). Today, 30Mt of bituminous coal are gasified per year in 97 Lurgi gasifiers in South-Africa; see Coetzer and Keyser (2003). During the era of Nationalsozialism in Germany some, 4 million tons of liquid were produced until the end of World War II, which amounts to 90% of all transportation fuels in Germany in that period; see DTI (1999).

Table 5.5: The main processes of direct internal combustion DIC gasification. Source: DTI (1998).

	Entrained flow	Fluidised bed	Moving bed
Fuel Types	Solid, liquid, oil-feedstocks	High ash coal, lignite, waste, biomass	Coal, waste
Oxidant	O_2	Air	O_2 & steam
Ash impurities	Removed as molten slag	Unmolten solid ash	Unmolten solid ash
Fuel size	<0.5mm	0.5-5mm	5-50mm
Fuel residence time	1-10s	5-50s	15-30min.
Operation temp. (°C)	>1000	<1000	500 – 1000
Gas outlet temp. (°C)	900-1400	700-900	400-500
Energy efficiency			High
Field of utilisation	Refinery IGCC	IGCC, KoBra[a]	Town-gas, chemicals, IGCC
Variants	Texaco, Shell[b], PRENFLO®, Destec	HTW[c], MBEL[d], ABGC[e], IGT[f] KRW[h]	Lurgi dry ash, BGL[g]

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[a] German acronym for Integrated Lignite Gasification Combined Cycle. This approach will be pointed out in Sec. 5.1.5.3.

[b] 100 units of Texaco and Shell in operation worldwide.

[c] HTW is High Temperature Winkler.

[d] MBEL is Mitsui Babcock Energy Ltd.

[e] Originally developed by the British Coal Cooperation. Now owned by a consortium of MBEL, Alstom and Scotish Power.

[f] IGT is Institute of Gas Technology. Appropriate especially for biomass gasification; see Hamelinck and Faaij (2002).

[g] British Gas Corporation and Lurgi; this is different to the original Lurgi dry ash gasifier in that it melts the ash and forms slag.

[h] KRW is Kellogg-Rust-Westinghouse.

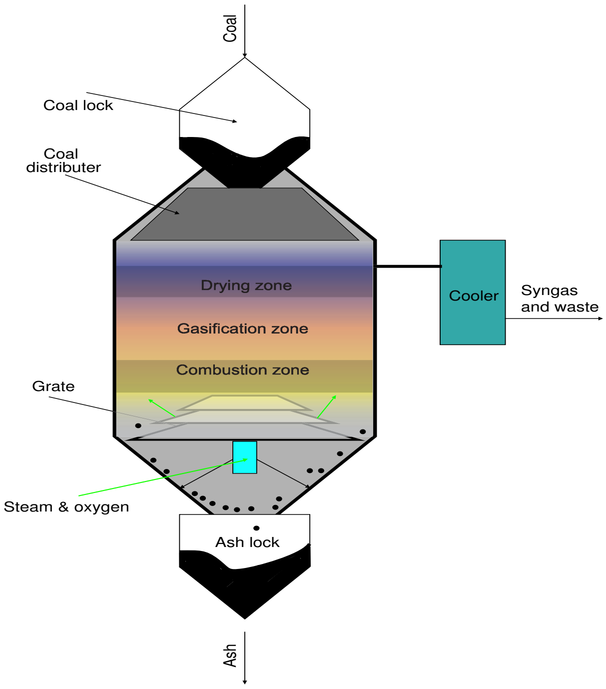

Figure 5.12: Scheme of a Lurgi gasifier. Source: DTI (1998).

into the reactor for combustion and for oxidisation. Ash moves through the grate and is collected in the ash lock below the entrance of oxygen and steam. The main control issue is that the amount of oxygen has to be low enough in order not to burn all of the fuel, but enough to produce the process heat for gasification. The hot syngas dries the coal and moves outward. The outgoing syngas has to be cooled for subsequent cleaning; this step will be discussed below.

The Lurgi process operates at (relatively) low temperatures and does not melt the ash in the coal. This implies that the Lurgi gasifier is not appropriate for ash-rich coal with a low melting-point of the ash. The melting of ash consumes a considerable amount of energy and reduces the overall efficiency of the process. This problem is important for entrained flow gasifiers discussed below.

A Lurgi gasifier operation can be found in Beulah, North Dakota. In this plant lignite is gasified primarily for synthetic fuel production and methane, which is mixed with conventional methane gas. 6Mt lignite are gasified per year. The original construction costs of the total plant were 2bil.$US and operation started in 1984.[22]

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[22] It had been a strategic reaction to the high oil prices in the early 1970ies. In this plant CO_2 is captured and transported to the Weyburn oil field in Saskatchewan, Canada, for enhanced oil

In fluidised-bed gasifiers the temperature ranges from 700 to 900°C, which is sufficient for biomass gasification; see Wokaun (1999) and McKendry (2002). The technical difference compared to the Lurgi-gasifier is that both, the feedstock and the steam/oxygen mixture, are fed in from below and that the combustion process is a fluidised-bed combustion. Fluidised-bed combustion can reduce the amount of sulphur impurities in the outgoing syngas stream, if an inhibitor like lime is added to the feedstock. The sulphur reacts with the lime and can easily be removed. This makes this option attractive for high-sulphur feedstocks.

The entrained flow gasifiers require the most extensive pre-treatment of the feedstock, work at the highest temperatures and pressures and are designed to remove impurities and ash in molten form, which is energy-intensive. Usually, this type of gasification is used in refinery operations, where petroleum residuals are the feedstock, and it is most often proposed for IGCC plants; see Ch. 5.1.5.3. The syngas contains 75 – 80% of the energy content of the coal; see Hendriks (1994, p. 148). The gas outlet temperature of 900 – 1400°C is higher than for the other two types. Prior to the cleaning of the syngas it has to be cooled down from these high temperatures.

The entrained flow gasifiers are the most steadily working gasifiers in terms of volumes and energy flow. This makes them particular suitable for electricity production (described in Ch. 5.1.5.3), but their drawback is that the heat consumption is highest. There is some dispute which of the entrained flow gasifiers is the most suitable for delivering the syngas for that utilisation, which is discussed in some detail next.

Hendriks (1994, Ch. 6) reports syngas shares of the Shell and the Texaco-type entrained-flow gasifiers. The study assumes the costs to be the same for both types. The syngas shares are given in Tab. 5.6. Although the Texaco type plant seems to have a better performance in terms of the hydrogen share, Hendriks (1994) proposes the use of a Shell based plant, because the oxygen requirement is 18% higher for the Texaco-type. This is in correspondence with the higher share of CO_2, due to the fact that more of the original feedstock has to be combusted.

A different view is provided by Davison et al. (2003), who analyse coal gasification and subsequent power production with and without carbon capture. Their study focuses on the investment costs related to the gasifier. It finds that the investment costs of the Shell gasifier are higher, which is not offset by the higher energy

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recovery; see Sec. 5.5.4.

Table 5.6: Comparison of syngas shares and investment costs in $\frac{\$\mathrm{US}}{\mathrm{kW}e}$ of the Texaco and Shell-type entrained flow gasifiers. Source: Hendriks (1994, p. 163) and Davison et al. (2003).

	H_2	CO	CH_4	CO_2	other	$\iota_{w/oCCS}$	$\iota_{withCCS}$
Shell	30.4	63.5	0.0	1.2	4.9	618.6	821.
Texaco	35.8	54.2	0.2	8.7	1.2	514.6	435.6

efficiency. The result is the same for both cases with and without carbon capture. The investment costs ι of the gasifiers are reported in Tab. 5.6. The unit is in terms of the electric power units $\mathrm{kW_e}$. A similar study by Holt et al. (2003) confirms these results. Moreover, this study found that investment costs increase with decreasing coal quality.

A problem that is common to all DIC gasification processes and related to the feedstock is the cleaning of the syngas – especially SO_2 and dust – for subsequent utilisation. This cleaning stage in the overall process is important, because the gas has to be cooled to about 200°C. This has a negative impact on the energy efficiency of the process, although the energy can be recovered for other purposes trough heat exchangers. Hot gas cleaning is seen as a high priority coal gasifiaction.

A promising approach for IEH gasification of solid fuels is solar cracking of coal that is pursued at the ETH Zürich and PSI, Villigen, in Switzerland; see Zedtwitz and Steinfeld (2003). The main advantages compared to DIC gasification are fourfold. First, the discharge of air pollutants is avoided, because none of the feedstock is combusted. This avoids, second, the cleansing of the syngas. Third, the energy content of the syngas is *upgraded*; i.e. the energy content of the outgoing syngas is higher than that of the feedstock. The avoidance of combustion, fourth, does not mix the syngas with nitrogen, nor is the ASU needed. This eases carbon capture.

Solar heat is generated using a solar tower or a solar tower-reflector system for large scale collection and concentration of solar energy. The system uses either parabolic mirrors or hyperbolidiale reflectors, respectively. The process is illustrated in Fig. 5.13 and described in the following. The solar heat is inducted into the solar reactor with a solar energy absorption efficiency of 91%. The carbon based reactant and steam enter the reactor at temperatures of 27°C and 1077°C, respectively.

In summary, the production of syngas from fossil fuels and other feedstock like biomass is operational. The gasification of coal for subsequent carbon capture re-

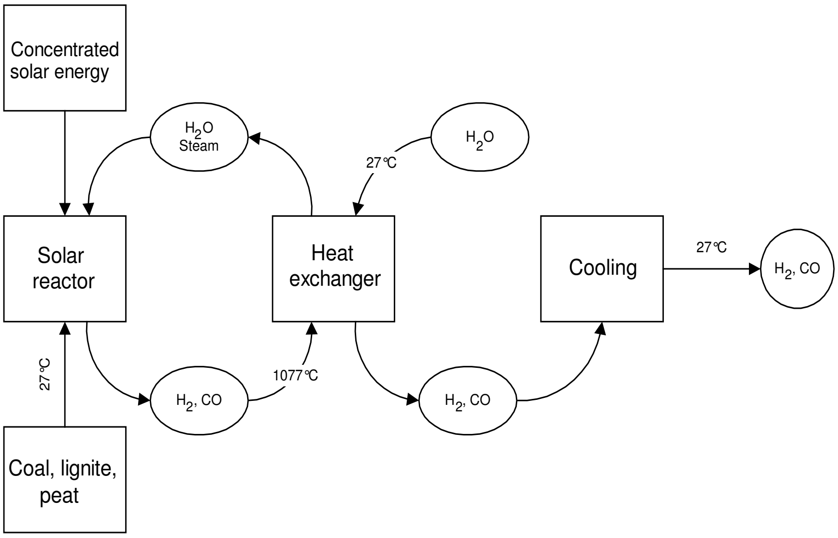

Figure 5.13: Scheme of a solar cracking gasifier. Source: Zedtwitz and Steinfeld (2003).

quires oxygen-blown gasifiers. The choice of a gasifier, when subsequent carbon capture is considered, is disputed and the implications for the investment costs are considerable.

5.1.5.2 Carbon Capture and Hydrogen Production

Several industrial plant types with carbon capture following the syngas concept integrate the combined production of hydrogen and capture of CO_2. As laid out above, the hydrogen could either be sold as an intermediate good or it could be used in subsequent process steps.[23] This sub-section introduces the techno-economics of combined hydrogen production and carbon capture.

Two approaches are mainly discussed in the literature:

1. shift reaction and subsequent physical absorption;
2. separation by a membrane and optional simultaneous shift reaction in a reactor.

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[23] Today, hydrogen is an important ingredient in the chemical and refinery industry. The overall capacity is $133GW_t$ or $75GW_e$. The production capacity for hydrogen from natural using SMR is 300MW; see WBGU (2003, p. 86). It is used for the production of ammonium (~50%), petroleum refinery (~37%) and methanol (~8%). There exists a total of 1200km hydrogen pipelines in the USA, Germany, The Netherlands and Great Britain.

In the first approach the shift reaction converts the CO with steam into CO_2 and hydrogen in the presence of appropriate catalysts; the resulting gas stream is labelled shifted syngas. After that the CO_2 shifted syngas is separated by physical absorption. The remaining gas stream consists primarily of hydrogen. Moreover, cleaning of the gas stream is necessary either before or after the shift. This is necessary because SO_x and dust would damage equipment of subsequent production steps or commercial standards; and environmental regulations would impose the cleansing anyway. An important problem of cleansing is that the gas stream has to be cooled before, which implies loss of useful energy.

The shift reaction could follow the gas cleansing or *vice versa*. The sequence depends on the catalysts used for the shift reaction, since some are sensitive with respect to sulphur while others are not. The shift reaction requires temperatures of 180 – 500°C and the pressure is ~25bar.

The shift reaction is a considerable extra effort with respect to energy. About 10% of the energy content of the syngas stream is not contained in the shifted syngas; see Hendriks (1994) and Chiesa et al. (1999). This extra effort has two aspects. First, about 2/3 of the energy loss of the water-shift reaction are due to the fact that a high conversion rate of CO and H_2O into CO_2 and H_2 requires excess steam relative to theoretical needs. This implies that more steam than necessary is heated in the shift reactor; see Göttlicher (1999, p. 23). Second, the shift reaction produces heat and therefore the shift reactor has to be cooled in order to keep the process temperature constant. Although the heat is recovered by producing steam, this is an energy loss because the steam is of relatively low quality.

The shifted and cleansed syngas consists primarily of H_2 and CO_2. This is introduced into the physical absorption process in order to capture the CO_2. The technical apparatus works like chemical absorption (see Ch. 5.1.3.1), but the energy demand is much lower. This capture process is viable because the pressure of the shifted syngas is above 10bar and the CO_2 share is high, but the gas stream has to be cooled down to 40°C. The cooling stages are combined with heat recovery by heat exchangers or steam generation. The hydrogen content of the CO_2 lean gas stream is about 80%.

The separation of CO_2 is an extra effort with respect to energy for three main reasons. First, the shifted syngas has to be cooled. Second, the gas separation process is based on the alteration of pressure. Third, removing the CO_2 from the stream of shifted syngas reduces the pressure of the remaining gas stream, which is an additional energy loss of about $0.1\frac{\mathrm{kWh}}{\mathrm{kgC}}$; see Göttlicher (1999, p. 12).

The CO_2 compression requirements for pipeline transportation are lower in comparison to other capture concepts because the pressure of the captured carbon is already above atmospheric pressure. Hendriks (1994, Ch. 5) notes that half of the CO_2 is released at atmospheric pressure of 1bar and the other half at 4bar. Although the target pressure for pipeline transportation is 80bar, the difference is significant, because the energy and capital requirements increase logarithmic with the ratio of inlet and outlet pressure; see Sec. 5.2.

There are other ways of capturing the carbon after the shift reaction that are of minor importance because the energy loss is higher. One example are chemical absorption based gas separation processes, membranes etc., which are not treated here.

The second main route to CO_2 capture is application of a hydrogen separation membrane (HSM). In this approach, the hydrogen is separated from the gas stream by gas separation membranes GSM; see Ch. 5.1.3.1. Using membranes it is easier to separate the hydrogen from the gas stream rather than the CO_2 due to technical features.

Fig. 5.14 illustrates the design. The pressurised syngas is introduced into the membrane chamber. The hydrogen permeates through the membrane depending on the pressure of hydrogen.[24] The permeated gas is rich in hydrogen; the share depends on the membrane used. The CO from the gasifier is contained in the residual gas stream alone with some rests of hydrogen (about $4-5\%$). The study by Hendriks (1994, Ch. 6) found that about 1/3 of the energy is contained in the hydrogen rich permeate gas stream and 2/3 are contained in the residual gas stream. Therefore, the residual gas is combusted in an oxygen-blown gas-turbine. This off-gas then consists nearly exclusively of CO_2.

A major problem is that the residual gas has to be combusted in oxygen in order to attain highly concentrated CO_2. As has been pointed out in Ch. 5.1.4, the production of oxygen requires considerable amounts of capital and energy. The need for the production of oxygen can be reduced by improving the selectivity of the membrane for hydrogen. If the share of valuable gases that are contained in the

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[24] Gasifiers with high shares of hydrogen are preferred; Tab. 5.6 shows that the Texaco gasifier is preferable to the Shell gasifier with respect to this criterion.

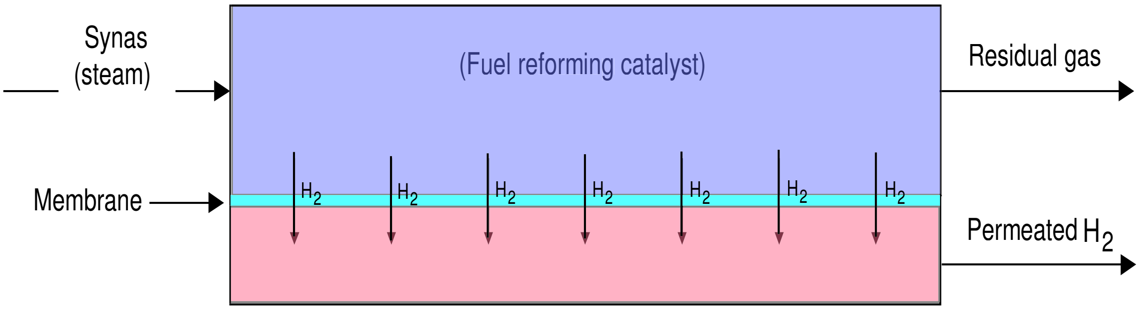

Figure 5.14: Scheme of a hydrogen separation membrane HSM and optional augmentation by integration of the water shift reaction to increase the separation of hydrogen indicated by (·). Source: Damle and Dorchak (2002).

residual gas is decreased, less oxygen is required.

There are two ways to deal with this problem. First, the share of hydrogen that permeates through the membrane can be increased. Second, the water-shift reaction is implemented within the reactor in order to convert CO with water into H_2 and CO_2. The reaction increases the pressure of hydrogen, which permeates through the membrane. This is called hydrogen separation membrane reactor (HSMR).

This approach forms a field of current research. Damle and Dorchak (2002) give an overview of research activities and related problems. Jordal et al. (2002) do emphasise the development of new membranes operating at high pressure and temperature, which improve the performance of the HSMR.[25]

The production costs of hydrogen by SMR are $5 - 6 \frac{\$US}{GJ}$, if the natural gas price is assumed at $3 \frac{\$US}{GJ}$; see Kaarstad and Audus (1997). WBGU (2003, p. 86) reports the costs at $11 \frac{\$US}{GJ}$; the production costs of hydrogen using electrolysis are twice. A detailed analysis using discounted cash flow financial modelling provided by the Foster Wheeler Company, who operate a SMR plant, is given in FosterWheeler (2001).

Yamashita and Barreto (2003) provide an overview on the production of hydrogen from different technologies with and without carbon capture. The results are summarised in Tab. 5.7. The study does not identify economies of scale for hydrogen production.

Hydrogen as an energy carrier is important for four distinct purposes. First, hydrogen could be used as an energy carrier in small installations like cars, houses and laptops. Second, the hydrogen is used as an energy carrier for electricity production;

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[25] Kreutz et al. (2002) and Kaarstad and Audus (1997) provide preliminary economic studies.

Table 5.7: Technical and economic features of hydrogen production processes without (Ref.) and without (Cap.) carbon capture. For natural gas base SMR a price of $3.1\frac{\$US_{2000}}{GJ}$ and a load factor of 80% is assumed. For coal gasification a price of $1.3\frac{\$US_{2000}}{GJ}$ and a load factor of 90% are assumed. The discount rate is 15%, the electricity price is $40\frac{millsUS_{2000}}{kWh_e}$ and the CO_2 is compressed to super-critical conditions. Source: Yamashita and Barreto (2003, p. 12).

	Feedstock ratio $\frac{GJ}{GJ_{H_2}}$	Electricity ratio $\frac{GJ_e}{GJ_{H_2}}$	Capture efficiency %	ι_{H_2} $\frac{\$US}{Nm^3H_2/day}$	H_2 costs $\frac{\$US}{GJ_{H_2}}$	Miti.[a] costs $\frac{\$US}{tC}$
Gas+PSA Ref.	1.23 – 1.35	-.018 – -.01	0	34 – 50	5.8 – 6.4	-
Gas+PSA Cap.	1.24 – 1.26	-.04 – -.07	70	39 – 45	6.6 – 7.5	65.
Coal+PSA Ref.	1.54 – 1.69	.037 – .081	0	101 – 112	6.6 – 7.5	-
Coal+PSA Cap.	1.29 – 1.86	-.176 – .054	87 – 92	108 – 133	7.6 – 11.	56.
Coal+HSMR Cap.	1.26 – 1.58	-.029 – .044	94 – 100	99 – 127	7.1 – 8.4	15.

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[a] Miti. is Mitigation.

this is the approach that will be presented in Sec. 5.1.5.3. Third, it can be mixed with natural gas: so called hythane contains 15% hydrogen, which implies the decarbonisation of methane. Hythane can be transported through existing pipelines for methane and it can be used fuelling cars; see Gaudernack and Lynum (1997) and Haines and Polman (2004). Finally, hydrogen could be used as a fuel for the combined production of heat and power at small to medium scales using solid oxide fuel cells (SOFC).

5.1.5.3 Integrated Coal Gasification Combined Cycle

The integrated coal gasification combined cycle IGCC approach is primarily motivated by the technological development of highly efficient gas turbines GT and the development of the natural gas combined cycle NGCC power plants. The IGCC approach applies the NGCC process design for using coal in the combined cycle. The coal has to be gasified and cleansed for the utilisation in the GT. Therefore, a gasifier and several cleaning processes have to be integrated into the process design.

The major problem of using gasified coal in gas turbines is that the hot gas produced in the gasifier has to be clean because of the vulnerability of the GT blades. Gas cleansing processes require gas cooling because hot gas cleaning is yet not an available technology. The several cleaning stages to remove ash, sulfur etc., the gasification and the combined cycle constitute a complex design that is hard to

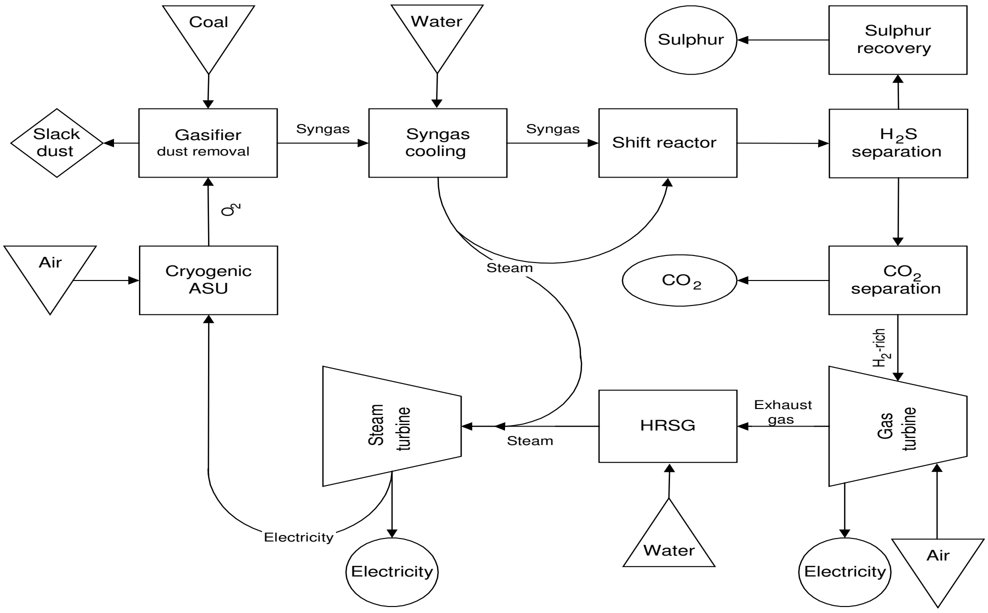

Figure 5.15: Scheme of an IGCC with shift-reaction and physical absorption, sulphur removal, CO_2 capture and a cryogenic ASU. The boxes indicate the following: ☐ is a technical process, ◯ is a saleable product, ◊ is a non-saleable output, ⬭ is a gaseous output not saleable, ▽ is an input. Source: based on Hendriks (1994, p. 114).

operate without interruptions.

The IGCC approach has advantages and drawbacks. The first advantage is that all technological progress from GT improvements can be used in IGCCs. The increased efficiency leads to lower fuel costs and environmental damaging emissions. Second, the need to cleanse the coal after the gasification brings ancillary environmental benefits; espec. with regard to SO_2.

The drawbacks are at first the high initial investment costs. Second, the IGCC concepts considered oxygen-blown gasifiers. Therefore, an air separation unit ASU is required, which increases the electricity own consumption and the investment costs. Third, the reliability of IGCCs developed so far is low; e.g. the Buggenum plant has had about 57% load factor for 1997 – 2001; see Hannemann et al. (2002). Fourth, the plants are low in flexibility, because the start-up times are very high (up to two weeks). This is especially due to the complexity of the process design and the requirement that all components have to work simultaneously; see DTI (1998).

There are five pilot plants in operation today with installed capacities in the range of 100 – 300MW$_e$, the efficiencies are at 39 – 43% and mostly oxygen blown[26]:

1. Wabash River, Indiana, with a Destec, oxygen-blown gasifier;
2. Tampa, Florida, with a Texaco oxygen-blown gasifier;
3. Buggenum, The Netherlands, with a Shell gasifier fuelled with high quality coal;
4. Puertollano, Spain, with a PRENFLO gasifier fuelled with low quality coal;
5. A relatively new project is in Pinon Pine, Nevada, which is based on a KRW air blown gasifier.

These pilot plants are not intended to capture CO_2. The motivation of their deployment was to increase the efficiency of using coal for power generation and to reduce the regional air pollutants. There is a market potential for IGCC without carbon capture, if carbon emissions has a price and the gas price is increasing. For the north-eastern US electricity market the potential for IGCC units until 2010 for IGCC is assessed by Stiegel and Maxwell (2001) for investment costs assumed at $1200\frac{\$\mathrm{US}}{\mathrm{kW_e}}$; the results are summarised in Tab. 5.8. Note that IGCC plants are competitive for moderately increasing gas prices, if the carbon price is high, but that the qualitative sensitivity of IGCC units with respect to the carbon price changes, if the gas price increase is very high.

If carbon capture is intended, the overall process design has to be augmented by an additional process step: the water-shift reaction of the syngas in order to produce a gas stream that mainly of consists hydrogen and CO_2, and to separate these two gases. A detailed overview of the overall process is given in Fig. 5.15. Note that the hydrogen rich gas is combusted in an air-blown gas turbine, since the CO_2 is removed prior to the combustion process. Therefore, some authors call this approach the pre-combustion capture. There are several techno-economic

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[26] In Japan an IGCC R&D-project is going on initiated by Mitsubishi Heavy Industries, which uses an air-blown gasifier; see Shinada et al. (2002). It is questionable whether air-blown gasification is appropriate for CO_2 capture, because the N_2 concentration in the gas stream is high, but investment costs and energy own-consumption is lower. A study by Doctor et al. (1997) suggests that the oxygen-blown route is more adequate for CO_2 capture, but air-blown gasification is preferred without CO_2 capture.

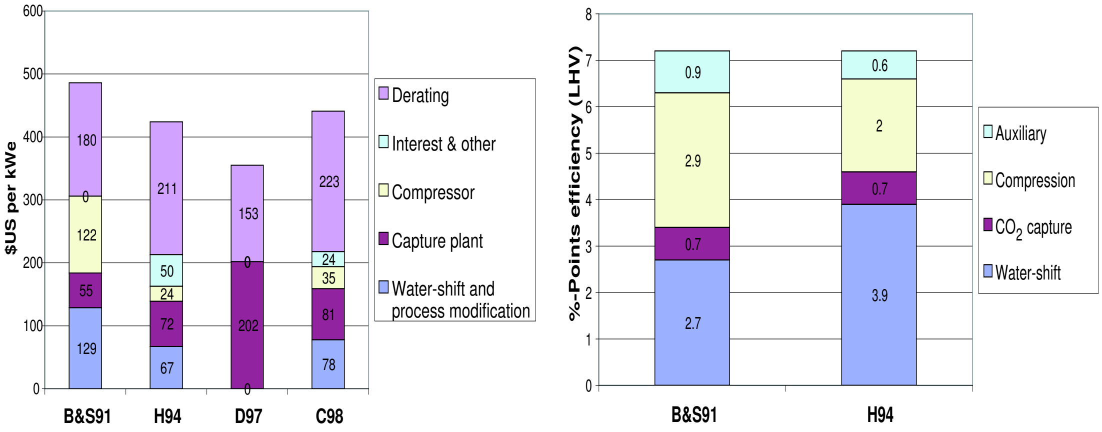
Table 5.8: Market potential for IGCC plants without carbon capture in North-East US under varying circumstances of growth rate of gas price per year and carbon tax in $US per tonne of carbon; numbers indicate the numbers of IGCC plants for base-load. Source: Stiegel and Maxwell (2001, p. 96).

		Carbon tax in $US per tC			
		0	25	50	100
Gas price increase in % p.a.	0.54	19	3	0	0
	1.5	64	38	7	0
	3.	65	66	64	25
	4.5	65	66	67	71

assessments for IGCC plants with carbon capture because it is seen as the most economic way of capturing carbon in coal fire plants. The studies are undertaken in the same way as those in Ch. 5.1.3.2; i.e. by applying simulation models. The study by Hendriks (1994, Ch. 5) ***H94*** is the only one that relates the reference plant to a real-world pilot plant; in that case Buggenum, The Netherlands. The studies are different with respect to the gasifiers and apply the concept of water-shift reaction and subsequent physical absorption for gas separation as presented in Fig. 5.15.

Fig. 5.16(a) compares the break down of the additional investment costs for some studies. Booras and Smelser (1991) ***B&S91*** has the highest costs, which is mainly due to the high costs for the compression plant and the water-shift reactor, but it ignores the interest payments and the CO_2 separation plant is the cheapest of all studies. The cost components in H94 and Chiesa et al. (1999) ***C99*** are quite similar. The study by Doctor et al. (1997) ***D97*** only took the capital derating and the CO_2 capture plant.

The break down of the energy efficiency losses is only provided by B&S01 and H94 and is presented in Fig. 5.16(b). The reduction of the energy efficiency in the IGCC power plant with carbon capture is mainly due to the water-shift reaction and compression. Hendriks (1994, p. 128) found that 3.9%-points efficiency reduction are attributable to the water-shift reaction and only 2.2%-points to CO_2 compression. The gas separation leads to a reduction of 0.7%-points, only. The overall efficiency reduction is the same in B%S91, but compression requires more energy than the water-shift reaction. The efficiency reduction due to carbon capture – in a narrow sense – has been reduced to 0.7%-points.



(a) Investment costs

(b) Energy requirements

Figure 5.16: Comparison of IGCC plants with additional carbon capture by B&S91, H94, D97 and C98.

The results of the water-shift and the compression are confirmed by a literature review by Göttlicher (1999, p. 27). But this study founds higher efficiency losses for the gas separation (2.5 – 3%). Moreover, there is a pressure loss due to the gas separation, which accounts for additional 0.8%-points efficiency loss; see Göttlicher (1999, p. 95).

The reduction of power plant efficiencies are about 7%. Some studies have much lower reductions like R95, D97 and T01 (about 4%) and some have much higher reductions S98 and A01 (about 9%). The low estimates seem questionable, since the requirements for compression and the water-shift reaction alone might even be higher.

The investment costs of the base case vary over a considerable range from 1265 – $1600\frac{\$\mathrm{US}}{\mathrm{kW_e}}$. The range of the relative increase of investment costs of 24.5 – 53% is also considerable and therefore the investment costs of the IGCC plant with carbon capture range from 1730 to $2400\frac{\$\mathrm{US}}{\mathrm{kW_e}}$. This is due to the speculative nature of new technologies. The studies do not exhibit a relationship of investment costs to the gasifier as is suggested by the studies of Holt et al. (2003) and Davison et al. (2003); see Ch. 5.1.5.1.

Table 5.9: Techno-economic assessments on IGCC plants without (Ref.) and with CO_2 capture (Cap.) using the syngas carbon capture concept. Source: based on David (1999) and David and Herzog (2001).

	B&S91[a]	H94	R95	D97	C99	S98	H00	A01
Gasifier	Texa.	Shell	N.A.	KRW	Texa.	N.A.	N.A.	Shell
Fuel cost (millsUS/kWh$_t$)	4.38	4.38	7.2	4.38	4.38	4.38	4.38	5.3
Load factor (%)[b]	0.75	0.75	N.A.	0.75	0.75	0.75	0.75	N.A.
Capital charge per year (%)	15.	15.	N.A.	15.	15.	15.	15.	10.
Compression (bar)	152.	80.	52.6	145.	80.	137.	80.	N.A.
Ref. efficiency (%LHV)[c]	36.8	43.6	41.7	38.4	46.0	47.3	42.0	46.
Cap. efficiency (%LHV)	29.6	36.3	37.1	35.0	39.3	37.2	35.4	38.
Energy penalty (%)	19.5	16.7	11.0	8.5	14.5	21.4	15.8	17.4
Δ efficiency (%-points)	7.2	7.3	4.6	3.4	6.7	10.1	6.6	8.
Ref. emission (gC/kWh$_e$)	236.7	207.3	N.A.	215.5	193.4	183.8	201.8	193.6
Cap. emission (gC/kWh$_e$)	28.6	10.9	N.A.	48.0	19.4	24.0	24.5	36.5
Δ emission (%)	87.9	94.7	N.A.	77.7	90.	86.9	87.8	81.1
Ref. COE K.[d] (millsUS/kWh$_e$)	36.5	28.9	N.A.	30.4	35.1	29.7	30.	27.
Cap. COE K. (millsUS/kWh$_e$)	49.1	41.1	N.A.	38.5	43.7	40.3	39.	41.
Ref. COE Fu.[e] (millsUS/kWh$_e$)	11.5	9.7	17.3	11.0	9.2	8.9	10.	11.5
Cap. COE Fu. (millsUS/kWh$_e$)	14.3	11.7	19.4	12.1	10.8	11.4	12.	13.9
Ref. COE O&M[f] (millsUS/kWh$_e$)	10.4	6.5	N.A.	9.3	7.1	7.9	6.	9.
Cap. COE O&M (millsUS/kWh$_e$)	18.8	9.4	N.A.	11.2	8.7	10.8	8.	14.
Ref. COE Tot.[g] (millsUS/kWh$_e$)	58.5	45.0	52.	50.7	51.3	46.5	46.	48.
Cap. COE Tot. (millsUS/kWh$_e$)	82.3	62.1	73.	61.8	63.2	62.5	60.	69.
COE[h] increase (%)	40.7	38.0	40.4	21.9	23.2	34.4	30.4	43.8
Ref. investment ($US/kWe)	1600.	1265.	1561.	1332.	1536.	1300.	1300.	1470.
Cap. investment ($US/kWe)	2152.	1799.	2400.	1687.	1913.	1767.	1730.	2200.
Δ investment (%)	34.5	44.2	53.7	26.7	24.5	35.9	33.1	49.7
Mitigation cost[i] ($US/tC) ($US/tC)	113.7	88.0	107.	66.0	70.0	99.0	77.	135.7

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[a] The studies are B&S91 $\widehat{=}$ Booras and Smelser (1991); H94 $\widehat{=}$ Hendriks (1994, Ch. 5); R95 $\widehat{=}$ Riemer and Omerod (1995); D97 $\widehat{=}$ Doctor et al. (1997); S98 $\widehat{=}$ Simbeck (1998); C99 $\widehat{=}$ Chiesa et al. (1999); H00 $\widehat{=}$ Herzog (2000); A01 $\widehat{=}$ Audus (2001).

[b] Fraction of hours of a year ($8760\frac{\mathrm{h}}{\mathrm{y}}$) the plant is running.

[c] LHV is the lower heating value to measure the fuel input.

[d] COE K. are the costs of electricity due to capital.

[e] COE Fu. are the costs of electricity due to fuel.

[f] COE O&M are the costs of electricity due to operation and maintenance.

[g] COE Tot. are the total costs of electricity.

[h] COE is the costs of electricity.

[i] The mitigation costs are computed as follows: (Cap. COE Tot. – Ref. COE Tot.) $\cdot$ (Ref. emissions – Cap. emissions)$^{-1}$.

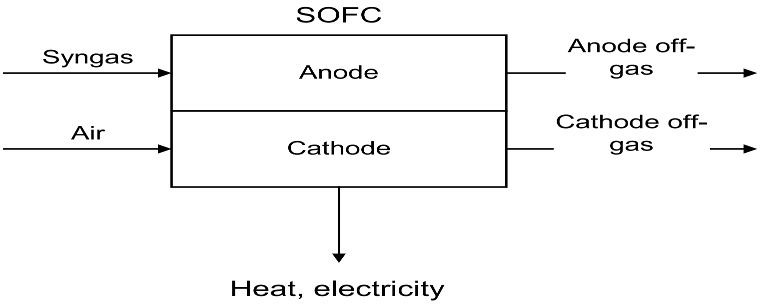

Figure 5.17: Scheme of a SOFC with emphasis on the gas streams. Source: Maurstad et al. (2004).

5.1.5.4 Solid Oxide Fuel Cells

Solid oxide fuel cells SOFC offer the possibility to capture carbon with very little extra effort. This is mainly due to the fact that SOFC bring the fuel in contact with oxygen in the air without mixing and thereby producing high temperature heat and electricity. The approach is speculative because the price of SOFC is high and the technical lifetime is short. It is uncertain to what extent both impediments could be improved. The technology is introduced and an overview of the costs and forecasts of investment costs of SOFC is provided in the following.

Fig. 5.17 illustrates the principle of a SOFC: the syngas enters the anode, while air enters the cathode. The SOFC produces heat and electricity. The anode off-gas is rich in CO_2 and the cathode-off gas is rich in nitrogen and exhausted in oxygen. The gas streams in the SOFC are not mixed and therefore the anode off-gas does not contain nitrogen. This is a technical feature of the SOFC, which does not require additional effort. Moreover, this allows high shares of captured carbon.

The integration of a SOFC within a power production plant requires three things. First, cleansing of the syngas is required, if it comes from a coal fuelled gasifier in order to prevent damage of the SOFC. Second, the SOFC does not convert all energy containing gas. Therefore, anode off-gas should be utilised; this is similar to the hydrogen separation using membranes in Ch. 5.1.5.2. The heat produced by the SOFC has to be integrated into the plant design; e.g. it is necessary to pre-heat and pressurise the air stream that enters the SOFC.

The choice of the fuel is crucial. So far, technical studies focus on natural gas, which is easier to handle compared to coal. Jansen and Dijkstra (2003) and Maurstad et al. (2004) for example assume natural gas as input.

The efficiency reduction due to carbon capture is relatively low. Maurstad et al. (2004) focus on several variants of utilisation of the anode off-gas within a computer based simulation study. They find a range of efficiency reductions of 3.1 – 5.7%-points compared to the reference plant that exhibits 70.5% efficiency. This includes the compression of captured CO_2 to 200bar, which accounts for 2.5%-points of the efficiency reduction.

The study by Jansen and Dijkstra (2003) applied computer simulation methods, too. The natural gas fuelled reference plant exhibits an efficiency of 67.2%. The integration of carbon capture reduces the efficiency by 6.5%-points, of which compression accounts for 1.7%-points.[27]

Economic assessments of SOFC based power plants are inherently speculative. Today the investment costs of SOFC are high and the technical lifetime is short. The SOFC unit is the essential component of the total power plant investment costs. The following provides an overview of current investment costs today and forecasts for the future.

The current cost level is reported to be at 3000 – 5000$US per kW; see Bessette et al. (2001) for the higher end and Massardo et al. (2003) for the lower end. The German Federal Ministry for Economics – noting the great uncertainty – estimated the costs at even 10000$US/kW and emphasised that the lifetime of a SOFC rarely exceeds five years. Competitiveness is reached at 1250$US/kW; see BMWi (2001). The Entwicklungsgesellschaft Dresden, Germany, assumes investment costs at 3000 – 4000US/kW_e$ to be competitive; see Enwicklungsgesellschaft-Dresden (2003).

The future expectations on SOFC investment costs are also speculative. At Forschungszentrum Jülich, Germany, it is assumed that the target costs cannot be lower than 1000$US/kW; see FZ-Juelich (2003). At US-DOE a newly established project called SECA (Solid State Energy Conversion Alliance) proposed target costs of 400$US/kW for small capacities of 3 – 10kW$_e$; see SECA (2003). A project at EPRI (Electric Power Research Institute) concluded that a target cost of 500$US/kW is achievable; see EPRI (2002). A pessimistic view is kept by Massardo et al. (2003), who estimate the minimum achievable costs to be at 1500$US/kW. Enquete-Kommision (2002) reports the investment costs at 1050$US/kW in 2010 and expected them to move downwards to 700$US per kW

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[27] The outlet pressure is not reported.

until 2030 at a lifetime of 15 years. The optimistic view came up ∼2 years ago and is justified by break-troughs in ceramic materials of which SOFCs are made.

This overview indicates that the future of power plants based on SOFC is uncertain. This is related to the reference case without carbon capture and to the plant with carbon capture. An economic assessment of a power plant utilising a SOFC is provided in Ch. 5.1.6 below; this capture approach is not based on the syngas.

5.1.5.5 Steel Production and CO_2 Capture

Iron production in blast oxygen furnaces BOF can be augmented by carbon capture with two different concepts. The post-combustion has already been introduced in Ch. 5.1.3. The second concept refers to the syngas approach. This is due to the fact that oxygen-blown furnaces are in essence gasifiers, in which coke coal is the feedstock.

The primary purpose of the combustion of the feedstock is to produce the process heat that is required for iron production. The flue gas of the furnaces is a syngas mixture, with considerable energy content that is recovered for utilisation.[28]

Gielen (2003) proposed to use the furnace gas for electricity production that is augmented by carbon capture. The furnace gas consists of 21% CO and 3% H_2, which contains 3MJ energy per m^3. For the efficient utilisation in a combined cycle process the energy content has to be increased by mixing the furnace gas with e.g. natural gas, in order to achieve efficiencies of 41 – 42%. The technical design of the combined cycle is simply an IGCC with carbon capture as already introduced in Ch. 5.1.5.3.

The study assumed compression of the CO_2 up to 100 bar. It found mitigation costs at 59 – 92$US per tC. This is in the range found for IGCC with carbon capture; see Tab. 5.9 on p. 201.

The study does not provide the assumption of an electricity price that lead to these capture costs. Since the study is applied to conditions in Japan, it might be at the higher end of electricity costs/prices found in the world. Moreover, the study does not take into account the opportunity costs that are due to alternative uses of the furnace gas.

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[28] In Germany the production of furnace gas has been 68TWh in 2000. This accounted for 6.3% of total gas consumption; see BMWi (2003, p. 23).

An additional problem of this approach is related to the relative competitiveness of iron BOF and the production of steel from scrap using electrical arc furnaces (EAF). The production using iron uses iron ore as input and requires additional process steps for the production of steel. The latter alternative is the technology of choice for steel production today due to higher flexibility in terms of scale and variations of output. Crompton (2001) notes that in 1970 the share of world steel production produced with EAF has been 15%. It has increased to 34% in 1997. The forecasts assess this share to increase in the future.[29]

It remains unclear which alternative – iron BOF with carbon capture versus EAF – is favoured when a carbon tax is introduced. Moreover, it is not clear whether the market share of iron BOF with carbon capture is a monotonous function of the carbon tax. This is a reasonable question because the competitiveness of technologies might be reversed, if the tax exceeds a critical level.

5.1.5.6 Fischer-Tropsch Synthesis: Production of Liquid Fuels

The production of liquid fuels for transportation including carbon capture will be studied in the following. These processes are based on oxygen-blown gasification and SMR technology. The objective is to produce straight-chain hydrocarbons that are liquid at ambient conditions; i.e. to produce a secondary energy carrier. The production process can be designed in order to capture carbon. When compared to the processes described above, an important feature is that only up to 30% of the carbon originally in the primary energy carrier can be captured, because the carbon is required to built the hydrocarbon chains.

The production of liquid fuels with integrated capture of CO_2 is viable for two processes reviewed in this section. First, the Fischer-Tropsch Synthesis and second the Carnol process.[30]

Syngas is used for the Fischer-Tropsch (FT) synthesis to produce liquid fuels for vehicles. In the FT process the syngas with a H_2:CO ratio of 1.7 – 2.1 reacts in presence of a catalyst to produce straight-chain hydrocarbons. The process operates at temperatures of 200 – 300°C and moderate pressure producing hydrocarbon chains

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[29] In the USA the share of EAF has been 43.8% and Japan 32.8%. Forecasts predict a rise of these shares to 50.1% and 36.5% in 2010, respectively.

[30] There is a great variety of liquefaction processes based on coal, reviewed in a technology report by DTI (1999).

Table 5.10: Techno-economic assessment on Fischer-Tropsch FT synthesis without (left) and with (right) CO_2 capture. Source: Marsh et al. (2002).

	O_2-blown, slurry reactor		O_2-blown fixed-bed reactor		air-blown, fixed-bed reactor	
Efficiency (% LHV)	56.1	55.0	54.8	55.6	53.7	54.5
C in feedstock (t/h)	63.2	63.2	63.2	63.2	63.2	63.2
C in product (t/h)	43.0	42.2	43.4	44.6	42.2	43.5
C to atmosphere (t/h)	20.2	6.0	19.7	1.9	21.0	8.9
C avoided	-	14.2	-	17.8	-	12.1
% reduction of C	-	22.5	-	28.2	-	19.1
Capital cost 10^6\$US	346.	389.	390.	446.	388.	428.
Product cost (\$US/bbl)[31]	24.5	28.7	26.4	29.5	30.2	32.6
Abatement cost (\$US/tC)	-	98.27	-	83.24	-	110.00

and heat. The heat is recovered and used to produce steam; see Ravikumar (2002).

Marsh et al. (2002) provide a techno-economic assessment considering three different process designs. The production capacity is assumed to be 10000 barrel per day (60% diesel and 40% naphta), which requires a capacity of $600MW_t$. Results on process and cost performance are given in Table 5.10. The cost performance in terms of \$US per barrel as well as the CO_2 mitigation costs are calculated. To assess the emissions from the refining process and the end-use in cars the authors calculated the well-to-wheel efficiency.[32] The liquids have to fulfill EU emissions standards. The base case is a conventional Middle East oil fuelled fleet of 1 million cars.

The calculations indicate that the greatest amount of CO_2 emissions per km arises from the vehicles rather than the refinery. In the base case 85% of the CO_2 emissions a generated from the cars; 63% in the FT case without capture and 78% with capture. The emissions of the FT fuel from the car is 21% less the reference case, but the difference is less, if the CO_2 emissions at the refinery are taken into account. Therefore, the advantage reduces to 15%. Without capture the emissions in the FT system are even 5% higher than the base case. CO_2 emissions would increase slightly, if FT fuels are introduced without capture and decrease when carbon capture is integrated. The economic assessment reveals that the plant specific mitigation costs

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[32] The well-to-wheel efficiency accounts for the transmission of energy from fuel combustion to output in terms of km travelled.

Table 5.11: Techno-economic assessment on an IGCC plant without CO_2 capture and an IGCC plant with CO_2 capture and Fischer-Tropsch FT synthesis. Source: Ravikumar (2002).

	IGCC no CO_2 capture	IGCC+CO_2 capture + FT synthesis
Electricity output [MWe]	503.	102.
Liquid output[barrel/day]	0.	7860.
CO_2 emissions [tC/d]	2824.7	310.6
Relative Total Capital	1.0	1.04
Base case ROE [%]	17.0	11.3
ROE liquid price 35$US/bbl [%]	17.0	13.2
ROE liquid price 40$US/bbl [%]	17.0	15.1
ROE electricity price 3cUS/kWhe [%]	14.0	10.6
ROE electricity price 4cUS/kWhe [%]	19.9	11.3
ROE carbon tax 33.3$US/tC [%]	11.8	10.7
ROE carbon tax 66.5$US/tC [%]	6.0	10.1

are less than $100\frac{\$US}{tC}$ for the oxygen-blown gasifiers.

Several authors propose to use the flexibility of syngas by producing several outputs from several inputs simultaneously. The advantage is that variations of the input and output ratios enable the firm to adapt to changes of market prices. Carbon capture can be integrated in order to address the problem of positive prices for carbon emissions as it is expected in the future. The problem in reviewing such studies is that the comparison among such studies is more difficult.

In the following two studies are reviewed on the co-generation of synthetic fuels with the FT-process and electricity production using a combined cycle. The combined cycle is fuelled by the syngas that is not used in the FT-synthesis.

A study by Ravikumar (2002) compares an IGCC[33] without carbon capture and an IGCC plant with CO_2 capture and FT synthesis. The criterion for assessing the relative profitability in that study is the return on equity (ROE); i.e. the net profits related to the share of market financed capital, given that all outputs are sold. He assumes fixed prices and taxes to compute the ROE for various assumptions of the exogenous parameters. The results are given in Tab. 5.11.

The assumptions are a loan-to-equity ratio of 70:30 and an interest rate of 8%. The base case assumptions are a price of electricity 3.5cUS per kWh_e, the price of liquids at 30$US per barrel and no carbon tax.

The base case IGCC is more profitable for standard assumptions. Variations in these assumptions show that the FT alternative becomes profitable in case of higher prices for liquids, but can not outperform the reference IGCC. The FT al-

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[33] The concept of IGCC has been explained in detail in Sec. 5.1.5.3.

Table 5.12: Techno-economic assessment on an IGCC plant without CO_2 capture and an IGCC plant with CO_2 capture and Fischer-Tropsch FT synthesis. Source: Yamashita and Barreto (2003, p. 24).

	FT capacity $\frac{TJ_{FT}}{d}$	Feedstock ratio $\frac{GJ}{GJ_{FT}}$	Electricity ratio $\frac{GJ_e}{GJ_{FT}}$	Capture efficiency %	ι_{Co-Gen} tril.$US	O&M costs $\frac{mil.\$US}{y}$
FT&IGCC	190.	2.2	.32	-	2.2	118.
FT&IGCC & capture	190.	2.2	.32	90.	2.5	123.

ternative becomes profitable when the carbon tax rises above ~40$US per tC, but its profitability decreases as well. A variation of the price of electricity has a more pronounced impact on the IGCC, because this is the only output.

These numbers indicate that the plant specific mitigation costs are quite low. The problem is that this study does not allow to compare the numbers to another benchmark. With regard to that point the study by Marsh et al. (2002) is preferable, because it takes into account a real world benchmark.

A second study on co-generation of electricity and transportation fuels is given by Yamashita and Barreto (2003). Since the design principle is the same as given above the results are summarised in Tab. 5.12.

Next, the focus turns to the second approach that proposes the co-generation of methanol, electricity and elementary carbon from hydrogen and CO_2. This approach combines a de-carbonisation process with the utilisation of captured CO_2, which results in a re-carbonisation of hydrogen. Effectively methanol is produced – a liquid energy carrier – which can be used for transportation.

The process and the corresponding numbers are taken from Steinberg (1997). CO_2 is captured at a power plant using chemical absorption described in Sec. 5.1.3.1. Hydrogen stems from oxygen-blown coal gasification with shift reaction. The hydrogen and CO_2 react in order to produce methanol, elementary carbon, water and heat. The heat is used to run the CO_2 capture plant and the elementary carbon is a saleable product, which can be used for tire production. Methanol can be used as a transport fuel.

The study uses computer simulations assuming a 900MW_e coal fired power plant with the option to add a chemical absorption based CO_2 capture technology with 90% of the CO_2 captured from the flue gas. The base case is a system without carbon capture and use of gasoline fuelling cars. The conclusion is that the whole system reduces the C-emissions per kWh output relative to the base case by 56%, if an internal combustion is fuelled with methanol, and by 77%, if a fuel cell car is fuelled with methanol. The methanol is delivered at 18$US per barrel.[34]

In summary, this subsection reviewed studies dealing with the production of transportation fuels and integrated carbon capture. The studies are on a preliminary level, yet, although there is considerable experience from producing liquid fuels from coal. The reason for their speculative nature lies in the choice of a reference case, because the produced fuels is not on the market, as crude oil derived gasoline is currently in use. The differences between these options is related to more than the comparison of two plant types, only. The overall infrastructure related to both fuels has to be changed. Therefore, the extra effort of carbon capture is difficult to assess.

Moreover, several authors – not all reviewed here – have proposed co- and multi-generation of products with various inputs. The problem of assessing the effort using such proposals is even more difficult, because inputs and outputs are difficult to compare. Assumptions of exogenous prices are hard to justify because espec. crude oil prices experience considerable and persistent ups and downs.

5.1.6 Zero Emission Coal

The ZECA approach[35] is an alternative option to use coal for power production including carbon capture. The difference to the capture concepts presented so far is that the overall design of the power plant deliberately produces a gas stream with high CO_2 concentration. The above processes always add one or more process component that produce a CO_2 concentrated gas stream, but this process component is always an extra investment and an extra energy consumer. The alternative approach discussed in this section reduces these extra efforts of the capture process to a minimum; with respect to the geological sequestration only the compression of CO_2 is still a necessary extra process.[36] This does not imply that the CO_2 capture

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[34] A further study using the Carnol process focuses on oxygen fuelled processes in combination with a magneto-hydro dynamic power generation in Ishikawa and Steinberg (1998).

[35] ZECA (Zero Emission Coal Alliance) is a collaboration of researchers and firms of the coal industry based at Los Alamos National Laboratory, USA. The alliance has been founded in 1999. Members are primarily coal firms from the US and Canada. The only non-North-American member is the German company Ruhrkohle AG Coal International; see RAG (2002, p. 70 – 72).

[36] Another alternative aiming at this particular goal is chemical looping; see e.g. Mattisson et al. (2001) and Ryu et al. (2002).

is for free because these new plants may be less economic compared to alternative power plants fuelled with coal.

The ZECA approach is based on a sequence of interacting reaction-recycling loops and deviates from the IGCC approach in at least two points. First, the gasification of coal does not require oxygen and therefore the air separation unit ASU is not required. Second, the hydrogen is not combusted for electricity production, but introduced into a solid oxide fuel cell SOFC.[37]

The following description of the interacting reaction-recycling loops follows Ziock et al. (2002). The process is illustrated in Fig. 5.18. Coal enters the gasifier, where it reacts with hydrogen. This produces CO_2 and methane and the reaction releases a small amount of heat. Therefore, water is introduced to keep the temperature constant. The gas mixture is cleansed and enters a carbonation stage. Here the methane reacts with steam to hydrogen and CO_2. The CO_2 reacts with lime (CaO) to calcium carbonate $CaCO_3$. Half of the hydrogen from the carbonation stage goes back to the gasifier, the second half is introduced into the SOFC after a cleansing stage. In the SOFC the hydrogen is converted to electricity and heat. The calcium carbonate has to be recycled into lime in the calcination chamber, where it releases the CO_2.[38] The heat for this reaction stems from the SOFC and is carried over by CO_2. The SOFC produces heat and electricity by contacting the hydrogen and the oxygen in air.

The essential feature with respect to the carbon capture is that the CO_2 is not mixed with the air, but leaves the SOFC separate in highly concentrated form; see Ch. 5.1.5.4. The electricity is delivered to the grid and heat is used to recycle the calcium carbonate into lime in the calcination chamber.[39] The excess CO_2 that is released in this recycling process is available for sequestration.

This approach inherently produces concentrated CO_2. Additionally, all sulphur

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[37] A third issue is that the ZECA approach involves the sequestration of CO_2 by mineralisation, i.e. the CO_2 reacts with abundant mineral materials in order form another mineral that is not harmful and stable for geological time scales. The problem with this approach is that the scale of masses, which have to be transported is extraordinary.

[38] An alternative approach to ZECA using carbonation-calcination cycle using traditional combustion is given by Abanades et al. (2002).

[39] Another field for SOFC naturally is the use within a gas turbine combined cycle. Such installations are plants to be introduced commercially at a 1MW level by Siemens for distributed electricity generation; see George and Hassmann (2001).

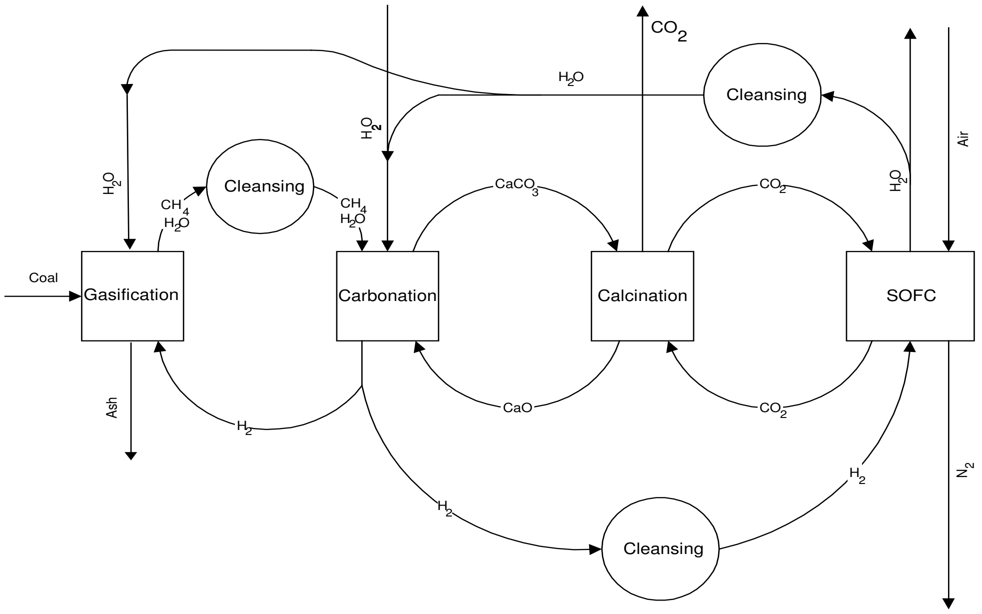

Figure 5.18: Scheme of ZECA with gasification and SOFC. Source: Ziock et al. (2002).

impurities have to be removed, because the SOFC would be damaged. The problem of NO_x is solved, which is a feature of the SOFC.[40]

Ziock et al. (2002) assert very high energetic efficiency and low costs of this process. Based on HHV[41] the overall efficiency is estimated to be at 68.9%. The installation costs are expected to be at 1518$US per kWh_e. The SOFC is the major cost component assumed at 893$US per kWh_e.

Assuming 12% discounting rate p.a. and a capacity utilisation of 90% the resulting production costs for electricity are at 4.32mills$US per kWh_e. This price includes a stream of pure, but uncompressed CO_2; see Mourits (2002) and Nawaz and Ruby (2002).

Therefore, the price assumption for SOFC in Ziock et al. (2002) is in the middle range of the prospects, but these targets are related to small installations far away from the $200MW_e$ scale that are proposed in the ZECA plant. It seems not possible to reach scale effects with SOFC, like it is typical for thermal power plants. This

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[40] NO_x are generated in a high temperature flame, but fuel cells convert the chemical energy of a fuel into electricity without combustion and heat.

[41] This is the higher heating value of a fuel. Usually, the efficiency of a thermal power plant is lower (about 1%-point) using the concept of a lower heating value than using the concept of the LHV.

implies a linear relationship between investment costs and capacity at the plant level.

5.1.7 Summary and Conclusion

The focus of the following discussion is put on the extra efforts that are required to capture CO_2. Then the differences of the EP and ND approaches are discussed.

Most of all studies reviewed here dealt with carbon capture at power plants. This is reasonable, because power plants represent a considerable amount of CO_2 emissions from large point sources; see Ch 2.3.2. There are other sources that offer carbon capture at large point sources at lower costs, but the overall amount of CO_2 is not as large. This is especially important for all industrial plants that generate a stream of highly concentrated CO_2 by default like hydrogen production. Although there is not much to say about these technologies, they are important because of their low cost capture opportunities. The post-combustion capture concept seems to be more reasonable at cement or iron BOF plants than at coal power plants because the CO_2 concentration of the flue gas stream is higher. The rare techno-economic assessments available confirm this.

Next, the focus is on the studies related to capture at power plants. The overwhelming number of studies can be attributed to one of four clusters of studies: those focusing on post-combustion capture at PC (Post-PC) and NGCC (Post-NGCC) plants, oxy-fuel capture at PC plants (Oxy-PC) and syngas based capture at IGCC plants (Syngas-IGCC). The purpose is to look for qualitative robust features that distinguish these four groups. Three aspects are important for comparative economic analysis of carbon capture technologies:

1. The techno-economics of carbon capture are characterised by the increase of energy own-consumption and extra investments. This leads to the question whether there is a systematic relationship between these two factors that is suggested by the techno-economics of carbon capture.

2. In order to analyse whether the ordering of technologies changes due to carbon capture the cost of electricity COE for the reference case and the capture case are compared.

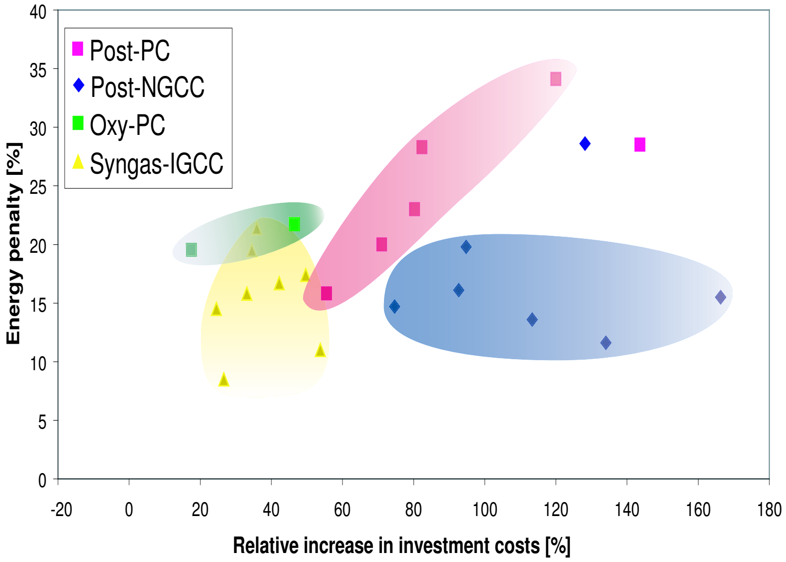

Figure 5.19: Comparison of the relative increase of investment costs and the energy penalty, including post-combustion PC (Post-PC), post-combustion NGCC (Post-NGCC), oxy-fuel based PC (Oxy-PC) and syngas based IGCC (Syngas-IGCC). The ellipses represent the ranges found in the literature review. The shading of the ellipses represents the subjective reasonability of the corresponding number.

3. Comparison of the investment costs of the reference and the capture case allows to assess the capital effort required for carbon capture.

The first question is best addressed by plotting the relative increase of the investment costs based on \$US per kW_e against the energy penalty. Fig. 5.19 gives a clear indication that the studies can be located at particular regions of that plot, which is indicated by the coloured ellipses.

Looking at the *overall* picture of the graph there is a slight positive relationship between the energy penalty and the relative increase of the investment costs. There is a clear positive relationship, if Post-NGCC were left out of the picture and the focus were on carbon capture at coal power plants.

If we look *into* the groups and ask whether there is such a positive relationship we only find one for Post-PC plants. For Post-NGCC the relationship even exhibits a slightly negative relationship. The two studies within Oxy-PC do not allow a statement regarding relationships. Syngas-IGCC indicates a positive relationship, but the variations are to large for a robust feature.

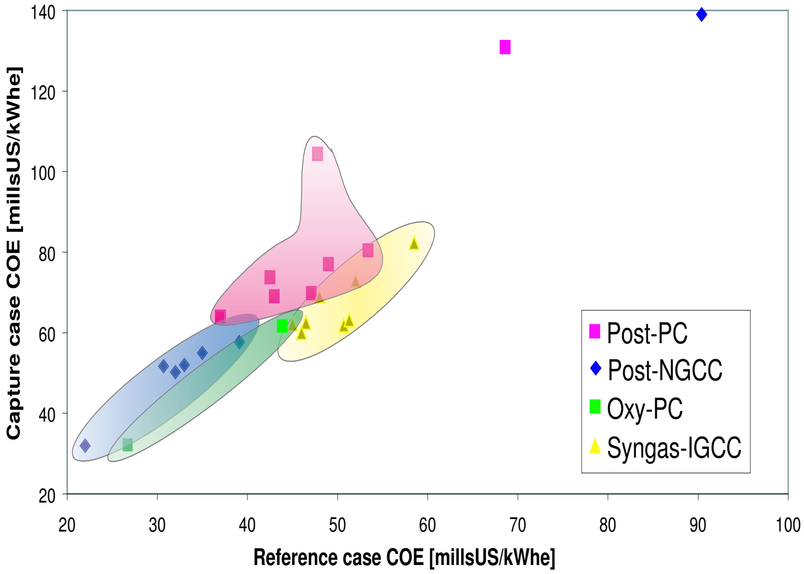

Figure 5.20: Comparison of COE of reference plant plotted against the COE of the capture plant, including post-combustion PC (Post-PC), post-combustion NGCC (Post-NGCC), oxy-fuel based PC (Oxy-PC) and syngas based IGCC (Syngas-IGCC). The ellipses represent the ranges found be the literature review. The shading of the ellipses represents the subjective reasonability of the corresponding number.

If we look at the locations per type, we observe that the two post-combustion based groups exhibit considerably higher increases of the relative investment costs compared to oxy-PC and syngas-IGCC. The comparison of oxy-PC and syngas-IGCC shows that the oxygen-fired combustion has a higher energy penalty although the relative investment cost increases are roughly within the same range. The reason for this is that the regional air pollutants are captured simultaneously in the oxy-fuel concept and these obsolete investments partially offset the investment and increased own-consumption due to the air separation unit ASU.

The second question is analysed by plotting the COE of the reference plant against the COE of the capture plant. Fig. 5.20 again shows that the studies of each group are adjacent to each other.

If we focus on the reference plant COE only, we observe that NGCC plants have the lowest COE of all.[42] The coal based electricity generation technologies are characterised by higher COE. The exception of the very low COE PC plant that is

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[42] This is why it is sometimes called the technology of choice today.

augmented by the oxy-fuel capture concept is due to the low discounting rate and the low fuel costs. The other PC plants show considerably higher costs.

If we compare PC plants with IGCC plants of the reference case, it can be observed that the COE of IGCC plants are remarkably higher. In addition to this difference we have to take into account that PC plants are a commercial available technology and that the IGCC technology is still subject to operational problems.

Looking at the COE of the capture plants we observe that Post-NGCC is still the most competitive technology, if one considers the very low-cost oxy-PC plant as an exception. The order reverses within the coal based technology. The syngas-IGCC plants show a slight cost advantage compared with the Post-PC plants. But if PC plants are augmented by the oxyfuel concept, we observe that the PC plants are still competitive with IGCC.

With respect to comparison of Post-NGCC plants with the coal based plants, one has to take into account that the CO_2 emissions per kWh_e are considerably lower for gas fired plants due to the higher efficiency and the lower carbon intensity of natural gas.

Now the discussion turns to the third question regarding the investment costs of the reference and the capture plant. Above the focus has been on the relative increase of investment costs, but it is also worth to focus on the absolute numbers as the capital for the corresponding investments has to be provided by private firms who are faced with credit restrictions.

Fig. 5.21 compares the ranges of the investment costs of the reference and the capture plants found in the literature review. With respect to the reference plants the first thing to note is that gas fired power plants require considerably lower investment costs than coal fired power plants. This is mainly due to the fact that natural gas is more easy to handle than coal. Moreover, the investment costs of the reference IGCC plants are considerably higher than for the PC plants. This corresponds with the higher COE of the IGCC reference plant found above.

For the capture plants natural gas still has the lowest investment costs, but the order changes within the coal power plants. For the coal fired power plants Post-PC has the highest investment costs and syngas-IGCC is now competitive. This is due to the fact that the carbon capture is easier in syngas-IGCC plants, but the design of the power plant has to be changed and this increases the costs of the reference plant. The difference between syngas-IGCC and oxy-PC is the other way around.

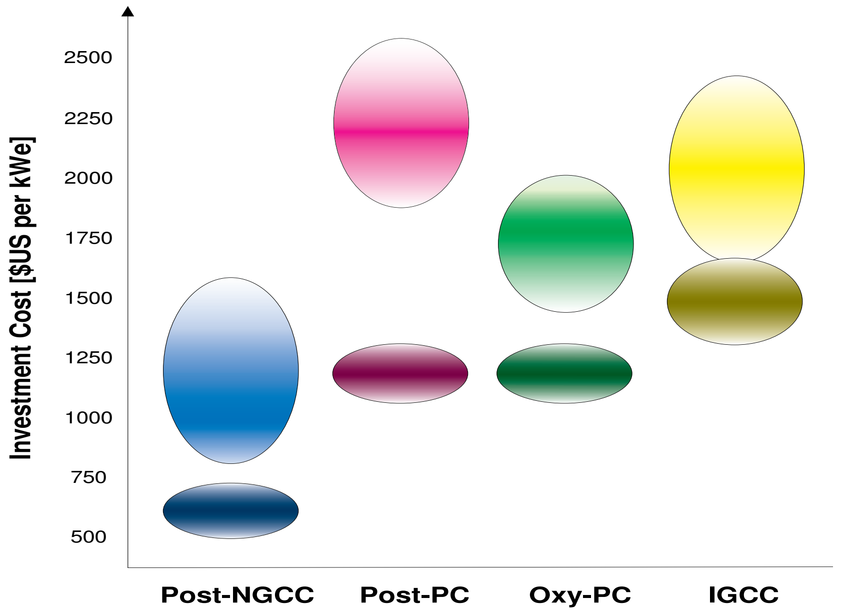

Figure 5.21: Comparison of the investment costs for the base case and the capture plants, including PC, NGCC, IGCC, ZECA and lignite based oxyfuel. The grayed ellipses represent the base case plants, the full colour ellipses show the CO_2 capture plants, including post-combustion PC (Post-PC), post-combustion NGCC (Post-NGCC), oxy-fuel based PC (Oxy-PC) and syngas based IGCC (Syngas-IGCC). The ellipses represent the ranges found be the literature review. The lower ellipses represent the reference plants, the upper the capture plants. The shading of the ellipses represents the subjective reasonability of the corresponding number.

The investment costs for an oxy-PC plant are lower than for a syngas-IGCC.

If carbon capture is considered, the oxy-PC concept allows to keep to the conventional PC technology without the very large additional investment costs implied by the post-combustion concept. Nonetheless, there is no operational experience with the long-term use of oxygen combustion in power plants.

This brings us to the discussion of EP and ND approaches of carbon capture. As pointed out above there is difference between carbon capture technologies that leave the production processes unchanged (called EP approaches) and those that change the production processes in order to reduce the extra efforts of carbon capture (called ND approaches).

The focus is at first put on the process NDs. In the field of electricity production there are obviously high extra efforts for the post-combustion concept of carbon capture. The reduction of the extra effort with respect to coal power plants is possible with two concepts. The oxy-fuel concept leaves the major principle of the plant unchanged, while the syngas concept changes the overall design of producing electricity from coal.

There are two criteria in order to assess the superiority for applying one of these two concepts. First, we can broadly assess the levels of technology maturity. Second, we can assess the economic performance from the literature review as has been done above.

The technological maturity of both are uncertain, since there is no long-term operational experience with oxy-fuel combustion in a power plant as well as with IGCC plants with carbon capture. The advantage of the oxy-fuel concept is that it is based on conventional PC plants. The economic criteria favour the oxy-fuel approach, although this result of oxy-PC is mainly based on one study.

This is in conflict with the focus of research in carbon capture technologies that mainly focus on IGCC related technologies. This is indicated by the number of studies related to this type of plants.

The product NDs are more difficult to assess because the system that is studied is not well delimited. There are two major product groups that are being investigated now: the production of hydrogen and the production of liquid fuels. Both are related to the consumers (mainly transportation), which are characterised by an enormous number of end-use appliances. It is not clear how the consumers shall be persuaded to buy cars that use new fuels – espec. hydrogen – if there is no additional benefit to them. It is also uncertain why private firms should make large scale investments, when it is unclear whether the market is large enough to sell the output.

The difference between EP and ND can be seen as the difference between technologies that are mature and available, but expensive and technologies that are cheaper, but speculative. The availablity of a technology is important for the assessment of the extent and timing of its utilisation. It is not possible to draw a unique scientific conclusion about this because there are considerable techno-economic uncertainties.

Appendix: Overview on Gas Separation Processes

In this Appendix a short introduction to gas separation processes is given that are applied for carbon capture. A more technical introduction can be found in Meisen and Shuai (1997) and Göttlicher (1999, Ch. 2). The approaches relevant in this section are:

1. chemical and physical absorption;
2. selective membranes;
3. physical pressure swing adsorption PSA;
4. frosting;
5. cryogenic methods.

Chemical and physical absorbtion is based on the temperature and pressure dependence of absorption processes. E.g. CO_2 reacts with a chemical liquid at low temperature. The reaction is reversed, if the temperature is increased. Usually, CO_2 capture processes based on chemical absorption require considerable amounts of energy for the reversal of the reaction. Göttlicher (1999, p. 12) notes that physical absorption is superior to chemical absorption when the pressure of the gas mixture is above 10 bar.

A membrane acts like a sieve where particular gases preferentially pass, while others do not. There are two different approaches for selective membranes. Gas absorption membranes are closely related to chemical absorption by using the membrane as a contactor between the gas mixture and the reactive liquid. Different to that are gas separation membranes: The membrane separates lets only one component of the gas mixture pass due to its selectivity and the pressure differences between the two sides of the membrane.

Physical pressure swing adsorption PSA works like absorption. The absorber is a solid material or a liquid that induces intermolecular forces on gases in selective ways. The adsorption of a gas requires high pressure[43], while desorption happens at reduced pressure.

Frosting of gas mixture implies hydrate formation processes of some gas components, while others do not form hydrates. The hydrates can simply be removed.[44]

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[43] Temperature dependent physical adsorption processes are possible, but found to be less efficient; see Riemer et al. (1994) and Meisen and Shuai (1997)

[44] This seems a bit exotic, because gas streams in industrial plants use to be hot, but a research team in France recently proposed to reduce the energy requirements considerably: 4.4GJ/tC, compared to 13.8 – 15.4GJ/tC in conventional processes; see Clodic and Younes (2002).

The cryogenic method is a common practice. It is based on the different boiling-points of the components of a gas mixture. Decreasing the temperature of a gas mixture leads the gas component with highest SP to change its state of aggregation to liquid. This method is more appropriate for the separation of oxygen from air rather than the capture of CO_2; see Riemer and Omerod (1995). This is especially important for the ND approaches.

There are other approaches of gas separation like ultra centrifuges that are not important in CO_2 capture. A considerable approach is biological fixation of CO_2 in the flue gas through photosynthesis by algae. However, this approach is not of interest here as this thesis is deals with geological sequestration.

5.2 The Compression

The compression of CO_2 is necessary for three reasons. First, if CO_2 has to be transported through pipelines and injected in wells, a high density of the gas is most efficient. Second, geological sequestration also requires high density of CO_2 in order to prevent leakage because of the reduced buoyancy of CO_2 relative to water. Third, the sequestration capacity increases with the density of CO2.

It is desirable to achieve a supercritical state for CO_2 by compression. A supercritical state is characterised by high density and high viscosity. This allows for a high throughput through pipelines and wells with low energy losses due to friction. Supercritical CO_2 is produced by raising its pressure above 73.8 bar. The density of CO_2 in the supercritical state at ambient temperatures is 700 – 800kg CO_2 per m^3.

Hendriks et al. (2001, p. 969) and Hendriks et al. (2002, p. 8) provide formulas for the investment and energy needs for CO_2 compression. The energy and investment needs depend on two parameters that have to be chosen prior to the deployment of a compression plant: the ratio of the inlet and the outlet pressure $\frac{P_{outlet}}{P_{inlet}}$ and the amount of CO_2 that shall be compressed per period F. The investment costs ι_{comp}

in $\frac{\$\mathrm{US}}{\mathrm{tC/y}}$ can be computed from F in units of $\frac{\mathrm{tC}}{\mathrm{y}}$ as follows:[45]

$$\begin{aligned}\iota_{comp} &= C_1 \cdot F^{C_2} + C_3 \cdot \ln\left(\frac{P_{outlet}}{P_{inlet}}\right) \cdot F^{C_4}; \qquad (5.1)\\ C_1 &= 6586 \frac{\$\mathrm{US}}{(\mathrm{tC/y})};\\ C_2 &= -0.71;\\ C_3 &= 29279 \frac{\$\mathrm{US}}{(\mathrm{tC/y})};\\ C_4 &= -0.6;.\end{aligned}$$

The electricity needs for compression E_{comp} are linear in F:

$$E_{comp} = 0.389 \frac{\mathrm{kWh_e}}{\mathrm{tC}} \cdot \ln\left(\frac{P_{outlet}}{P_{inlet}}\right) \cdot F. \qquad (5.2)$$

Fig. 5.22 shows the functions for $\frac{P_{outlet}}{P_{inlet}} = 80$, which is a commonly assumed benchmark. The marginal investment costs per tC and year are given in Fig. 5.22(a) and the energy need for the amount compressed within a year is given in Fig. 5.22(b). The non-linearity of the marginal investment costs is significant and varies over the range that is of interest for carbon capture from large point sources. The constant energy need for compression is $389 \frac{\mathrm{kWh_e}}{\mathrm{kgC}}$, which is quite considerable.

These functions are now compared with other studies. The assumption on electricity need assumed by Hendriks (1994, p. 39) is $0.281 \frac{\mathrm{kWh_e}}{\mathrm{kgC}}$, which is a difference of 39.5% compared to the study noted above. Göttlicher (1999, p. 78) even reports $0.451 \frac{\mathrm{kWh_e}}{\mathrm{kgC}}$.[46]

With respect to the investment costs Hendriks (1994) assumes investment costs for compression of $19.2 \frac{\$\mathrm{US}}{\mathrm{tC}}$. The corresponding number provided by Eq. 5.1 is $32 \frac{\$\mathrm{US}}{\mathrm{tC}}$. This is a difference of even 67%.

Differences in electricity need are more significant because this is the major cost component of compression. Hendriks et al. (2001) notes that the capital costs share is ~20% only.

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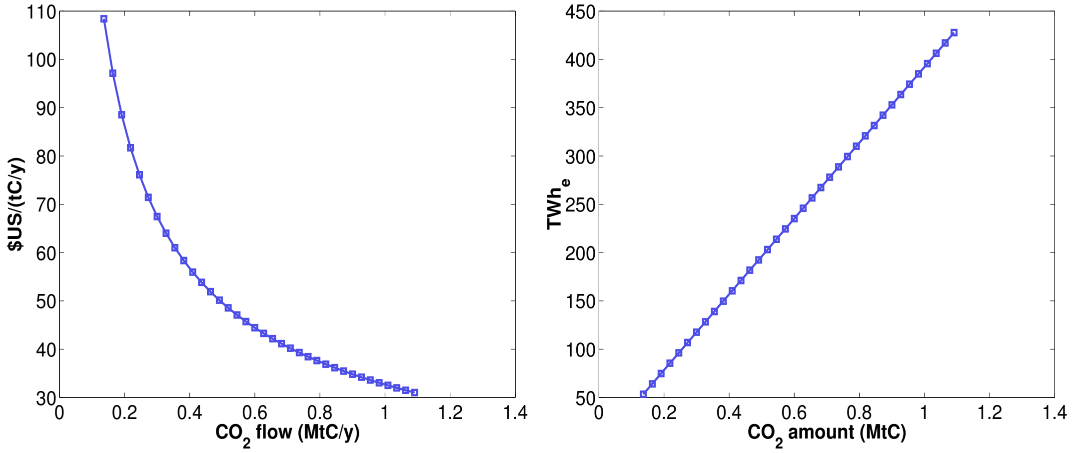
[45] Note that the units of cost coefficients C_1 and C_2 do not convert exactly with the units of F into that of ι_{comp} because of the degression coefficients C_2 and C_4, which represent economies of scale. It is common practice not to take this into account for the conversion of units.

[46] Based on 85% isentropic efficiency that is the same as in all the studies by Hendriks.



(a) Marginal investment costs (b) Energy need

Figure 5.22: Investment costs and energy requirements for CO_2 compression. Source: based on Hendriks et al. (2002, p. 8).

In summary, compression is an inevitable step of CCS. It is based on pure mechanical work. Investments for the equipment constitute an extra effort. Moreover, the electricity consumption is considerable. Data on investment and electricity requirements are scarce in the literature on CCS and the figures do not provide a consistent overall picture.

5.3 Pipeline Transportation

The efficient transportation through pipelines requires super-critical CO_2. The transportation by pipeline basically depends on the amount of CO_2 that has to be transported and on the distance to be covered.

There are considerable economies-of-scale related to pipeline transportation because the trough-put through the circular area of a pipeline cross-cut increases quadratically with the diameter, while investment costs increase linear with diameter, only.[47]

On-shore pipelines are built above or below ground. In densely populated regions

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[47] See Berndt (1991, Ch. 3) for an overview on this issue on empirical grounds of economies-of-scale arising from fundamentals of geometry.

Table 5.13: Investment costs for pipeline material and construction for on-shore underground pipelines. Source: Hendriks et al. (2001) and Heddle et al. (2003)

Through-put ktC p.a.	Diameter m	Material mil.$US per km	Construction mil.$US per km
273.	0.3	0.23	0.48
545.	0.6	0.47	0.8
1091.	1.0	1.22	1.60

the sub-surface option can be considered as default. The advantage of underground pipelines is that the temperature is lower than above ground; i.e. ∼10°C. At this temperature and 80bar the density of CO_2 is 800kg per m^3. On the other hand, the investment costs due to higher construction efforts are increased.

The investments costs for pipeline transportation facilities are caused by material and construction. Tab. 5.13 gives an overview on the investment costs and their corresponding capacities. The overview shows the linearity of costs depending on the diameter, but the through-put depends on the circular area of the cross-cut. The authors remark that a landing facility costs 34mil.$US, without specification of the capacity. The study does not provide specification on the power required for pumping the CO_2 through the pipeline.

Fig. 5.23 shows the dependence of cost of pipeline transportation depending on the distance and on the size of the pipeline indicated by the through-put per year. The costs for no transportation correspond to the costs of compression.

Doctor et al. (2001) report CO_2 pipeline projects in operation already. The data is summarised in Tab. 5.14. The most recently deployed project transports CO_2 from North Dakota to the Weyburn oil field in the Canadian province Saskatchewan. The study noted a pressure loss amounting to ∼0.15bar per km. Therefore, re-compression is required at intervals of 130km to reach required 150bar. This pressure is higher than the numbers reported in Hendriks et al. (2001). Allinson and Nguyen (2001) note that for a pipeline with 0.5m diameter the pressure drop is 0.12bar per km.

Doctor et al. (1997) note that the costs of pipeline transportation are 31$US per tC for 500km, which would add 7.8millsUS/kWh_e to the electricity costs. Moreover, 2% of the transported CO_2 leak from the pipelines. The pumping requirement in this study specified at 1.64MWe for 71tC per hour. On-shore and off-shore transporta-

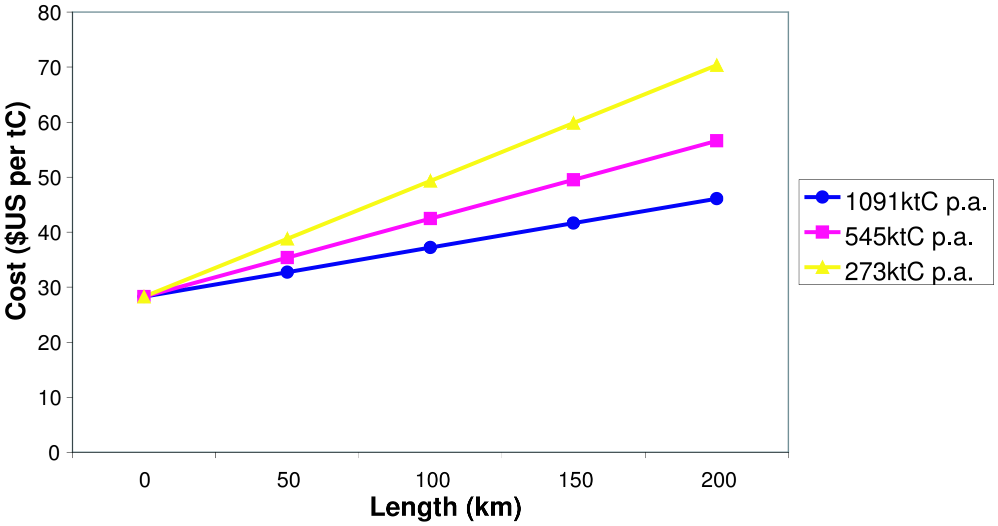

Figure 5.23: Costs of compression and underground on-shore transportation of CO_2 at supercritical pressure of 80bar. Source: Hendriks et al. (2001).

tion by pipeline are estimated to be 3.6 and 2.5$S per tC and 100km, respectively. Riemer and Omerod (1995) noted that this number is expected to be the maximum.

Herzog (2004) provides data on on-shore pipeline transportation. The numbers are given in terms of $US per tC and 100km for several mass flow rates in terms of MtC per year. The results are given in Fig. 5.24. For comparison the corresponding numbers by Hendriks et al. (2001) are added to the graph. One can observe a similar pattern of economies-of-scale for both studies, but the numbers given by Hendriks et al. (2001) are 50 – 60% higher compared to Herzog (2004).

Doctor et al. (2001) note that the presence of economies-of-scale offers the possibility to collect CO_2 from various plants to exhaust the cost reductions of greater pipelines. The authors note that this could reduce the transportation costs by 60%, without noting methods and assumptions for computing this cost reduction. More detailed studies using geographical information and cost data indicate that pipeline networks require special conditions: the collection of a large number of CO_2 sources and the transportation to a distant injection site. These prerequisites vary regionally and the presence of considerable economies of scale seems questionable; see Singh (2004, p. 82), Dooley et al. (2004a) and Wildenborg et al. (2004).

An important problem with respect to transportation of highly concentrated

Table 5.14: Investment costs for CO_2 pipeline material and construction for on-shore underground pipelines. Source: Doctor et al. (2001).

Project Location	Shell McElmo[a] Cortez, Col.	Arco Oil&Gas Sheep Mountain, Col.	Amoco Oil Bravo Dome, NM	Gasification Beulah, ND
Length [km]	800.0	650.0	340.0	330.0
Diameter [m]	0.76	0.51	0.51	0.25
Pressure [bar]	177.0	N.A.	N.A.	N.A.
Trough-put [ktC p.d.]	43.6	31.1	43.6	5.
Investment [bil.$US]	1.2	N.A.	N.A.	0.11
Investment [mil.$US/km]	1.50	N.A.	N.A.	0.33
Begin of operation	1984	1983	1985	2000

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[a] McElmo Dome is a natural source of CO_2.

CO_2 is the release of CO_2 by accident in populated areas. This is due to the health effects of CO_2 known as asphyxiant; see Doctor et al. (2001). There s therefore the risk of suffocation. The use of CO_2 pipelines have to address this problem, especially in populated areas. Their installation is in such areas is simply due to the spatial location of energy production and consumption.

Kruse and Tekiela (1996) assessed a minimum distance to populated areas based on the safety criterion that after an instantaneous emission and subsequent interruption of transport the concentration of CO_2 in populated areas should not exceed 5% for 60 seconds. This exposition would lead to headache, breathing difficulties and weakness. The minimum distance is assessed to be 600m.

A study by Barrie et al. (2004) reviews safety issues from the point of view of long-term operation and expected fatigue of pipelines due to corrosion. The study refers to ten incidents of CO_2 pipelines faults over the period 1990 – 2001 in the US, reported by the responsible Office of Pipeline Safety. These incidents did not lead to serious damages.

5.4 Injection into Geological Formations

Carbon sequestration in geological formations requires the injection of CO_2 into great depths. The sequestration in a geological formation itself does not require any additional effort, but the injection into a geological formation does. There are a

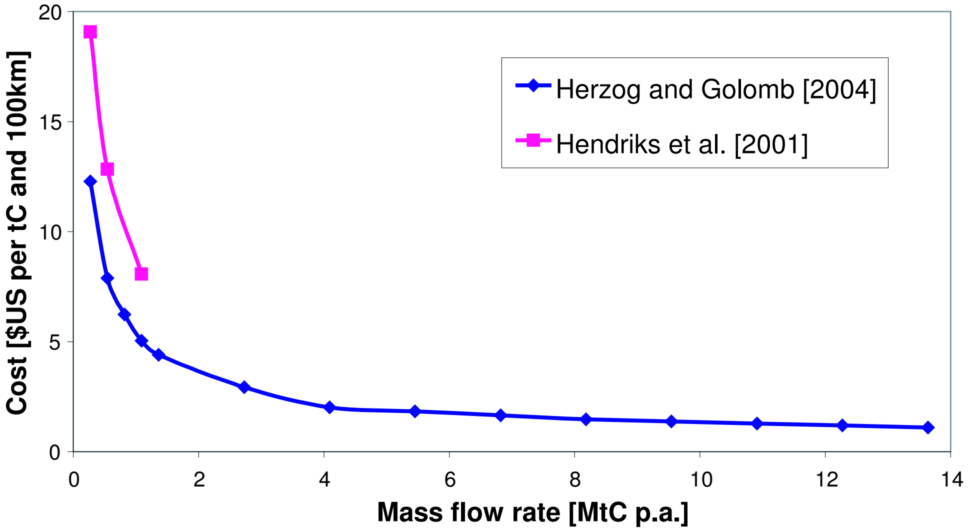

Figure 5.24: Costs of CO_2 pipeline transportation depending on the mass flow rate. Source: Hendriks et al. (2001) and Herzog (2004).

considerable links between the operation of injection and the possibility CO_2 leakage as well as the sequestration capacity that will be discussed in Ch. 5.5.3.

Fig. 5.25 illustrates the scheme of an injection well that goes through a heterogenous sequence of geological layers; see Smith et al. (2001). It is an installation fixed at a particular location that is difficult to move. The injection tube is embedded within an annulus, which in turn is embedded in a cement grout. The packer is required to generate a greater surface of the injector in order to spread the CO_2 into a greater volume of the geological formation. The cement grout near the injection zone has to be acid resistant to prevent possible leakage because the acidity of CO_2 that is solved in the formation water causes corrosion. The CO_2 is injected through several nozzles in the injection zone. In the illustration a confining layer is above the injection zone. The injected CO_2 establishes a bubble or a plume around the injector indicated by grey shading. As long as CO_2 does not leak out, the freshwater layer above the injection zone is not affected.

At the end of the operational period the injection tube and the annulus are removed and the cement grout is pushed into the bore hole in order seal the hole in the confining layer. For the discussion of sequestration and of leakage through boreholes it is important to note that this is the same mode of finishing the operation

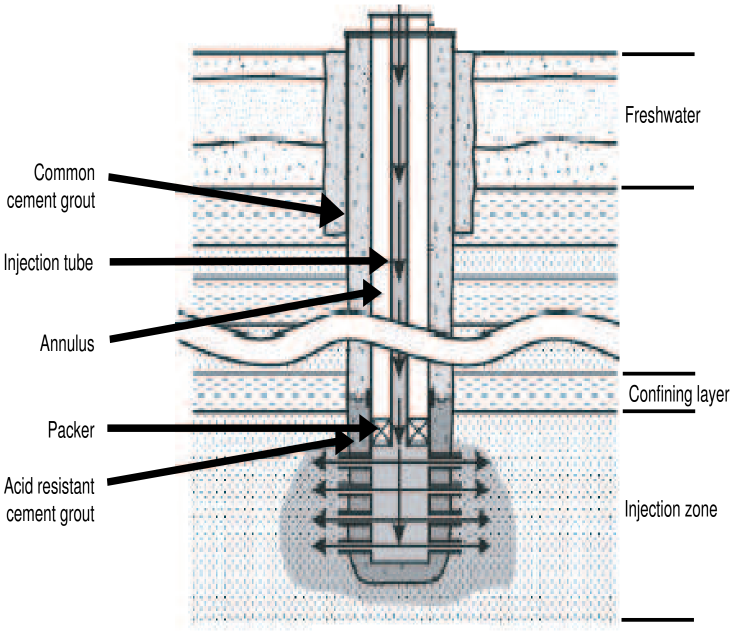

Figure 5.25: Technical installation of an injection well in a saline aquifer. Note that the proportions are biased. Source: Smith et al. (2001).

of wells in the oil and gas industry.

From an economic point of view the effort to find a specific site has to be taken into account as well as the effort for the injection equipment specific to that site. Moreover, the injection of CO_2 requires energy to move the CO_2 into the geological formation.

The finding effort contains all the costs that are necessary to find a site for injecting CO_2 that allows for the accounting of avoided CO_2 emissions within a framework of climate policy institutions. This includes the costs of planning, exploration of a sequestration site as well as the administrative effort of legal licensees etc. The costs of exploration for finding a specific site have to be weighted with the inverse of the success rate.

The physical injection of CO_2 into a geological formation requires equipment, which presupposes investments into drilling, injection wells and auxiliary facilities. These investments depend on site specific characteristics:

1. the kind of location whether, i.e. it is on-shore or off-shore;

2. the amount of CO_2 to be injected per year by an injection well;
3. the depth of injection;
4. the injection pressure.

The injection of CO_2 requires energy due to re-pressurisation and the movement of mass using pumps and blowers. With respect to the re-pressurisation the findings for compression in Ch. 5.2 apply.

Data on the finding costs are rare. According to Hendriks et al. (2001) exploration costs are assumed to be 2mil.$US per sequestration site with a success rate of 50%. Gupta et al. (2002a) give a range of 0.3 – 1.3mil.$US per site for the exploration costs. Torp and Brown (2004) report 2mil.$US costs due to preparatory scientific studies for the Sleipner West, Norway, project.

For the installations costs Hendriks (1994) gives a calculation for the 25 year operation of an injection plant that is devoted to the injection of 1.1MtC p.a., which corresponds to the CO_2 produced by a $600MW_e$ coal fuelled power plant. The assumptions are as follows:

1. injection is on-shore and the injection depth is 2000m;
2. the fixed costs for drilling one injection well are 1mil.$US;
3. the variable drilling costs are assumed to be $1250\frac{\$US}{m}$ ($3000\frac{\$US}{m}$ for off-shore);
4. surface facilities, which include distribution of CO_2 via pipelines $750\frac{\$US}{m}$ and CO_2 compressors for re-pressurisation to 240bar;
5. the installation is assumed to operate for 25 years and the construction period is 2 years;
6. electricity costs are assumed to be 50millsUS per kWh_e.[48]

The results of these calculations are shown in Fig. 5.26 in terms of sequestration costs in $US per tC for various flow rates tC per well and year. The costs are distinguished into costs of the surface facilities, the operation and maintenance costs and the well investment costs. The highest costs are due to surface facilities. The cost pattern indicates the importance of the flow rate on all cost components.

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[48] millsUS are 0.001·$US.

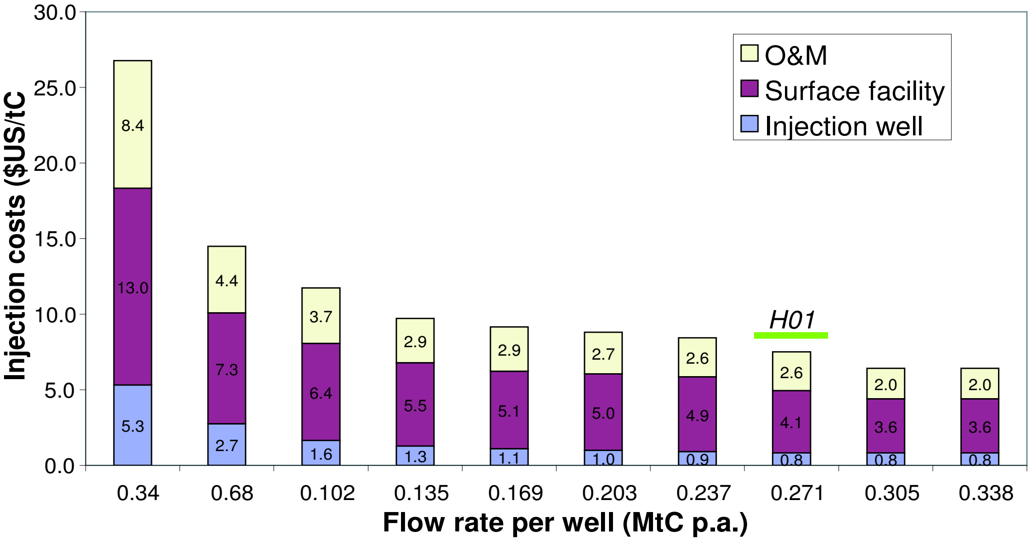

Figure 5.26: Costs of CO_2 injection into a saline aquifer depending on the CO_2 flow rate per well and year. Source: Hendriks (1994) and Hendriks et al. (2001).

The green bar in the figure denoted with H01 indicates the finding by Hendriks et al. (2001), who assessed the costs depending on the injection depth and location. The injection rate in that study is 0.27MtC p.a.[49]

The corresponding assumptions lead to injection costs of $\sim 9\frac{\$US}{tC}$ at an on-shore sequestration site. Compared to Hendriks (1994) this represents an increase by 20%. The costs rise moderately with injection depth until 3000m, where a remarkable increase occurs. If the operation is located at an off-shore site the injection costs increase to about $25\frac{\$US}{tC}$.

A study by Torp and Brown (2004) compared the costs of CO_2 injection at Sleipner West, Norway, and Weyburn, Canada. The investment cost for a 1000m vertical and 4000m horizontally drilled CO_2 injection well were reported at 15mil.$US.

The calculation by Ormerod et al. (1994b) for costs of deep saline aquifer injection excludes the cost of purifying and compressing the CO_2. Capital costs include a 30 km pipeline, wells, project development and land acquisition. Operation costs are included for surface facilities. The initial injection rate of 200ktC p.a. would fall

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[49] This benchmark is a reasonable assumption, since the CO_2 injection at the Sleipner West gas field is exactly this amount. It has to be noted that Sleipner West conditions for CO_2 injection into the geological formation are very favourable and might not be found everywhere. Therefore, it is reasonable to assume that the injection rate might be lower at other sequestration sites.

to 160ktC p.a. over 30 years because the capacity of the sequestration site reaches its limit. The cumulative amount injected over a 30 year period is therefore 5.2MtC per well. Six wells would be required for a 500MW$_e$ coal fired power station. This leads to injection costs of $4.7\frac{\$US}{tC}$.[50]

The injection costs vary with the location. These exhibit varying characteristics. The difference between on-shore and off-shore might be the most important one. There are no comparisons between different patterns of organising the injection wells. It might be possible to exhaust economies of scale, if several injection wells share the same surface facilities. Nonetheless it can be concluded that the injection costs are small compared to the costs of carbon capture.

5.5 Sequestration in Geological Formations

So far this chapter has dealt with the process steps of CCS that require extra efforts in order to keep the CO_2 away from the atmosphere. This is different in this section. As soon as the CO_2 is injected into a geological formation it leaves the control of human action, which implies that no additional effort is required, but also that the CO_2 could leak into the atmosphere. Geological features determine the underground behaviour of the CO_2. In principle there are two different possibilities. Either the CO_2 remains in the geological formation or it leaks into the atmosphere. In the former case geological mechanisms are at work that keep the CO_2 underground; in the latter case these mechanisms fail.

The sequestration of CO_2 in geological formations is the theme of this section. This is a disputed term, which requires some clarification of the difference to the term storage, since both terms are used in the scientific discussion with different meanings. This discussion is in itself useful because it enhances the understanding of the problem at hand.

From an economic point of view sequestration is not a common term, while storage is. Storage usually means that an economic agent stores a produced good in a stockroom with the intention of using it in subsequent periods; e.g. underground storage of oil and gas. With respect to CO_2 that is injected into a geological formation because of climate protection it is not reasonable for economic agents to extract that CO_2 thereafter. It is desired that the CO_2 remains in the geological formation;

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[50] Riemer and Omerod (1995) report the same number without details on the calculation.

this is the reason to term it sequestration. The term sequestration includes the possibility of leakage, although it is not wanted.

Geologists do frame the problem according to a different criterion. The feature that distinguishes sequestration and storage is whether the CO_2 could possibly leak from a geological formation. As long as this is possible the carbon is stored, only. If a geological process has occurred that prevents the CO_2 from possible leakage (e.g. the CO_2 reacts with geological material and is then absorbed in solid material), a geologist would term this sequestration, because the CO_2 will be absorbed for very long time scales; see e.g. Kaszuba et al. (2003) and Bachu and Adams (2003).

This is primarily an economic study, although it will be necessary to introduce insights from the geological sciences that are related to the geological terms of storage and sequestration. But there is no reason to mix the meaning of the terms and therefore the economic terminology regarding storage and sequestration is applied in the following.

CO_2 sequestration is a geological process that takes place after the injection of CO_2 into a geological formation. There are several geological mechanisms that induce containment of the CO_2 in a geological formation, which will be denoted as sequestration mechanisms (SM) in the following. If these mechanisms do not work, CO_2 leaks out. There are several mechanisms that could lead to such failure of SM called leakage mechanisms (LM). Moreover, there are different types of geological formations that are considered for CO_2 sequestration that are termed sequestration alternatives (SA). An SA is characterised by at least one SM that keeps the CO_2 underground. A sequestration site (SS) is a concrete geological formation that is characterised by several features like depth, size, etc. Each SS is a member of an SA. An essential feature of SA as well as SS is the sequestration capacity (SC), which describes the cumulative amount of CO_2 that can possibly be injected over time.

This section is structured as follows. First, some notes are made on experiences related to the behaviour of gases other than CO_2 that have been injected into the underground (Ch. 5.5.1). After that, an overview of sequestration mechanisms is given in Ch. 5.5.2 and leakage mechanisms in Ch. 5.5.3. Then the most important sequestration alternatives are introduced in Ch. 5.5.4, which is followed by a review of the literature with respect to the global capacities of the sequestration alternatives (Ch. 5.5.5). Finally, the findings are discussed and conclusions are drawn in Ch. 5.5.6.

5.5.1 Experience from Commercial Operations

Experience with the injection of gases into geological formations from at least three different fields. First, natural gas is stored in geological formations for strategic reasons and seasonal balance of demand and delivery of natural gas. Second, acid gases are by-products of natural gas extraction and are injected into geological formations. Third, CO_2 is injected into mature oil fields to enhance oil production. In the end some notes on the experience that can be drawn from these operations is added.

Underground gas storage (UGS) is performed for commercial and strategic reasons. The commercial reasons are related to seasonal variations of demand and the steadiness of supply due to the utilisation of capital at constant rates.[51] UGS balances the demand variations with the supply constancy. The strategic reasons are related to the dependence of several countries on supplies from foreign countries as well as the shortages of unintended supply interruptions.

UGS has first been applied in 1916 in Canada. Today, it is common commercial activity in several countries. An overview of UGS in Germany, the European and Central Asian region is given in Sedlacek (1999), Sedlacek et al. (2001) and Sedlacek (2002). For example, the UGS capacities in Germany are ∼0.57EJ and in Europe, including the former Soviet Union, ∼5.9EJ of natural gas.[52]

The types of geological formations used for UGS are also considered for the purpose of carbon sequestration. UGS operations show that geological formations are suitable to keep gases underground for some time, although the time scales and the intention of injection are quite different. Another difference is that natural gas does not become an acid, if it comes in contact with water. The experience can be used for carbon sequestration; see May et al. (2002).

The second source of experience of the behaviour of injected gases is related

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[51] For example, the winter peak of natural gas consumption in a city like Berlin, Germany, is 15 times the consumption in summer.

[52] For comparison, the total amount of natural gas consumption in Germany in the year 2000 has been 3.0EJ; i.e. ∼19% of gas consumption p.a. is stored underground within Germany. The city of Berlin has a UGS in Grunewald, where since 1992 at maximum $850*10^6 m^3$ can be stored 800 – 1000m below the ground. This is equivalent to one year consumption of West-Berlin. The original reason has been to be independent of gas supply cuts by the Soviet Union. In November 1996 the facility has been sold for 300mil.$US; see Berliner Zeitung 16.06.1997, 17.06.1997 and 14.04.2001.

to acid gas injection. The emission of acid gases (i.e. H_2S) contained in natural gas are regulated in some countries. Canada introduced environmental regulations, which lead gas firms to inject the acid gases into geological formations since the early 1990ies. Until 2003 2Mt of acid gases have been injected at 48 sites. Although not regulated, 0.7MtC of CO_2 were injected along with the acid gases, because the separation would have been to costly. This type of operation provides even better experience, since acid gases might behave more analogous to CO_2 than natural gases. An overview on this issue is given by Bachu and Gunter (2004). A major difference to carbon sequestration is that the quantitative scale is quite different, since CO_2 injection will amount to 0.27MtC of CO_2 p.a. and well. This implies much higher pressure on geological formations, which could exceed threshold values that guarantee their stability.

The third field of experience is the injection of CO_2 into mature oil fields to enhance oil recovery (EOR). This kind of activity has been initiated in the USA during the period of high oil prices 1973 – 1986. In EOR CO_2 is a scarce production factor that is injected to decrease the viscosity of the oil by solution of CO_2 in the oil and therefore to ease the extraction. The purpose of this injection activity is to increase the extraction of crude oil. CO_2 that is extracted with the oil is recovered and re-injected to further increase the production; see Jessen et al. (2005).

EOR has lead to important insights into the injection and migration processes of CO_2 in porous media that contains oil and – sometimes – water. Several geological simulation models are available that help to improve the performance of EOR and that are applied in the field of carbon sequestration, too. Additionally, several legal codes are related to the injection of gases into the underground, which are important for regulation of carbon injection and accounting for carbon sequestration.

5.5.2 Sequestration Mechanisms

Geological formations that are considered for CO_2 sequestration are sediments and coals. Both are porous media, which are characterised by using two technical terms: porosity and permeability. A geological formation consists of solid material with spaces that contain fluids. The porosity is simply the share of these spaces to the total volume and therefore the maximum volume that could be filled with CO_2 or any other fluid; e.g. water, natural gas or crude oil.

The permeability influences the velocity of the flow of a fluid through a porous

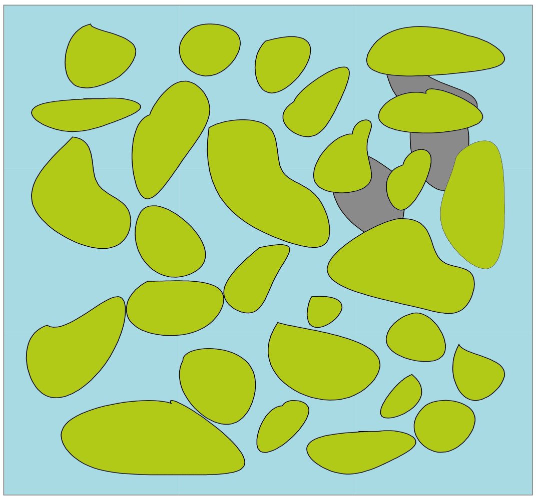

Figure 5.27: Porosity and permeability in sediments containing a fluid (e.g. water). A barrier lowering the permeability is illustrated in the upper right corner. The figure does not catch the 3-dimensional characteristics explicitly. Source: Press and Siever (1995).

medium. It denotes the volume of the fluid that passes a cross sectional area per period. Usually there is a difference between horizontal and vertical permeability, which is described as the permeability ratio. Usually, the horizontal permeability is higher than the vertical.

Obviously, these two terms describe different features of a geological formation. A sediment can have a high porosity but a low permeability, like it is the case for shales. The permeability of porous media found in the real world varies over a very large range; Freeze and Cherry (1979, p. 29) note that it varies over *fourteen* orders of magnitude. Moreover, porosity and permeability are not static features, but vary over time and are changed by human action.

Fig. 5.27 gives an illustration of porosity and permeability. It contains three different features: the grains, cementations between the grains and the fluid like formation water. The cementations are due to geological processes and are important, for example for the build-up of sandstone. Cementations lower the permeability of the fluids. The build-up and degeneration of cementations depend on the material of the cementations, the ingredients of the water and the conditions of pressure and temperature.

The major problem of CO_2 in geological formations – assuming usual conditions – is that the supercritical CO_2 has a density of $700 - 800\frac{\mathrm{kg}}{\mathrm{m}^3}$, which implies buoyancy relative to water, which would result in leakage.[53] The buoyancy can be overcome by four different SM:

1. Buoyancy of supercritical CO_2 can be hindered by impermeable barriers.
2. CO_2 is solved in water and crude oil.
3. CO_2 is absorbed by coal.
4. CO_2 reacts with geological materials.

In the first SM the CO_2 does not change its phase; i.e. it remains a supercritical fluid. The CO_2 displaces the formation water around the injection well. The disposition in the super-critical phase implies that the CO_2 is subject to buoyant forces and might therefore leak. There are two variants of barriers blocking the buoyant CO_2: geological trapping and hydrodynamic immobilisation.

Geological trapping means that the upwards migration of CO_2 is hindered by a confining layer. This is a layer with a much lower permeability compared to the one where the CO_2 is injected. This can be a so called geological trap that has proved its impermeability by having contained oil or natural gas over geological time scales. Alternatively, it may consist of low permeable layers, which have sufficient thickness. A special variant are salt domes that are washed out. Since the preparation of these so-called salt caverns is quite expensive, they will not be treated any further.[54]

Hydrodynamic trapping is based on a higher horizontal than vertical permeability of porous media. When the injected CO_2 has spread from the area of influence of the injection well, the natural horizontal flow of the formation water will take the CO_2 with it. This leads to the dilution of CO_2 in a greater volume over a larger area. Since the velocity of formation waters is slow (some cm per year) the CO_2 is said to be trapped hydrodynamically; see Bachu (2000, p. 960). It is difficult to assess whether hydrodynamical trapping is sufficient for sequestration without leakage.

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[53] Note that a density of $700\frac{\text{kg}}{\text{m}^3}$ is consistent with a pressure gradient of 11.5bar per 100 and a temperature gradient of 3°C per 100m. If the temperature gradient is 6°, the density will be less than 500°C even for a depth of more than 3000m; see Hendriks (1994, Ch. 7).

[54] In Rüdersdorf, Germany, near Berlin a salt cavern is currently prepared for underground gas storage. Two caverns (65000m^3 each) are out-washed with water at a depth of 1000m. The investment costs are 100mil.$US; see Berliner Zeitung 18.02.1999 and 12.03.2003.

Bachu and Adams (2003, p. 3153) note that the retention time by hydrodynamical trapping could vary between a few months and several million years.

The displacement of water in a porous medium by a supercritical fluid like CO_2 can happen in two different modes. In the regular mode the fluid spreads evenly; i.e. the front of the bubble extends like an inflating balloon. In the viscous fingering mode the fluid extends unevenly taking preferential paths; i.e. it branches out. The difference is that in the viscous fingering mode the fluid spreads over a larger area than in the regular mode. Viscous fingering is highly complex and modelling is very difficult and not commonly applied; see Saghir et al. (2000). It is assessed that, if viscous fingering occurs, sequestration capacity for a given sediment volume is reduced; see e.g. Bergman and Winter (1995, p. 525).

The behaviour of injected CO_2 in the regular mode can be modelled using semi-analytical models in order to assess important features like the maximum outreach of the CO_2 after a particular time horizon. This information is useful because it helps to determine the area that has to be explored with respect to eventual leak holes and for monitoring; see e.g. Saripalli and McGrail (2002).

Numerical models of CO_2 migration in porous media usually represent the regular mode diffusion of CO_2, only. Two examples are given in the following. The examples are chosen in order show the behaviour of CO_2 in a cross section and show the influence of the shape of a confining layer.

Numerical computations of the behaviour of CO_2 in a sediment are given in Fig. 5.28. The figure shows that there are two different zones of horizontal migration of CO_2 in the sediment below the confining layer. The red shading indicates the concentration of CO_2; the more intense, the higher is the CO_2 concentration. In the injection zone the CO_2 spreads around the injection well, where the formation water transports some of the CO_2 away. The primary effect is that the CO_2 migrates vertically along the borehole due to buoyancy until it reaches the confining layer that acts as a barrier. At that barrier the CO_2 migrates horizontally along the confining layer. After 10 years the CO_2 has extended an area with 1.5km radius under the confining layer, which grows to more than 2km after 20 years.

One important assumption is that the confining layer is completely flat. Since buoyancy drives a fluid always in the direction of the greatest vertical migration, the pattern of a migrating CO_2 plume might look quite different, if this assumption is changed. Fig. 5.29 shows the result of a similar study, but for a particular geo-

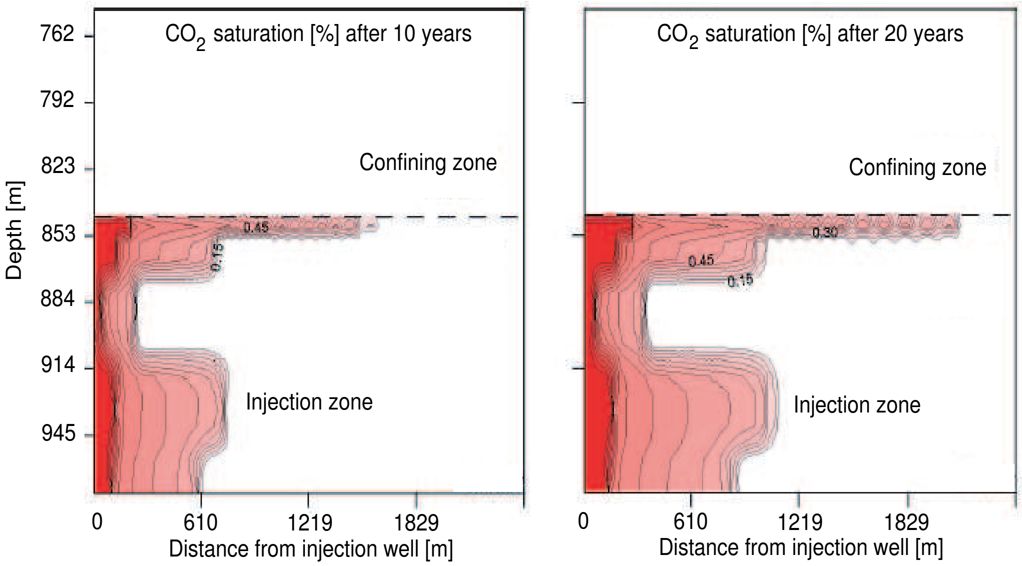

Figure 5.28: Simulation of CO_2 injection into an aquifer with a sandstone closure. Source: Gupta et al. (2002b).

logical formation that is inclined relative to gravity. The layer that is considered for sequestration is shown. Above that layer – but not shown – resides the confining layer. The figure shows the limit of the sequestration layer and the confining layer.

The CO_2 is injected on the lower left side of the figure. The CO_2 concentration has a clear and obvious preference for migrating upwards. Since the buoyancy drives the CO_2 in one particular direction, the outreach is much larger compared to the previous example. The CO_2 migrated about 30km in ten years. The figure indicates a fault that is a potential leak hole.

The second SM is the solution of CO_2 in either water or oil. First some notes on dissolution in water are made and then the focus turns to the essentials with respect to oil.

The solution of CO_2 in the formation water implies that the CO_2 changes its phase and therefore does not displace the formation water. Solution in the formation water is seen as a mechanism for long-term sequestration, because water with solved CO_2 has a higher density and therefore moves downwards. The solubility of CO_2 in water increases with pressure and decreases with water salinity and temperature. A consequence of the solution process is that the pH-value of the formation water decreases; i.e. it becomes acidic.

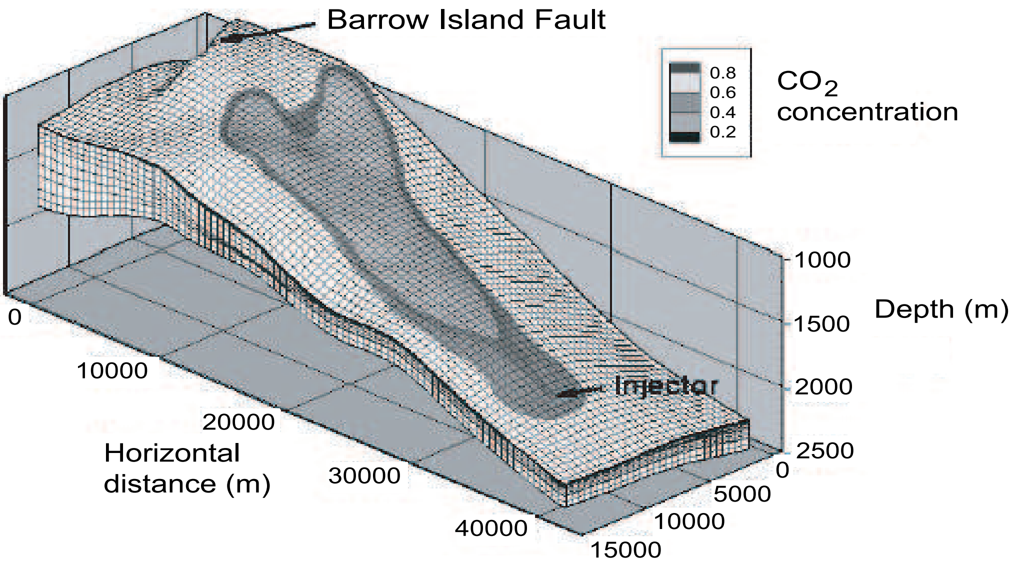

Figure 5.29: Simulation of CO_2 injection into a particular geological formation (Carnarvon basin, Australia) with a confining layer. The CO_2 concentration is given ten years after injection. At right hand the point of CO_2 injection is indicated and at left hand a fault is indicated. Source: Ennis-King et al. (2004).

Koide et al. (1995, p. 506) estimated that for a porosity of 20% about 14kgC per m^3 can be dissolved, if the formation water is not saline.

The solution of CO_2 in oil is interesting for so called tertiary oil recovery methods. The solution process reduces the viscosity of oil and therefore increases the oil recovery. Some notes on that issue will be added in Ch. 5.5.4.

The third SM is the absorption of CO_2 by coal. The absorption effect is based on intermolecular forces. This means that the CO_2 molecules are immobilised by absorption into the coal matrix. The coal matrix is the stable structure of carbon molecules that constitutes the solid character of coal. The absorptive force of coal on CO_2 is larger than on methane, which naturally occurs in coal seams. Therefore, the injection of CO_2 could eventually be used to produce methane from coal seams and simultaneously sequester the carbon.

The fourth SM is the reaction of CO_2 with geological material; see e.g. Press and Siever (1995, Ch. 6). The geological material could be (i) solid material of sediment grains or the cementations between them or (ii) particles in the formation water. Which reaction actually take place depends on the concentration of the materials as well as temperature and pressure. The reaction of CO_2 with geological material on the one hand constitute an SM, while on the other it changes the structure of the porous media. This latter effect could have positive or negative effects on the hydrodynamical immobilisation of supercritical CO_2. This is a very complex question and the answer is different from sediment to sediment.

In the following the focus is limited on two points. The first point is related to the time-scales on which these reactions happen. Kaszuba et al. (2003) and Soong et al. (2004) analysed the chemical behaviour of CO_2 in an experimental apparatus that increased the pressure and temperature to aquifer conditions. They conclude that the reactions happen within a time scale that is considerable for both sequestration by mineral trapping as well as leakage, but the authors make no explicit. Both studies found that the reactions were triggered by the increased acidity.

An important reaction with respect to leakage concerns the corrosion of cements of injection wells and abandoned wells of previous operations. As explained in Ch. 5.4 the wells for CO_2 injection and hydrocarbon extraction are embedded in a cement grout. This cement reacts with injected CO_2, if it is not made of special cement materials.[55] Obviously, the bore holes of injection wells or abandoned wells are possible leakholes that will be treated in Ch. 5.5.3.

For a particular SS several SM will be present. The intensity of each varies over time. If no leakage occurs, the supercritical CO_2 will be sequestered by some mechanisms. Such a mechanism – like hydrodynamical trapping – is possibly an intermediate state only before it is taken over by another SM, like dissolution in water. The time paths of intensity of each SM will vary from sequestration site to sequestration site.

5.5.3 Leakage Mechanisms

Leakage in this thesis means that the CO_2 injected into a geological formation leaks into the atmosphere. Another meaning of leakage regards the leakage of saline water into fresh water aquifers as a consequence of CO_2 leakage; see Wang and Jaffe (2004). This kind of environmental effect is not considered here.

There are at least five different leakage mechanisms LM:

1. The confining layer is permeable for CO_2.

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[55] Ch. 5.1.3.2 introduced the calcination reaction that splits $CaCO_3$ into CO_2 and CaO. The reaction taking place here is simply taking the inverse direction.

2. The supercritical CO_2 is transported to a location where no confining layer counteracts the buoyancy.

3. The injected CO_2 could lead to fracture of the confining layer.

4. The CO_2 reacts with geological materials, which leads to fractions in a confining layer.

5. The injection well is inappropriately installed or abandoned.

A confining layer usually does not imply a complete barrier for every fluid. The intention of the term confining denotes a *sufficient* barrier. It is the question whether this LM leads to considerable leakage of CO_2 or whether it is negligible.

This LM comes with the problem of classifying a particular geological formation as a candidate for CO_2 sequestration. The definition of a SS implicitly assumes that this LM is considered not to become effective or not to be significant. Therefore, the absence of this LM is the minimum requirement a geological formation has to meet in order to be considered for CO_2 injection.

The second LM emphasises the fact that confining layers are of limited lateral extent and that the CO_2 below it is migrating. The migration of CO_2 is due to the forced displacement of the formation water induced by pressure differences and due to the natural flow formation water that transports the supercritical CO_2 with it.

There are two different possibilities for leakage. First, the CO_2 comes to the edge of the confining layer and therefore there is no barrier that counteracts the buoyant force of the CO_2. Second, there could be a fault. Faults are fractures of geological layers along which there has been displacement of the sides relative to one another; see Bates and Jackson (1980, p. 223). Such a fault has been indicated in Fig. 5.29.

The third LM is related to the stability of a confining layer. Two reasons lead to fracturing of the confining layer. The fracture is either naturally existent or induced by human action. Natural fracturing is due to endogenous geological processes.[56]

Anthropogenic inducement of fracture – in the case at hand – is related to the injection of CO_2. This is due to the change of patterns of pressure due to the

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[56] The term endogenous process in geological sciences describes all processes that are implied by forces from within the interior of the earth. This includes plate tectonics as well as volcanic activities. Exogenous process are implied by forces from outside the earth, including meteors or solar radiation; see Press and Siever (1995).

CO_2 injection. This might lead to continuous shifting of geological layers or to rearrangement of elastic energy within a wider geological region. Depending on the particular conditions the elastic energy could exceed a critical value, which leads to fracture.

Sudden fractures could even lead to seismic activity. Sminchak et al. (2001) report 20 seismic activities that are caused by the injection of fluids including 13 events that are related to the injection of CO_2 for the enhancement of oil recovery. The greatest seismic activity with respect to underground waste disposal has been reported in Denver, Colorado, where 5.5 at the Richter scale has been reached.[57] The authors note that seismic events can occur with a delay of several years and in remote areas. Moreover, it is not clear whether injection of fluids could counteract natural seismic activity, since the rearrangement of elastic energy does not necessary imply harming effects.

The CO_2 could also lead to small fractures that lead to channels for concentrated flow of CO_2. Such channels could path through the confining layer. This kind of fracturing is known from geological operations, where it is induced to increase the recovery of hydrocarbons. This kind of operation it is called fracing.

The fourth LM is related to the reaction of CO_2 with geological material. One can think of three different reactions that are related to leakage. First, the CO_2 reacts with the material that forms the confining layer, which leads to channels for leakage. Second, the CO_2 reacts with material that initially closed faults that have originated from natural processes. Third, the CO_2 reacts with cement of existing or abandoned wells. This is related to the way of operating and sealing boreholes as has been described in Ch. 5.4. The problem of leaky wells is analysed by Celia et al. (2004), who emphasis the large degree of uncertainty.

The fifth LM is related to inappropriate construction of injection wells. Bad construction of the cementation can lead to channels through which the CO_2 finds preferential path ways.

The LMs discussed above suggest that – in general – a lower injection rates decreases the probability of leakage, as this reduces the stress that is imposed on

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[57] The Richter scale is simply a logarithmic scale representing the maximum movement of the earth relative to a fixed point during a seismic activity without taking into account the spatial extent or the potential for destruction. Press and Siever (1995, Ch. 18) note that at Richter scale 6 destruction of buildings will happen. For purpose of comparison the San Francisco Earthquake 1906 reached 8.3 and the most severe earthquake ever reported is 9 at the Richter scale.

the geological formation. This is in trade-off with the costs of injection that depend negatively on the injection rate.

The leakage from the geological formation into which the CO_2 is injected through the confining layer does not necessarily imply that the CO_2 leaks into the atmosphere. It also depends on the layers that lie above the confining layer. If there is a second confining layer, the CO_2 will meet a further barrier. The effectiveness of that second confining layer depends on the buoyancy of the CO_2, which in turn depends on the pressure – an therefore the density – of the inleaking CO_2. As a rule, the second confining layer is more effective the deeper it is located. This implies that deeper injection reduces the risk of CO_2 leakage because the probability for the existence of a second confining layer is higher as well as the probability that it is effective. Deeper injection depths imply higher costs of well drilling and energy needs for injection.

There is considerable dispute about leakage rates. The discussion is framed along three questions. The first question is geological and explores the leakage rate of a particular SS; see e.g. Lindeberg (1997), Bradshaw et al. (2004) and Zhou et al. (2004). The second question is more economic and asks what leakage rates are acceptable in order to utilise CCS as an effective option for climate protection; see e.g. Pacala (2003), Dooley and Wise (2003) and Bauer et al. (2004). The third question is also economic and asks for the effectiveness of regulatory frameworks that motivate private investors to look for SS with low leakage rates; see Ha-Duong and Keith (2003), Edenhofer et al. (2004a) and Herzog (2004). This thesis is devoted to the second question that will be discussed at length in Ch. 7.

5.5.4 Sequestration Alternatives

There are several types of geological formations considered for CO_2 sequestration. The particular types of geological formations sites are summarised as sequestration alternatives SA. This subsection introduces the various types of SA with regard to SM and LM, which have been introduced above.

The SM are classified with respect to the description of the geology. In the literature on CO_2 sequestration the following four SA are discussed:

1. saline aquifers;
2. abandoned oil and gas fields AOGF;

3. deep lying coal seams;
4. oil fields in operation, so called enhanced oil recovery EOR.

These SA have different characteristics with respect to the SM and LM. Moreover, there are differences with respect to the operation of CO_2 injection. Tab. 5.15 gives a comprehensive overview of the most important characteristics of each SA. Afterwards the content of the table is discussed in more detail and specific information si added.

These SA are sedimentary tied to sedimentary basins, which cover about one third of the total land surface of the earth. Also, fossil energy carriers are extracted from sedimentary basins. This is an important feature for the spatial matching of CO_2 sources and particular sequestration sites.

Saline aquifers are deep lying sedimentary layers, which contain water in the pore space. The depth is essential for keeping the CO_2 in the super-critical state, which usually requires at least 800m. The formation water is usually of high salinity and contains several other ingredients. This low quality water is not useful for economic activity.

In saline aquifers there are three SM at work: immobilisation by a impermeable confining layer, solution in the water and reaction with geological material; see e.g. Meer (1996). All LM could possibly lead to leakage of the CO_2. This will be discussed in the following.

The injection of CO_2 into a saline aquifer requires the displacement of the formation water. Achieving the goal of a high injection rate over years depends on the particular conditions of a SS. The desired characteristic is that the porosity and the permeability is high because this allows the easy displacement of formation water; see e.g. Gunter et al. (1996). Moreover it reduces the probability of viscous fingering and build-up of pressure anomalies, which might lead fractures.

Unfourtunately, the high permeability is in a trade-off relation to the goal of reducing leakage. The buoyancy forces of the supercritical CO_2 would drive the injected CO_2 upwards at a higher rate. This in turn increases the probability of CO_2 finds a leaky hole in the confining layer.

There are two important features of the permeability of saline aquifers with respect to high injection rates and low probability of leakage. First, if the horizontal permeability is higher than the vertical permeability, the injected CO_2 would be

Table 5.15: Overview of sequestration alternatives SA regarding sequestration mechanisms SM and leakage mechanisms LM.

	Sequestration alternatives SA			
	Saline aquifers	Abandoned O&G fields	Deep lying coal seams	Enhanced oil recovery
Buoyancy barrier	yes	main SM		yes
Solution	water			oil
Coal absorption			main SM	
Geological absorption	long term			
Permeable layer	yes	possible		
Missing barrier	yes	yes		
Fracture	yes	yes		yes
Reaction leak hole	yes	yes		yes
Injection well	yes	yes		yes

forced to move horizontally, too. In Fig. 5.29 on p. 237 this would imply that the CO_2 bubble would be broader and the amount of CO_2 moving upwards along the injection well would be less.

The second desired characteristic is that the permeability within the saline aquifer is heterogenous. Law and Bachu (1996) note that the injection should be placed in highly permeable zones. From there the CO_2 could move into zones of lower permeability, where it is trapped hydrodynamically. The particular spatial distribution of low and high permeable zone as well as the location of the injection well are important determinants for the migration path of the CO_2. The flow of CO_2 within the aquifer could also occur towards a leaky hole, e.g. a fault. If the fault has been closed by cementation processes, the CO_2 could open a leak hole through chemical reactions. This depends on the particular geological material that closed the leak.

As the buoyancy is still present, the confining layer is of special interest. There are two main different types with respect to the strength of the barrier. The first are termed aquitard, the second geological trap. An aquitard is a layer with low permeability and sufficient thickness. A geological trap has very low permeability and a caveat like form that could have been an accumulation layer for either oil or gas. An aquitard does not exhibit such form and could even be nearly flat. Aquitards are more frequent than geological traps and are larger in tendency. Especially aquitards could be permeable for CO_2. In order to prevent leakage into the atmosphere, an aquitard should be sufficiently thick.

The share of pore space that could be occupied by CO_2 is called the sweep efficiency. This is an important feature of saline aquifers for the assessment of the overall sequestration capacity. The computed sweep efficiency depends on the geological conditions and on particular model assumptions. A study by Meer (1995) computed a range for the sweep efficiency of 1 – 6% with a most likely value of 3% for a representative saline aquifer. Higher numbers (13 – 26%) are computed by Holt et al. (1995, p. 538).

Over time a fraction of the injected CO_2 dissolves in the formation water. This depends on the geological conditions, the flow of formation water, the salinity, the pressure, the temperature and the injection of CO_2.

It is a disputed question whether either hydrodynamic trapping or formation water solution is the major sequestration mechanism. For example, Law and Bachu (1996, p. 1173) conclude that hydrodynamic trapping is the most important SM and only up to 30% of the injected CO_2 are solved in the formation water. Different to that McPherson and Cole (2000, p. 69) conclude that up to 98% of the injected CO_2 dissolves in the formation water. Bachu and Adams (2003, p. 3155) point out that such results depend on simulations methods used and time-scales taken into account.

The geological absorption through chemical reactions is a disputed question because the time scales for this SM could be very long. In experimental studies with sedimentary material and saline formation water the chemical reactions can be assessed; see Kaszuba et al. (2003). Soong et al. (2004) made experiments with formation water, only, and found that the acidity of the formation water is the key parameter for the reaction of CO_2 with geological material in the formation water.

There are at least three problems with such experimental studies. First, the experiments undertaken involve small volumetric scales without any flow of formation water and CO_2 or geological dynamics of SM and LM. Second, the experiment outcome depends on the particular material used. Third, the experimental conditions exaggerate the natural conditions in order to observe reactions over meaningful experimental time scales; Kaszuba et al. (2003) increased the pressure and temperature to 200bar and 200°C.

The Sleipner West, Norway, project injects 0.27MtC p.a. into a saline aquifer called Utsira formation. The aquifer lies 1000m deep and is confined by an aquitard of about 400km North-South and 100km East-West extension that is nearly flat. The aquifer exhibits high porosity and permeability as well as a high natural flow of the formation water towards the East. Although no leakage has been observed, it is clear that the formation water flow will bring the CO_2 to the edge of the aquitard, where the barrier is not present any more; see Arts et al. (2004).

In summary, deep saline aquifers are ubiquitous in regions consisting of sediments. The injected CO_2 has to displace the formation water, which makes high permeability and porosity desirable features. The high permeability is at odds with the prevention of leakage. Therefore, the permeability should be heterogenous in way that eases the injection but prevents leakage. The buoyancy of the super-critical CO_2 requires an effective confining layer to prevent leakage. Solution of the CO_2 in water depends on the conditions of the formation water. The geological absorption of CO_2 depends on a complex interplay of geological, physical and chemical conditions and it is ambiguous whether it is a pure SM or a step towards leakage. The studies reviewed did not make clear statements on leakage rates.

There are two competing economic practices with CO_2 sequestration in saline aquifers. First, some saline aquifers contain natural gas, which could be extracted with appropriate technologies; see BGR (2003, Ch. 3). Second, saline aquifers have a temperature that is considerably above ambient surface conditions and are therefore a potential for low temperature heat recovery. Both potentials can not be exhausted from a particular saline aquifer, if CO_2 is injected.

Next, the SA of abandoned oil and gas fields AOGF is introduced. With respect to long-term sequestration this SA has particular advantages and drawbacks. The advantages are that the main geological features are well known because extraction firms undertake several geological studies in the course of operation. Moreover, the geological trap has proved to be able to keep the buoyant hydrocarbons over geological time scales. The major drawback is related to the penetration of the geological trap with extraction wells.

The main SM at work in AOGF is due to the impermeable barrier – i.e. the geological trap – that counteracts the buoyancy of the supercritical CO_2. The main difference to saline aquifers is that the sweep efficiency is much higher. The CO_2 injection intends to fill nearly the entire pore space with CO_2. This can be done by repressing the poured formation water. The extent to which this can be done depends on the pressure of the flooding water and the threshold value for fracture of the geological trap; see Bachu and Shaw (2004).

The flooding water from underlying aquifers implies an additional permanent effect that prevents the complete repression. A fraction of the flooding water cannot be repressed because it fills small pore spaces from which it can not be repressed. Bachu and Shaw (2004) point out that the effect of the flooding water reduces the capacity for CO_2 sequestration by up to 30% in gas and 50% in oil fields.

The problem of CO_2 leakage through abandoned extraction wells – so called leaky wells – is an inherent problem of this SA. For example Celia et al. (2004) report that in Texas 1 million wells have been drilled into oil and gas fields of which the information on location, material and method of disuse are of different quality. If CO_2 is injected into an AOGF it might come in touch with an average of 240 (18) and up to 700 (130) abandoned wells, if the well drilling density has been high (low). These wells are potential leak holes. The actual leakage depends on the cement used and the method of disuse. There might be high permeable channels for preferential flow of CO_2 or the CO_2 might corrode the cement in order create such channels. This has been assessed by Celia et al. (2004) and Zhou et al. (2004). The latter study computes low leakage rates due to leaky wells (0.001% of cumulative injected CO_2).

The third SA is related to deep lying coal seams. The SM present in this SA is primarily the absorptive force that solid coal imposes on CO_2. The absorption is a connection between the coal and the CO_2 based on intermolecular forces that is assessed to be stable over geological periods of time. If the coal seam absorbs methane prior to the CO_2 injection, the methane is released because the coal prefers to absorb CO_2. This methane can be extracted by an additional well. This technique is known as Enhanced Coal Bed Methane. The prospects of this technology are disputed in the literature, which is mainly due to the large variability of geological characteristics of coal seams; see DTI (2001), Hamelinck et al. (2002) and Enquete-Kommision (2002, p. 473).

The fourth SA is related to oil fields that are already in operation. The CO_2 is injected into a mature oil field to dissolve the CO_2 in the oil. The solution process is not only an SM, but it to decreases the viscosity of the oil, which eases the extraction. CO_2 that is extracted with the oil is recovered and re-injected. This type of operation is known as enhanced oil recovery EOR.

CO_2 for the sake of CO_2 sequestration plays an ambiguous role in EOR. In commercial EOR operations the CO_2 is a scarce production factor and is used in way to increase the oil production. For the sake of CO_2 sequestration however as much CO_2 as possible should be sequestered in the oil field; see e.g. Jessen et al. (2005). Therefore, EOR is characterised by an inherent trade-off relationship with respect to the CO_2 uptake.

Moreover, the leakage of CO_2 from oil fields that are in operation is disputed. Enquete-Kommision (2002, p. 476) assessed that EOR would sequester only about 50% of the injected CO_2. Gunter et al. (1998, p. 218) assessed the retention time of CO_2 in EOR to be some decades, only. A more optimistic assessment is given by Walton et al. (2004) with respect to the EOR project at Weyburn, Canada.

The SAs are classified with respect to common geological characteristics. Therefore, each SA is different with respect to SM and LM, as has been discussed. But the SA are not homogenous classes with respect to the size of a single SS or leakage rates etc. It is possible to make plausible *ad-hoc* assumptions regarding the differences of leakage rates for different SA; e.g. the leakage rate of AOGF could be considered higher than that of trapped aquifers. But such assumptions would be highly disputable because the range of leakage rates within each SA is probably the same as the range between different SA. A viable exit from this dilemma of classification is to form classes across geological criteria with respect to classes of parameters that are of interest in a study.

5.5.5 Sequestration Capacities

The sequestration capacity SC of each SA is assessed at the global level in the following. The SC describes the maximum amount of CO_2 that could potentially be injected over time. It is not necessary that these capacities are exhausted.

The computations of capacities found in the literature mainly use rough estimates of the key parameters and combine them in simple linear relationships. The fundamental thought behind the capacity assessments is that an SC – at some regional scale – represents a fraction of the volume of an SA that could be filled with CO_2. Multiplication of this volume with the density of CO_2 then give the SC. Since the CO_2 density is assumed at supercritical conditions to be $700 - 800\frac{\mathrm{kgCO_2}}{\mathrm{m}^3}$, the assumptions about the overall volume of an SA and the fraction that can be occupied by the CO_2 are sensitive parameters of the SC.

There are two methods to compute aggregate data of SC for each SA for a region. The first method is top-down, the second bottom-up. In the top-down approach one starts at the regional level – e.g. Europe – and assumes representative values, which are assumed for the overall region. In the bottom-up approach one starts at the SS of a region and adds the capacities of all SS.

The drawback of the bottom-up approach is that detailed information and data on the subsurface of a region are required. This is not necessary in the top-down approach, because the required assumptions are based on information that are publicly available. The problem with the assumption of the representative parameters in the top-down approach is obviously that the heterogeneity of the geology of a region is not taken into account.

At first the results are summarised in Tab. 5.16 and then some comments are added.

The study by Hendriks (1994) applies a top-down approach. He distinguishes two

Table 5.16: Overview of sequestration capacities at the global level in 1000GtC. Source: see footnotes.

	Sequestration Alternatives SA									
	Untrapped aquifers		Trapped Aquifers		Abandoned O&G fields		Deep coal seams		Enhanced oil recovery	
	on[a]	off[b]	on	off	on	off	on	off	on	off
H94[c]	10.	5.	.04	.02	0.52					
RH95[d]	0.11				.13				.02	
MM01[e]	<1				0.5		.04			
H02[f]			.07		.18	.10	.07		.03	.01
D04[g]	1.54	1.06			.22		.05			

[a] on denotes on-shore.

[b] off denotes off-shore.

[c] Hendriks (1994, p. 186, 190, 194).

[d] Ribeiro and Henry (1995, p. 7, 20, 26).

[e] Moomwa and Moreira (2001, p. 251).

[f] Hendriks et al. (2002, p. 49 – 51).

[g] Dooley et al. (2004b).

types of saline aquifers: those with a geological trap and those without. Moreover, he assumes a distribution scheme of two thirds on-shore and one third off-shore. He assumes a global area under which aquifers (trapped and untrapped) are located of which in turn 1% is trapped. Then he assumes an average thickness and an average porosity, which is sufficient to compute the total pore volume. Assuming a sweep efficiency of 2% (5%) for untrapped (trapped) aquifers and a density of CO_2 at $700\frac{\mathrm{kgCO_2}}{\mathrm{m^3}}$ he computes the SC for the two types of aquifers. Most notably: the difference of SC between the trapped and untrapped aquifers is a factor of 250.

For the AOGF Hendriks (1994) uses the data of reserves and resources for conventional[58] oil and gas from the literature including depth, pressure and size in the reservoirs. In combination with the densities of oil and gas in the hydrocarbon reservoirs he computes the pore volume that accessible for the CO_2. This in turn is combined with the density of CO_2 in the reservoirs to compute the SC. No assumptions have been made on invading water into hydrocarbon reservoirs that could reduce the SC.

The other studies do not make explicit assumptions used to assess the SC. Ribeiro and Henry (1995) note that their study on saline aquifers refers to the

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[58] Unconventional oil and gas are not taken into account because the corresponding reservoirs will not be appropriate for CO_2 sequestration.

amount of CO_2 sequestered by solution in water. Dooley et al. (2004b) refer to a database, which indicates that they follow the bottom-up approach. Hendriks et al. (2002) give lower and upper 5% quantiles of the estimations.

The estimations by Hendriks (1994) are the highest numbers found in the literature. The computations suggest to assess it as the maximum potential for untrapped aquifers and AOGF. The numbers for the trapped aquifers could be even higher, since for Denmark the sequestration capacity with traps has been assessed to be 2.7GtC; see Larsen et al. (2002). The later study by Hendriks et al. (2002) does not take into account untrapped aquifers without giving reasons for that.

Comparison with the assessments on fossil fuel reserves and resources expressed in tons of carbon (see Tab. 4.4 on p. 111) indicates that a considerable share of the fossil resources could be sequestered, if untrapped saline aquifers are taken into account. The next most important SA are the AOGF that do have the undesirable potential for leakage through leaky wells. The potential of the remaining SA is not as considerable relative to the enormous amounts of fossil fuels assessed as reserves or even resources.

5.5.6 Summary and Conclusion

The sequestration of CO_2 in geological formations mainly relies on geological characteristics. There are several geological processes at work that enable long-term sequestration of CO_2. The location and rate of injection of CO_2 as well as activities prior to the CO_2 injection also determine the CO_2 sequestration capacity as well as possible leakage.

The geological conditions and the injection of CO_2 involve highly complex processes that act at small spatial scale and over long time scales that require detailed understanding. The implications for long-term sequestration of CO_2 are uncertain. This leads to several questions with respect to long-term carbon sequestration. The geological question related to the magnitude of leakage rates is not enough because it is not related to choices that shall be assessed. The economic questions with respect to the amount of carbon sequestration and with respect to the selection of sequestration sites augment the scope of this question. This thesis is related to the choice of the optimal amount of carbon sequestration.

Economic modelling of the characteristics of geological sequestration in order to address this question relies on geological data. The problem is that geological data – so far – does comprehend sequestration sites within sequestration alternatives that do not fully catch the characteristics that are relevant to answer the question of the optimal amount of carbon sequestration. The main issue is the capacity of sequestration alternatives. But for the estimation of leakage rates, location and depth of the sequestration sites etc. should also be taken into account. In a first step this thesis follows the geological classification scheme.

The capacities for geological carbon sequestration are enormous relative to the amount of carbon contained in fossil fuels. The most important sequestration alternatives are untrapped saline aquifers and abandoned oil and gas field. Both alternatives are disputed in the literature with respect to leakage. The other sequestration alternatives do offer much less capacity and therefore seem not to be viable to serve as considerable basis for long-term climate policy. A more detailed assessment would be required with respect to the untrapped saline aquifers and the abandoned oil and gas fields to enhance the data of the characteristics noted above.

Geological sequestration is related to several other questions that will not be treated in detail in this thesis. These questions include the issue of public safety, monitoring & verification, legal approval, institutional framework within the Kyoto-Protocol and the public perception and acceptance.

5.6 Concluding Discussion

In this chapter the literature on techno-economics and geology of carbon capture and sequestration has been reviewed. The most important conclusions are:

1. There is considerable experience from commercial operations with small to medium scale of capturing carbon and injecting it into geological formations. The carbon capture technologies employed so far are mainly based on conventional technologies – following the EP approach – that would impose considerable costs, if they are introduced at large point sources of CO_2 like coal power plants. The experience with CO_2 injection stems from commercially applied enhanced oil recovery, where the CO_2 is a production factor rather than waste product that should be kept from the atmosphere. The Sleipner West project in Norway is the only carbon capture and sequestration project that is motivated by the imposition of a carbon tax. The experience of the project shows

that the costs are considerable and the geological formation already shows no leakage.

2. The extra effort for carbon capture and sequestration is considerable. Of all cost components of CCS the carbon capture part accounts for about 80% of the total costs. Some components of these costs can not be reduced. The effort of CO_2 compression is inevitable for sequestration. The need to separate gases is a common characteristic of all proposals – some being speculative – which reduces the efficiency of industrial plants. There are some industrial plants that offer small extra effort for carbon capture because of the inherent production of a pure stream of CO_2. Most industrial plants that emit CO_2 do not offer such comfortable conditions for carbon capture.

3. Several proposals have been developed to reduce the extra effort for carbon capture. There is no experience at the large commercial scale with these proposals because the introduction would imply changes of the fundamental design of industrial plants or the introduction of new products that would require changes in consumer behaviour. This means that these proposals suggest the introduction of new designs into the market. Since these new designs do not offer direct benefits to the consumer and require long-term investments, a stable commitment of climate policy measures – like taxes, tradeable permits or regulations – is required in order to induce the corresponding investments by private firms. The stability of the political measures is essential for the innovation process to commit private firms to technologies that are not operational, yet. The political stability of climate policy is even more required, if it leads to investments that are related to consumer related infrastructure.

4. The sequestration of CO_2 in geological formations seems to be a viable option. Some features like leakage are still open to discussion and need further research. Such research has to be based on experience from field experiments because modelling studies are to a considerable extent based on assumptions that could turn out wrong. Although more research from limited spatial areas is necessary to understand the behaviour of CO_2 injected into geological formations. The data collected in the geological sciences should be organised in categories that allow subsequent assessment of geological carbon sequestration capacities at the global scale.

The title of this thesis refers to the question whether carbon capture is an option to buy time. The conclusions drawn so far suggest some doubts whether the technology is available, yet. This doubt is in part due to the scientific uncertainties related to the geological side of the problem. Another part of doubt is whether the capture technologies are available in technical terms. This technical side of the problem is intimately tied to the question whether private firms are willing to reformulate their investment strategies towards technologies that are not commercially proven, yet, and that are only profitable with a stable political framework.

The required political framework is motivated by the public objective of climate protection. This justifies the support of R&D by public funds, which includes subsidies to built pilot plants operated by private firms, which would require considerable amounts of money. Public R&D funding to private firms does not automatically guarantee the selection of the most appropriate proposals. The analysis so far showed that within coal fired power plants the oxy-fuel concept is comparable to the concept based on syngas; i.e. IGCC. Within the market of coal based power plants IGCC has not turned out to be competitive with conventional PC systems. The oxy-fuel concept does not require the fundamental change of the design of such plants and therefore suggests a more incremental improvement of coal based technologies. A decision on R&D funding should take into account these considerations.

The modelling effort in this thesis is based on the information collected from the studies reviewed in this chapter. The modelling approach using optimisation techniques is inherently weak in representing the process of long-term investment strategy selection of private firms. The interpretation of the model results requires the notion that private firms – especially in the energy sector – take into account much more real world data than could be modelled. Moreover, these firms form their expectations independently, which could lead to diametral different investment strategies of the firms. A possible development in the field of climate protection and CCS is that private firms could interpret the combination of innovation and political measures as a way to gain market power by demanding political regulations that harm their competitors. This would be a task in the field of public choice that is not in the scope of this thesis.

Chapter 6

Modelling Carbon Capture and Sequestration Endogenously

6.1 Introduction

In the preceding chapter the techno-economic and geological features of CCS technologies have been presented. In this section an approach for the modelling and integration of CCS is developed in order to set up the model *MIND1.1*. The approach represents the following features:

1. ***Energy consumption*** Carbon capture requires energy. The approach takes this into account and the corresponding energy has to be produced.

2. ***Investment*** The capture, transportation and injection of CO_2 requires investments. The capacities will be available for some periods, but the investment has to be financed before the capacities are available.

3. ***Operation and maintenance*** Carbon capture and sequestration demands additional input factors that are summarised in O&M costs. These are related to the period in which the CO_2 is captured and sequestered.

4. ***Different capture technologies*** There are five different technologies for carbon capture, denoted i, with different techno-economic attributes:

    (a) ***Low Cost*** Industrial processes like hydrogen production, which generate a stream of concentrated CO_2 without extra efforts. Dehydration and compression are required, only.

   (b) ***ND coal*** New design coal technologies.
   (c) ***Post-PC*** Conventional coal power plants with chemical absorption.
   (d) ***Post-cement*** Cement kiln fired with coal that use chemical absorption for carbon capture.
   (e) ***Post-iron*** Oxygen-blown blast furnaces fired with coal that use chemical absorption for carbon capture.

   CCS technologies related to gas fuelled power plants are not considered because the costs are too high to be employed.

5. ***Different sequestration alternatives*** There are different sequestration alternatives that have specific characteristics with respect to the investments, sequestration capacities and leakage rates. Each alternative requires specific investments that are sunk. There are six alternatives distinguished with j:
   (a) ***TA on-shore*** On-shore trapped aquifers.
   (b) ***TA off-shore*** Off-shore trapped aquifers.
   (c) ***UA on-shore*** On-shore untrapped aquifers.
   (d) ***UA off-shore*** Off-shore untrapped aquifers.
   (e) ***AOGF on-shore*** On-shore abandoned oil and gas fields.
   (f) ***AOGF off-shore*** Off-shore abandoned oil and gas fields.

   Sequestration alternatives characterised by enhancement of hydrocarbon extraction – i.e. enhanced oil recovery and enhanced coal bed methane – are not considered.

6. ***Integration*** CCS is coupled to the economy by investments, O&M costs and energy demand. It is coupled to the climate via avoided emissions and leakage. The integration of CCS is done by introducing the relevant quantities in the economic and natural balance equations.

In Ch. 6.2 the theoretical structure of CCS is developed. The integration into the *MIND* framework is introduced in Ch. 6.3. In Ch. 6.4 the parameters will be calibrated with respect to the studies that have been presented in Ch. 5. Finally, the modelling approach will be discussed in Ch. 6.5.

6.2 The Theoretical Structure

The theoretical structure of the CCS modelling approach is based on the view that the capture and sequestration of carbon demands production factors, avoids immediate emissions, is limited by economic, technical and natural capacity constraints and some carbon leaks from the sequestration sites into the atmosphere. The approach distinguishes several process steps, several carbon capture technologies and sequestration alternatives. Moreover, the sulphate emissions related to the captured carbon is avoided, too, because of technical reasons given above. Ch. 6.2.1 and Ch. 6.2.2 introduces the modelling of the process steps of carbon capture *cap*, pipeline transportation *pipe*, re-compression *comp* and injection *inje*. The modelling of sequestration and leakage will be introduced in Ch. 6.2.3.

The process steps share a common feature that will be introduced now. The modelling approach is based on the view that the process steps require technical or natural capacities in order to treat a flow of CO_2 per period. The technical capacities have to be built up, which requires investments. The linkage between investment and capacity is structurally the same for all technical capacities. Therefore, the corresponding equation is explained here. The capacity is $K_{p,q}$. p denotes the process step; q denotes either the i capture technologies or the j sequestration alternatives. The investment is $I_{p,q}$ and the investment costs are $\iota_{p,q}$. The available capacity in t is a composite of several vintages. A vintage is the capacity addition in a period $\iota_{p,q} \cdot I_{p,q}$. From a vintage added in $t - \tau$ a fraction $\omega_q(\tau)$ is available in t. The vintage approach is:

$$K_{p,q}(t) = \sum_{\tau} \omega_q(\tau) \cdot \iota_{p,q}^{-1} \cdot I_{p,q}(t - \tau). \tag{6.1}$$

6.2.1 Carbon Capture

The modelling approach of carbon capture is related to the techno-economic features and the *MIND* framework in which it is integrated. The modelling of multiple technologies is difficult because the fossil energy sector is an aggregate one. It would be a considerable modelling effort to disaggregate the fossil energy sector with respect to multiple conventional non-capture technologies and fossil fuels first and then to introduce the capture technologies. The assumption of a single capture technology is subject to the critique that the different characteristics of the various technologies not modelled and the aggregation biases the result.

The modelling approach developed in here is a compromise. On the one hand, the basic model structure of *MIND1.0* should remain unchanged, which is mainly related to the highly aggregate energy sector. On the other hand, several capture technologies should be integrated in order to take into account their specific techno-economic characteristics.

The ability to capture carbon with a technology i is characterised by a capacity $K_{cap,i}$ in units of $\frac{\mathrm{tC}}{\mathrm{y}}$ that has to be built up with investments $I_{cap,i}$ according to Eq. 6.1. Therefore, the amount of carbon capture with technology i during a year is $R_{cap,i}(t) \leq K_{cap,i}(t)$. The inequality means that the capacities need not be fully employed. The total amount of captured carbon per year R_{cap} is simply the sum of the contribution of all i technologies:

$$R_{cap}(t) \leq \sum_i K_{cap,i}(t). \tag{6.2}$$

The primary and secondary energy demands for carbon capture – $E_{P,cap,i}$ and $E_{S,cap,i}$, respectively – are proportional to $R_{cap,i}$. The factors for the linear relationship are $\varepsilon_{P,cap,i}$ and $\varepsilon_{S,cap,i}$:

$$E_{P,cap,i} = \varepsilon_{P,cap,i} \cdot R_{cap,i}; \tag{6.3}$$

$$E_{S,cap,i} = \varepsilon_{S,cap,i} \cdot R_{cap,i}. \tag{6.4}$$

The O&M costs $OM_{cap,i}$ are linear in $R_{cap,i}$, and the factor is $o_{cap,i}$:

$$OM_{cap,i} = o_{cap,i} \cdot R_{cap,i}. \tag{6.5}$$

The extent of carbon capture is limited by a static constraint and the investment in carbon capture vintages is limited by a dynamic constraint:

1. ***Static constraint*** So far, the optimisation procedure would select investment into only one CCS technology; namely that technology with the lowest costs. This would make the disaggregation redundant and lead to unrealistic results. To overcome this problem the technologies can be employed to some upper level, only. The upper limit of $R_{cap,i}$ is a fraction of the resource extraction in the BAU case R^{BAU}; i.e. the BAU case sets an assumption on the CPP case with carbon capture. This fraction is denoted $\varphi^{stat}_{cap,i}$. Additionally, it is multiplied with the capture efficiency of each technology $\gamma_{cap,i}$:

$$R_{cap,i} \leq \gamma_{cap,i} \cdot \varphi^{stat}_{cap,i} \cdot R^{BAU}. \tag{6.6}$$

2. ***Dynamic constraint*** If the velocity of building up of carbon capture capacities $K_{cap,i}$ is unconstrained, the model would invest nothing in early periods and suddenly built up a large capacity. This is due to the property of dynamic optimisation models to choose extreme paths. Such a result is unrealistic because this would imply that a considerable part of the fossil energy capital stock – determined by Eq. 6.6 – could be retrofitted with carbon capture facilities within one period. In this thesis the problem is addressed by limiting the investment into each technology in each period. The dynamic constraint aims to relate $I_{cap,i}$ to the dynamics of the fossil energy sector. The rationale is that this relates the built up of carbon capture facilities to the capital overturning of the fossil energy sector. The relationship is established by assuming that the upper limit of $I_{cap,i}$ is a fraction of the investments in the fossil energy sector I_F; see Eq. 4.16 on p. 92. This fraction is denoted $\varphi^{dyn}_{cap,i}$:

$$I_{cap,i} \leq \varphi^{dyn}_{cap,i} \cdot I_F. \tag{6.7}$$

6.2.2 Transportation, Compression and Injection

Transportation of CO_2 demands pipelines, only. Pipeline transportation requires investments to provide the capacity to move the captured CO_2 from the location of capture to the point of injection. Leakage during pipeline transportation is not considered.

The pipeline transportation is seen as the movement of CO_2 from a common pool of all captured CO_2 to sequestration sites that belong to a sequestration alternative j. A single pipeline is characterised by its length and by a capacity that provides a through-put $\theta_{pipe,j}$ of an amount of CO_2 p.a. For a given amount of CO_2 that has to be transported to a sequestration alternative $R_{sequ,j}$ the pipeline capacity $K_{pipe,j}$ has to be in place:

$$K_{pipe,j} \geq \frac{\lambda_{pipe,j}}{\theta_{pipe,j}} \cdot R_{pipe,j}. \tag{6.8}$$

The length $\lambda_{pipe,j}$ of a pipeline to a sequestration site of type j depends on the fraction of to which the capacity of sequestration alternative $R^{max}_{sequ,j}$ is exhausted. The increasing pipeline length depends on exhausted capacity $\sum_{\tau=1}^{t} R_{sequ,j}(t-\tau)$

because the probability for finding an sequestration site adjacent to a capture facility decreases. The relationship is as follows:

$$\lambda_{pipe,j}(t) = \lambda_{pipe,j}^{min} + \lambda_{pipe,j}^{max} \frac{\sum_{\tau=1}^{t} R_{sequ,j}(t-\tau)}{R_{sequ,j}^{max}}. \tag{6.9}$$

The non-linearity in the cumulative utilisation of sequestration alternatives implies that in the optimum the sequestration alternatives are utilised simultaneously with different intensities.

The injection of CO_2 into particular sequestration sites demands two different kinds of facilities: compressors and injection wells. The modelling approach takes into account that both facilities demand investments and the compressors need secondary energy, additionally. The facilities are specific to the sequestration alternatives and have to be built-up before the CO_2 could be compressed and injected.

The additional compression is necessary because the pressure of arriving CO_2 is not high enough for injection. The capacity of compressors $K_{comp,j}$ describes the amount of CO_2 that can be compressed per year and therefore has to meet $R_{sequ,j}$. $K_{comp,j}$ is given in units of $\frac{\mathrm{tC}}{\mathrm{y}}$ and therefore the constraint is:

$$R_{sequ,j} \leq K_{comp,j}. \tag{6.10}$$

The secondary energy demand is linear in $R_{sequ,j}$ and with parameter $\varepsilon_{S,comp,j}$:

$$E_{S,comp,j} = \varepsilon_{S,comp,j} \cdot R_{comp,j}. \tag{6.11}$$

The capacity for the CO_2 injection $K_{inje,j}$ is characterised by injection wells that provide a flow rate $\varphi_{inje,j}$. The constraint that has to be met is:

$$R_{sequ,j} \leq \varphi_{inje,j} \cdot K_{inje,j}. \tag{6.12}$$

The modelling approach ignores the secondary energy demand for injection as well as the leakage of CO_2 during injection. Moreover, the injection of CO_2 does not improve the production of hydrocarbons nor does the approach take into account trade-offs with other forms of utilisation.

All three process steps have in common that they need O&M costs $O\&M_{h,j}$, with $h = pipe, comp, inje$, which depend on the investment costs that are related to the capacity in operation by an percentage mark-up $o_{h,j}$:

$$O\&M_{h,j} = o_{h,j} \cdot K_{h,j}. \tag{6.13}$$

6.2.3 Sequestration

The modelling approach considers the capacity constraint of each sequestration alternative j and leakage of sequestered carbon.

The leakage rate $\lambda_{leak,j}$ is related to the CO_2 that is in a sequestration alternative; i.e. a given amount leaks exponentially over time. The amount of leakage R_{leak} is determined as follows:

$$R_{leak}(t) = \sum_{j=1}^{6} \sum_{\tau=\tau_1}^{t-1} \lambda_{leak,j} \cdot (R_{sequ,j}(t-\tau) - R_{leak,j}(t-\tau)) \tag{6.14}$$

The capacity of each sequestration alternative $R^{max}_{sequ,j}$ is the upper bound for the cumulative amount of CO_2 that is injected into each sequestration alternative:

$$R^{max}_{sequ,j} = \sum_{\tau=\tau_1}^{t} R_{sequ,j}(t-\tau) \tag{6.15}$$

6.3 The Integration

The integration of CCS into the *MIND* framework requires the extension of several equations introduced in Ch. 4.2. The investments and O&M costs have to be introduced into the budget equation. The energy requirements have to be introduced into the energy balance equations and the emission reductions and CO_2 leakage have to be introduced into the equations for CO_2 and sulphate emissions. Additionally, the corresponding exogenous assumptions of *MIND1.0* are removed.

The budget equation Eq. 4.2 now takes account of the investments $I_{p,q}$ and the O&M costs are contained in Ω:

$$\begin{aligned} Y = C + \sum_m I_m + \sum_i I_{cap,i} + \sum_j I_{pipe,j} + \sum_j I_{comp,j} + \\ \sum_j I_{inje,j} + \sum_n RD_n + \Omega, \qquad \forall\, t. \end{aligned} \tag{6.16}$$

The balance equation of fossil primary energy Eq. 4.17 has to be augmented by the extra energy need arising from carbon capture:

$$E_{P,F} + \sum_i E_{P,cap,i} = M \cdot R. \tag{6.17}$$

The balance equation for secondary energy Eq. 4.6 has to be augmented by the extra energy need carbon capture and compression at the sequestration sites:

$$E_S^A + \sum_i E_{S,cap,i} + \sum_j E_{S,comp,j} = E_{S,F} + E_{S,R} + E_{S,other}. \tag{6.18}$$

The CO_2 emission equation Eq. 4.23 has to be extended by the carbon that is captured and additional emissions from leakage:

$$E_{CO_2} = R + E_{CO_2,LUC} - R_{cap} + R_{leak}. \tag{6.19}$$

The emission equation for sulphate aerosols Eq. 4.24 has to be extended by those emissions that are not emitted because of the capture process:

$$E_{SO_2} = C2SO_2 \cdot (R - R_{cap}). \tag{6.20}$$

6.4 The Calibration

The calibration is based on the techno-economic and geological studies reviewed in Ch. 5. The capture part is treated in Ch. 6.4.1. The approach used repeatedly is to derive the cost coefficients per ton of carbon from these studies. The transportation, injection and sequestration are treated in Ch. 6.4.2.

6.4.1 Carbon Capture

In the following the assumptions of the parameter of the carbon capture technologies are developed. The overview is given in Tab. 6.1. First, the technologies *Post PC* and *ND coal* are treated and the others afterwards.

$\iota_{cap,i}$, $\epsilon_{P,cap,i}$ and $o_{cap,i}$ of capture technologies *Post PC* and *ND coal* are determined as follows. For each study in Tab. 5.2 and Tab. 5.9 the three parameters are computed and the averages are taken for the parameter. In the following equations physical conversion and scaling factors are omitted.

For ι_{cap} the following equation is applied:

$$\iota_{tC} = \frac{\iota_{cap,\mathrm{kW_e}} \cdot C_{cap,\mathrm{kW_e}} - \iota_{ref,\mathrm{kW_e}} \cdot C_{ref,\mathrm{kW_e}}}{\nu \cdot (E_{ref,\mathrm{kWh_e}} \cdot C_{ref,\mathrm{kW_e}} - E_{cap,\mathrm{kWh_e}} \cdot C_{cap,\mathrm{kW_e}})}. \tag{6.21}$$

The notation is as follows: ι_{tC} is the investment costs in units of \$US per ton of carbon and year. k distinguishes the reference ref or the capture cap plant. $\iota_{k,\mathrm{kW_e}}$ are investment costs in units of $\frac{\$\mathrm{US}}{\mathrm{kW_e}}$, $C_{k,\mathrm{kW_e}}$ denote capacities of plants in kW$_\mathrm{e}$, $E_{k,\mathrm{kWh_e}}$ are emission coefficients in $\frac{\mathrm{gC}}{\mathrm{khW_e}}$ and ν is the number of full load hours set to $6570\frac{\mathrm{h}}{\mathrm{y}}$.

For $\epsilon_{P,cap,i}$ the following equation is applied, where η_k denotes the conversion efficiency:

$$\epsilon_{P,cap} = \frac{\frac{1}{\eta_{cap}} - \frac{1}{\eta_{ref}}}{E_{cap,\mathrm{kWh_e}} - E_{ref,\mathrm{kWh_e}}}. \tag{6.22}$$

For $o_{cap,i}$ in $\frac{\$\mathrm{US}}{\mathrm{tC}}$ the following equation is used, where $O\&M_{k,\mathrm{kWh_e}}$ are the O&M costs per kWh$_\mathrm{e}$:

$$o_{cap} = \frac{O\&M_{cap,\mathrm{kWh_e}} - O\&M_{ref,\mathrm{kWh_e}}}{E_{cap,\mathrm{kWh_e}} - E_{ref,\mathrm{kWh_e}}}. \tag{6.23}$$

For the technology *Low Cost* the assumptions on investment costs without compression, primary energy consumption and O&M costs are taken from Farla et al. (1995). The investment costs for compression are taken from Hendriks et al. (2002) with the additional assumption that the average emission flow per plant is 0.27MtC p.a. The secondary energy demand for compression corresponds the coefficient provided in Hendriks et al. (2002).

For the technologies *Post-cement* and *Post-iron* the energy demand and the O&M costs are taken from Farla et al. (1995). The investment costs are taken from Hendriks et al. (2002) with the additional assumption that the average size of cement plants is 0.55MtC p.a. and for BOF iron plants 1.09MtC p.a.

The extra primary and secondary energy need, $\epsilon_{P,cap,i}$ and $\epsilon_{S,cap,i}$ respectively, are derived from the energy penalty that is related to units of $\frac{\mathrm{MJ}}{\mathrm{tC}}$. The O&M cost coefficients $o_{cap,i}$ are related to the extra O&M costs in units of $\frac{\$\mathrm{US}}{\mathrm{tC}}$.

The static constraints $\varphi^{stat}_{cap,i}$ are chosen in accordance with the findings in Ch. 2.3.2. The capture efficiency $\gamma_{cap,i}$ is assumed at 0.85 for all technologies. The dynamic constraint parameters $\varphi^{dyn}_{cap,i}$ are the product of $\varphi^{stat}_{cap,i}$ with a parameter that indicates the capital turnover that allows for the addition of CCS to the fossil energy sector. This later parameter is based on *ad-hoc* assumptions.

Finally, a depreciation scheme is assumed $\omega_{cap}(1) = 1$, $\omega_{cap}(2) = 0.95$, $\omega_{cap}(3) = 0.9$, $\omega_{cap}(4) = 0.85$, $\omega_{cap}(5) = 0.5$. The initial capital stocks equal zero. Both assumptions are equally applied in the following.

Table 6.1: Exogenous model parameters of carbon capture.

		Low Cost	ND Coal	Post PC	Post-cement	PC-iron
$\iota_{cap,i}$	$\frac{\$US}{tC/y}$	98.5	156.0	338.0	443.6	311.8
$\epsilon_{P,cap,i}$	$\frac{GJ}{tC}$	.03	9.35	16.0	12.53	12.53
$\epsilon_{S,cap,i}$	$\frac{GJ}{tC}$	1.47			1.14	1.3
$o_{cap,i}$	$\frac{\$US}{tC}$	1.69	19.56	42.89	20.93	15.11
$\gamma_{cap,i}$		.85	.85	.85	.85	.85
$\varphi^{stat}_{cap,i}$		.06	.2	.2	.05	.05
$\varphi^{dyn}_{cap,i}$		.012	.05	.07	.0125	.0125

6.4.2 Transportation, Injection and Sequestration

In the following the assumptions on the exogenous parameters for the transportation, compression, injection and sequestration of the captured CO_2 are introduced. All parameters are summarised in Tab. 6.2.

The investments for the pipelines and through-put are taken from Hendriks et al. (2001). The magnitude of the O&M parameter – as for compression and injection – is a multiplier. The assumptions on pipeline lengths are based on *ad hoc* assumptions.

The investment costs and the secondary energy need for compression as well as the investment costs for injection wells are based on Hendriks et al. (2001).

The assumptions on the maximum capacities for the sequestration alternatives are a guesstimation based on the numbers discussed in Ch. 5.5.5. The assumptions on leakage rates are based on *ad hoc* assumptions.

6.5 Discussion of the Approach

The modelling approach requires some discussion prior to the numerical analysis. Six points should be discussed.

The first point is related to the disaggregation of the capture technologies. The representation of several capture technologies allows to choose the levels to which the option is used. Increasing amounts of carbon capture require more and more

Table 6.2: Exogenous model parameters of carbon transportation, compression, injection and sequestration.

		OnTA	OffTA	OnUA	OffUA	OnAOGF	OffAOGF
$\iota_{pipe,j}$	$\frac{\text{mil.\$US}}{\text{km}}$	3.1	4.2	3.1	4.2	3.1	4.2
$\theta_{pipe,j}$	$\frac{\text{MtC}}{\text{y}}$	10.	15.	10.	15.	10.	10.
$o_{pipe,j}$		.03	.03	.03	.03	.03	.03
$\lambda^{min}_{pipe,j}$	1000km	.05	.05	.05	.05	.05	.05
$\lambda^{max}_{pipe,j}$	1000km	1.	1.	1.	1.	1.	1.
$\varepsilon_{S,comp,j}$	$\frac{\text{GJ}}{\text{tC}}$	3.1	3.1	3.1	3.1	3.1	3.1
$\iota_{comp,j}$	$\frac{\text{\$US}}{\text{tC/y}}$	3.5	3.5	3.5	3.5	3.5	3.5
$o_{comp,j}$		.03	.03	.03	.03	.03	.03
$\iota_{inje,j}$	$\frac{\text{mil.\$US}}{\text{well}}$	2.75	13.2	2.75	12.7	2.25	12.2
$\theta_{inje,j}$	$\frac{\text{MtC}}{\text{well/y}}$	.27	.27	.27	.27	.27	.27
$o_{inje,j}$		.03	.03	.03	.03	.03	.03
$\lambda_{leak,j}$		.005	.005	.005	.005	.005	.005
$R^{max}_{sequ,j}$	GtC	35.	20.	2500.	1000.	100.	66.

costly technologies, which requires up-front investments that have to be financed from a scarce budget that has to be allocated to competing uses.

In the modelling approach introduced above each technology is essentially characterised by constant marginal costs. These could be interpreted as average costs of a technology. As is known from linear programming this modelling approach can induce jumps in the optimal solution for small parameter variations. A solution to this problem could be to further disaggregate the technologies in order to represent the various possibilities as a continuous sequence of alternatives.

Fig. 6.1 illustrates the difference. Two different marginal cost functions MCF of two profit maximising firms are distinguished in a static setting. Firm **I** is characterised by a smooth MCF – shown in the right panel. Firm **II** is characterised by a stepwise MCF and shown in the left panel. Assume that the price of carbon is given exogenously. Profit maximisation leads the firms to increase the CCS amount until

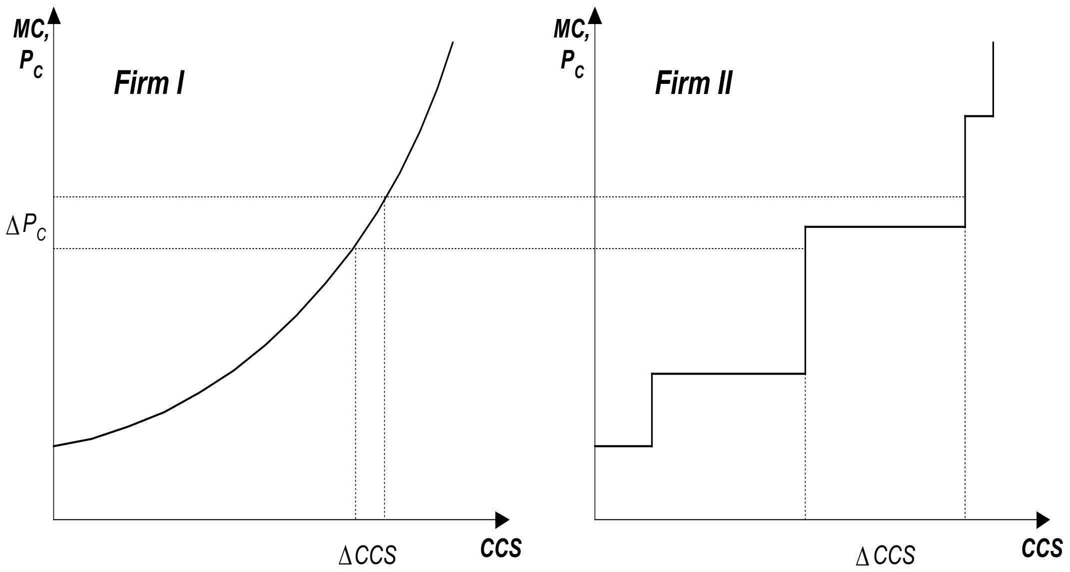


Figure 6.1: Smooth and stepwise constant linear marginal cost functions MCF for two profit maximising CCS firms.

the marginal costs of CCS equal the price of carbon. When the price of carbon increases both firms will react differently. Firm I increases its CCS amount smoothly, while firm II reacts stepwise.

A behaviour similar to that of firm II might also be observed for the dynamic model. A solution to this problem could be the introduction of a smooth carbon capture cost function, but this is at odds with the feature of up-front investments because a MCF is a purely static approach. Therefore, the linear features of a number (here five) of capture technologies is a compromise between the disaggregation of alternative technologies and the dynamic property of capital stocks.

The second point is related to the approach that a disaggregate CCS module is added to an aggregate fossil energy sector. The various energy carriers, conversion technologies and forms of end-use energy are not represented. Therefore, the modelling approach lacks of a rigorous engineering based energy system that represents the various energy carriers, conversion technologies and end-uses of various forms of energy. This modelling task will be addressed in the future.

The third point is related to leakage and the integration with a climate model. The modelling approach allows to assess the short-term consequence on CCS activity induced by longer-term consequences of delayed emissions. A problem with the modelling of leakage is that the exponential leakage process omits the dynamics within sequestration sites. This would require to split the CO_2 within a sequestration site into at least two parts: a save part and a free part and only the latter is subject to leakage. Depending on time the free part is transferred to the save part.

The fourth point is related to the so-called source-sink matching. This is the geographic problem that the points of carbon capture and the locations, where the corresponding carbon is injected, have to be connected with pipelines explicitly. The above approach to model this feature by increasing the length of pipelines as the sequestration capacities are exhausted is to weak to represent the essence of the problem. This is that there are some sources that are very close to sequestration sites and others are very distant; even some are so distant that they are out of reach to any sequestration site; e.g. large area earthquake areas like east Asia. Sophisticated research on this problem is provided by Dooley et al. (2004a).

The fifth point is related to the modelling of sequestration alternatives. As already discussed above, sequestration alternatives characterised by geological categories do not fit with the economist's point of view. An assessment of CCS would require the knowledge of sequestration alternatives along criteria like capacity and availability distinguished by leakage rates.

The sixth point is related to the choice of parameters. The lack of data implied to ignore some energy needs, espec. that for pumps and blowers for pipeline transportation and injection of CO_2. Moreover, the static and dynamic constraint parameters imply a high flexibility of the CCS sector.

Chapter 7

Scenarios, Results and Uncertainty Analysis

7.1 Introduction

In this chapter the results gained with *MIND1.1* are introduced. The primary focus above has been put on the behaviour of several model variables for different scenarios. The focus in this chapter is different in that it asks for the robustness of endogenously determined CCS, since this outcome depends on uncertain exogenous parameters.

In this chapter the focus is limited only on two scenarios: the business as usual BAU scenario without climate constraints and the climate protection path CPP scenario with constraints imposed by the climate window and CCS is an available mitigation option.

Presentation of the results requires the introduction of the base case result. The base case is the set of parameters laid out in detail in Ch. 4.3 and Ch. 6 for which the two scenarios are computed. The base case result is then summarised in comprehensive indicators that serve as the reference point for the detailed analysis of parameter uncertainties.

The presentation is organised along four questions. The first question is related to the optimal time path of carbon capture and sequestration and in what respect it is different from the exogenous path assumed in *MIND1.0* in Ch. 4. Moreover, the importance of the various capture technologies and sequestration alternatives is assessed.

This leads to the question of the robustness of the base case result that might crucially depend on uncertain exogenous parameters. This question is answered using two methodologies.

The first method is the sensitivity analysis with which the robustness of the result is tested by deterministic variations of parameters in low dimensional spaces. The sensitivity analysis provides insights into the dependency of the optimal result on exogenous variations of single parameters. Of special interest is the shape of such dependencies, since the result might vary strongly, if the exogenous parameter passes a threshold level.

The second method is the Monte-Carlo analysis with which the robustness of the result is tested by stochastic variations of parameters in high-dimensional spaces. The Monte-Carlo analysis provides insights into the robustness of the result around the base case parameter set.

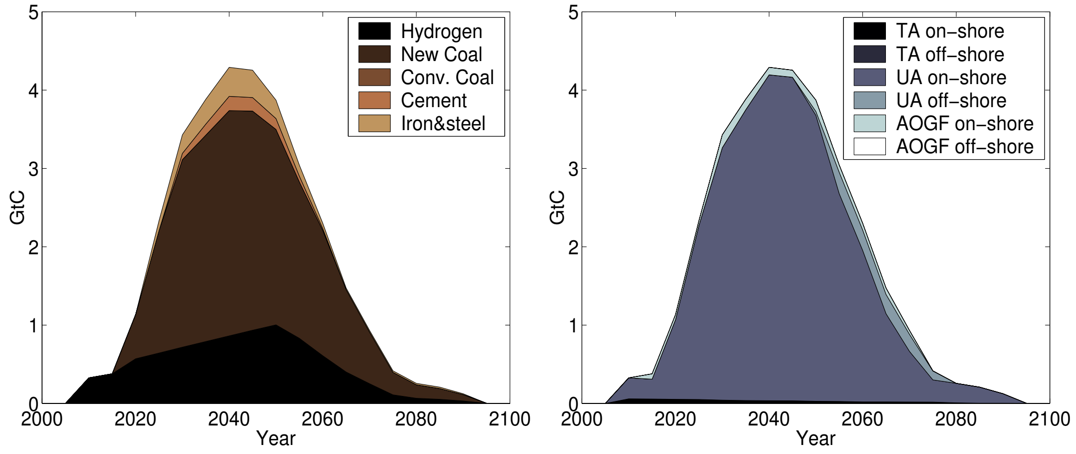
The third question is related to the consequences on future work of integrated assessment modelling. Since the modelling approach developed in this thesis has draw-backs it is necessary to identify areas that alter the result significantly. The sensitivity analysis provides insights into the importance of single parameters for the result and which parts of the model should be modelled and analysed in more detail in order to improve the assessment of CO_2 emission mitigation strategies.

The fourth question is related to the comparison of the results with those of other studies. The comparison of results is related to other studies also focusing on CCS.

The chapter is structured as follows. In Ch. 7.2 the base case result is introduced. In Ch. 7.3 the results of a series of sensitivity analysis is presented. In Ch. 7.3.4 the results of the Monte-Carlo Analysis (MCA) are shown. In Ch. 7.4 the results are compared with those of other studies. Finally, the results are discussed and conclusions for further modelling efforts are drawn in Ch. 7.5.

7.2 Base Case Result

This section presents the endogenously determined path of CCS for the CPP scenario distinguished by the capture technologies (see Fig. 7.1(a)) and sequestration alternatives (see Fig. 7.1(b)) on which it relies. Notice that the envelope is the same



(a) By carbon capture technology

(b) By sequestration alternative

Figure 7.1: Time path of total global CCS differentiated by capture technologies and sequestration alternatives.

for both figures.

The total amount of CCS over time is qualitatively similar to the exogenous path assumed in Ch. 4 taken from WBGU (2003). It increases sharply in the coming decades, reaches a maximum at 4.3GtC around the middle of the 21st century and decreases to zero until 2100. The main difference compared to the WBGU-path is that the endogenous CCS path increases more sharply in the coming decades and that the cumulative amount over the 21st century is lower.

Therefore, it is concluded that CCS is an option to buy time. CCS is an option that is used only temporarily over the coming decades within the optimal climate protection strategy. CCS is mostly needed in the near to mid-term along with increased energy efficiency. In the long-term the renewables option contributes the largest part. This means that CCS defers the need of the transformation of the energy system relative to the CCP^0 scenario, which implies that the burden of learning investments and lower energy production is postponed to subsequent decades.

The property of temporary contribution of CCS to CO_2 emission mitigation has been derived analytically in Edenhofer et al. (2004a). The reason is that fossil energy carriers become scarce and the shift to a backstop technology is inevitable. Therefore, CCS can only be a temporary option and no steady state solution. This result is also in accordance with the over-shooting of optimal emissions found in Ch. 3.6.1. These findings show that transitional phenomena are important from a qualitative as well as a quantitative point of view.

The reason is explained next. The application of CCS is increased as long as the returns from investments into renewables are offset. Since CCS increases the costs and decreases the efficiency of utilisation of fossil energy carriers it acts as if their scarcity is increased. As in the analytical model in Edenhofer et al. (2004a) this brings forward the transformation of the energy system relative to the BAU scenario.

The CCS path relies heavily on new design coal technologies and the low cost technologies summarised. The high cost technologies based on the post-combustion capture concept contribute only a little amount; capture at coal power plants does contribute nothing in the base case.

This means that the potential of CCS is not exhausted, since it is possible to capture even more in each period than realised. The sharp increase of new coal technologies is due to the high degree of flexibility with respect to the addition to the existing capital stock. Additionally, the application of the various technologies follows the pattern that the low cost technology is employed first, then ND coal is introduced and so forth. At the end of the century the low cost technology fades out lastly etc.

This sheds some light on a shortcoming of the modelling approach that is related to the integration of CCS into the highly simplified energy system model. The high level aggregation of the various forms of energy does not take into account the values of different forms of energy. Fossil energy carriers enable the production of high-temperature heat when needed, which in turn is used in various industrial processes. Although renewable energy technologies could substitute for some of them, they might not be appropriate for other purposes. The assumed perfect substitutability is problematic, because it is reasonable that fossil energy technologies with CCS remain the better choice in several areas of industrial production. This could lead to a considerable amount of CCS that could not be substituted; e.g. cement production.

Fig. 7.1(b) shows the amount of carbon that is injected into the various available sequestration alternatives. As is expected by the modelling approach the on-shore saline aquifers are used to the largest extent. This is due to the assumption that it offers the largest capacity and the lowest costs. The other alternatives are used only to the extent that the distances of this alternative become longer as the capacity of the untrapped onshore aquifers is exhausted. As has been outlined in Ch. 5.5 the modelling approach along geological criteria does not allow for a reasonable differentiation of geological formations along economic criteria.

7.3 Sensitivity Analysis

In Ch. 4.5.3 two effects have been introduced that are related to the determination of CCS. First, the benefiting effect of CCS allows for the continued utilisation of relatively cheap fossil energy carriers and implies positive near to mid-term economic effects. Second, the crowding-out effect of CCS on renewables implies that deferring the transformation of the energy system through CCS implies negative long-term effects. The endogenous determination of CCS has to take into account these two effects in the intertemporal optimal allocation of investments into CCS capital.

The qualitative character of the optimal path leading to the temporary utilisation of the CCS option depends on these two effects. The quantitative time path of CCS could be the result that depends on a limited set of parameter values and that it changes dramatically, if parameters pass critical thresholds.

In this section a series of sensitivity analysis will be undertaken. In these sensitivity analysis existing parameters will be varied as well as new constraining parameters will be introduced in order to gain insights into the importance of particular model assumptions.

The aim of these studies is to find parameters and model assumptions that have significant influence on the outcome of the model in terms of the comprehensive indicators defined above. The sensitivity studies contain parameters from four fields:

1. ***Macro-Economic*** parameters are important determinants of the energy demand and therefore the need of CCS to provide cheap fossil energy carriers. This is especially related to RD&D sectors and the intertemporal social welfare function; see Ch. 7.3.1.

2. ***Techno-Economic and Geologic*** parameters of the energy supply technologies are the natural candidates for sensitivity analysis. Parameters like the costs and the availability of carbon capture as well as the learning rate

and investment costs of renewable energy technologies will be analysed as well as leakage rates and the capacities of sequestration alternatives; see Ch. 7.3.2.

3. ***The Climate Window*** is an ambitious climate protection target. The guardrails of the climate window are varied; see Ch. 7.3.3.

7.3.1 The Economy

In this section parameters are studied that describe the macro-economic determinants of energy demand. Two sensitivity studies are performed:

1. The productivity of the RD&D expenditures for improving the labour and energy productivity of the macro-economic production sector are varied; see Ch. 7.3.1.1.

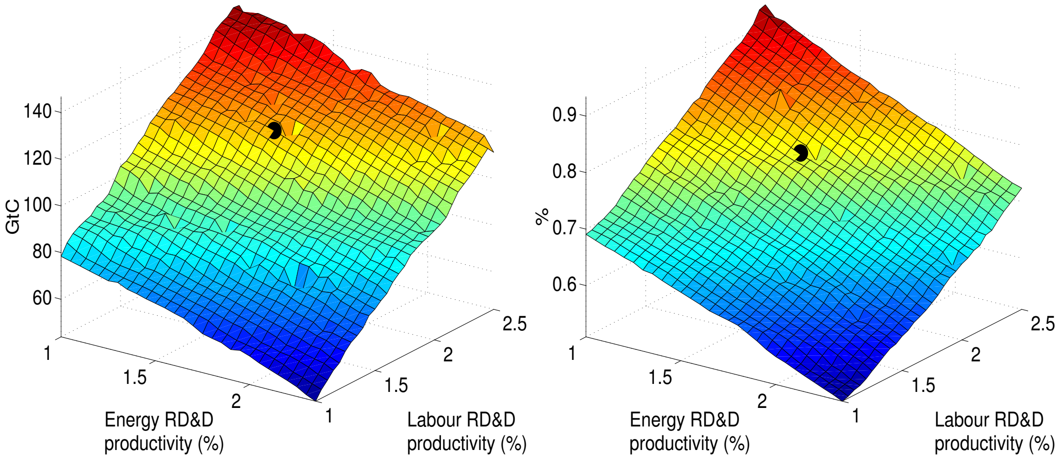
2. The intertemporal elasticity of substitution and the discounting rate are varied within the intertemporal welfare function; see Ch. 7.3.1.2.

Both sensitivity analysis address parameters that influence the energy supply. The changes of energy supply are due to changes of the macro-economic variables that also change the BAU path. Therefore, some notes have to be added regarding these changes.

7.3.1.1 Productivity of RD&D Expenditures

In the following the sensitivity of the RD&D sectors is analysed. For this purpose the parameters that determine the productivity of RD&D expenditures improving the labour and the energy productivity – α_L and α_E – are varied. Both parameters have influence on the growth of the world economy and on the corresponding energy demand.

One could think about several non-linear feedback loops between the RD&D sectors and the energy system, which induce opposite effects on the amount of CCS if the related parameters of the RD&D sectors are varied. For example, if the RD&D productivity for increasing the labour productivity is high, then on the one hand the energy demand growth is also high, which leads to an increasing need of CCS. On the other hand rich economies might have a higher ability to deal with



(a) Cumulative amount of CCS

(b) Cumulative relative GWP loss

Figure 7.2: Cumulative amount of CCS and relative cumulative GWP losses until 2050 for variations of the productivity parameters of the RD&D sectors for improving the labour and the energy productivity. The black balls in the surfaces indicates the base case result.

the macro-economic disruptions related to the transformation of the energy system, which reduces the need for CCS.

The parameter variation that is performed in this sensitivity analysis captures a considerable range of future developments of the economy and the energy demand. This range contains the IPCC SRES scenarios with respect to these two variables; see Nakicenovic and Swart (2000a).

Fig. 7.2(a) shows the cumulative amount of CCS until 2050 for variations of the two parameters of the RD&D sector. The CCS amount is approximately linear over the entire parameter range. The CCS amount increases for higher productivity of RD&D expenditures that improve the labour productivity and decreases for higher productivity of energy related RD&D expenditures. This implies that lower energy demand leads to lower cumulative CCS amount until 2050.

Fig. 7.2(b) shows that relative loss of GWP compared to the BAU scenario is also linear in the two parameters. Moreover, it also indicates that decreasing energy demand leads to lower GWP losses.

The observed sensitivity of the model could be attributed to two different arguments that are related to the magnitude and the timing of CCS. The first argument

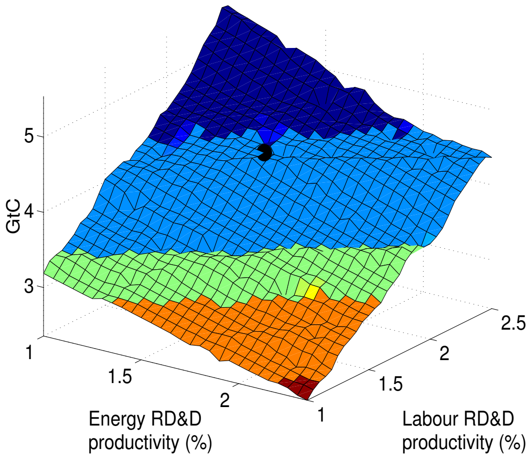


Figure 7.3: Maximum amount of CCS in a year in the period 2000 – 2100 for variations of the productivity parameters of the RD&D sectors for improving the labour and the energy productivity. The shading represents the period in which the maximum is reached. Deep blue indicates that the maximum is reached in 2035, light blue in 2040, green 2045, orange 2050, deep red in 2055; other colors are averages that are not of interest. The black ball in the surfaces indicates the base case result.

assumes that the timing is fix, but that the magnitude of CCS is decreased for lower energy demand growth and therefore the CCS time path is flattened. The second argument is based on the observation that deferring the CCS without changing the CCS amount would decrease the cumulative CCS amount also, because the cut-off year is 2050. The latter argument is suggested by the findings related to the relaxation of the climate protection window; see Ch. 7.3.3.

The significance of the deferring effect is captured in Fig. 7.3, since the color of the surface indicates the period in which the maximum is reached. The figure shows that decreasing energy demand growth leads to a lower maximum of CCS p.a. that is achieved later. The weight of the two effects can be assessed as follows. The cumulative amount of CCS in Fig. 7.2(a) varies from 44GtC to 147GtC, which is a factor of 3.3. Fig. 7.3 shows the maximum amounts of CCS p.a. in the 21st century that vary from 2.4GtC to 5.5GtC, which is a factor of 2.4. Since the sensitivity surfaces are nearly linear one can conclude that the larger part (73%) of the sensitivity of cumulative CCS can be attributed to the effect of a flattened CCS time path. The smaller part (27%) is due to the deferring of the CCS time path.

In summary, the cumulative amount of CCS and the relative loss of cumulative GWP differences varies linearly with respect to the RD&D productivity parameters.

The sensitivity of both indicators follows the argument that lower energy demand growth reduces the CCS amount and the relative GWP losses. The decrease of the CCS amount is to the larger part due to the flattening of the CCS time path and to the minor part due to deferring of CCS to later periods.

7.3.1.2 The Intertemporal Welfare Function

In the following the sensitivity of parameters in the intertemporal welfare function is analysed. The parameters are the discounting rate ρ and the intertemporal elasticity of substitution IES.

The latter parameter has been assumed to be one, which lead to the logarithmic utility function. For the sensitivity analysis a function with constant IES is used; see Smetters (2003, p. 698):

$$u(c) = \frac{c^{1-\eta}}{1-\eta}. \tag{7.1}$$

η is the elasticity of marginal utility and defined as the inverse of the IES. As noted above with respect to the Ramsey model, the IES has influence on the transition towards the steady state of intertemporal economic problems, while the discounting rate additionally determines the steady state. The empirical literature on the IES indicates that it is below 0.5.

Fig. 7.4(a) shows the cumulative amount of CCS until 2050.[1] The influence of the discounting rate shows no clear influence for the variations from 0.5 to 2.5%. The influence of the IES is also nearly constant around the base case value, but it exhibits a considerable non-linearity for values below 0.5, where the CCS amount decreases to zero for an IES less than 0.2.

The difference can be explained with the impact of the IES on the BAU GWP in 2050 that is shown in Fig. 7.4(b). The sensitivity of the GWP is high in the IES. The sensitivity is not as pronounced for changes of the discounting rate. The main reason is that the higher the IES is, the less willing is the economy – being relatively poor – to accept high saving rates in order to support economic growth that leads to higher consumption in the future. An additional effect pointing into the same direction is that the energy intensity in 2050 is higher, the lower the IES is. For

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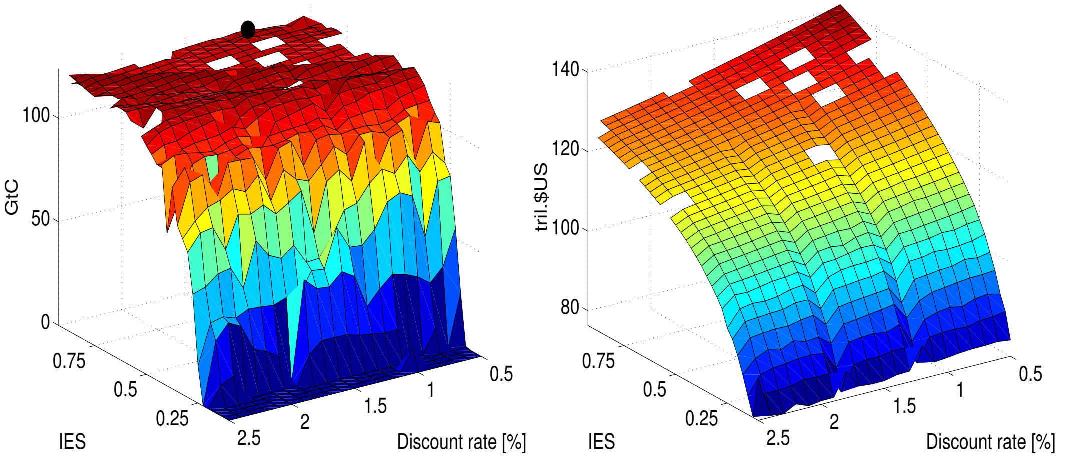
[1] Variations of the parameters in the intertemporal welfare function lead to computational problems. For some parameter combinations (about 10) the solver did not find optimal solutions. These case are indicated by blank crosses in the surfaces in the following.



(a) Cumulative amount of CCS (b) BAU GWP in 2050

Figure 7.4: Cumulative amount of CCS until 2050 and BAU GWP in 2050 for variations of the IES and the discounting rate. The black balls in the surfaces indicates the base case result.

an IES of 0.25 the energy intensity in the BAU is about 20% less than for the base case.

The long run effect of a low IES is different on GWP and energy intensity. The differences in the GWP are persistent, but the energy intensities converge to the same level until 2100. This implies that the IES influences the investment dynamics as has been discussed theoretically in Ch. 3.6.2.

This shows that the macro-economic transition dynamics is significantly influenced by the IES. It has a considerable effect on energy demand, which leads to lower CO_2 emissions for lower IES and therefore the climate constraint becomes important latter. This leads to decreasing CCS amounts until 2050.

7.3.2 Techno-Economics and Geology

In this subsection several parameters related to energy supply technologies are varied. In this section sensitivity analysis is used to gain insight in two distinct kinds of parameters. The first kind of parameters characterises a marginal unit of a technology that is added to the existing capital stock; e.g. investment costs. The second kind of parameters captures the inertia and physical constraints for adding additional capacities to the existing capital stock. The first kind of parameters affects the *preferability* of a marginal unit of an option, while the second kind represents the *availability* of an option.

The base case parameter set exhibits a great deal of flexibility with respect to the application of the mitigation options. As has been laid out in Ch. 5 this flexibility is highly questionable, which is represented by varying the static and dynamic constraints of the carbon capture technologies introduced in Ch. 6. Moreover, the addition of capacities of renewable energy technologies is considered to be limited by natural and technical constraints. In the base case no such constraints are modelled. Limitations on the renewable energy sector are introduced and described in detail below.

In this subsection six areas are studied using sensitivity analysis:

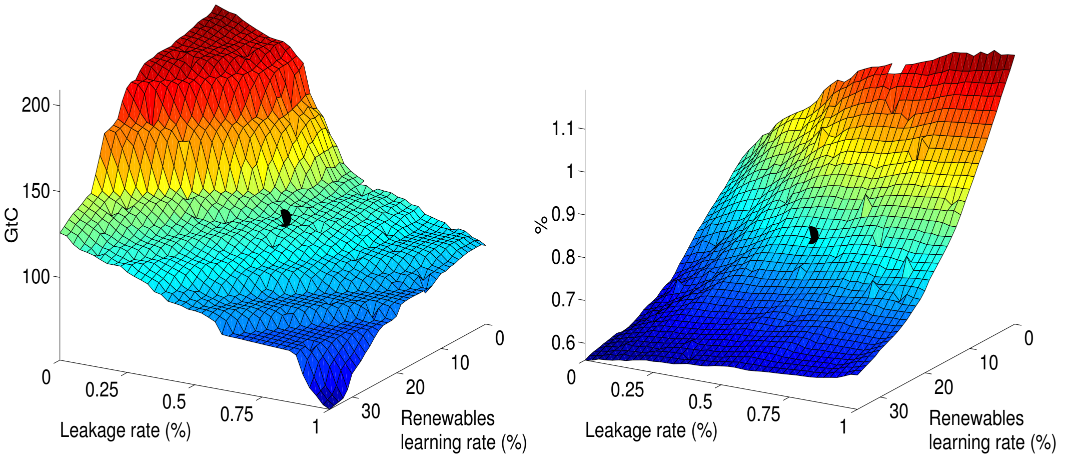
1. The leakage rate of sequestered carbon and the learning rate of renewables energy technologies are varied on a grid; see Ch. 7.3.2.1.
2. The assumptions on leakage rates and capacities of sequestration alternatives are varied; Ch. 7.3.2.2.
3. The static and dynamic constraints for introduction of carbon capture are varied; see Ch. 7.3.2.3.
4. The availability of renewable energy technologies is limited; see Ch. 7.3.2.4.

7.3.2.1 Learning Rate of Renewables and Leakage Rate

The learning rate of renewable energy technologies and the leakage rate of sequestered carbon are considered to be key parameters for CO_2 emission mitigation. The overview given in Ch. 4.3.6 suggests that learning rates of renewables might be in the range of 10 – 20%. The discussion of the leakage rate in Ch. 5.5 introduced the dispute about the leakage rate and that the question could be whether there is a critical leakage rate at which CCS is not employed or dramatically decreases.

In this section both parameters are varied over the ranges that seem reasonable. The learning rate is varied from 0 to 35% and the leakage rate from 0 to 1%. The leakage rate here affects all sequestration alternatives equally.

Fig. 7.5 gives the cumulative amount of CCS and the cumulative relative GDP loss until 2050. Fig. 7.5(a) shows that the sensitivity of the cumulative amount of CCS until 2050 is non-linear in the two parameters. Around the base case – indicated



(a) Cumulative amount of CCS

(b) Cumulative relative GWP loss

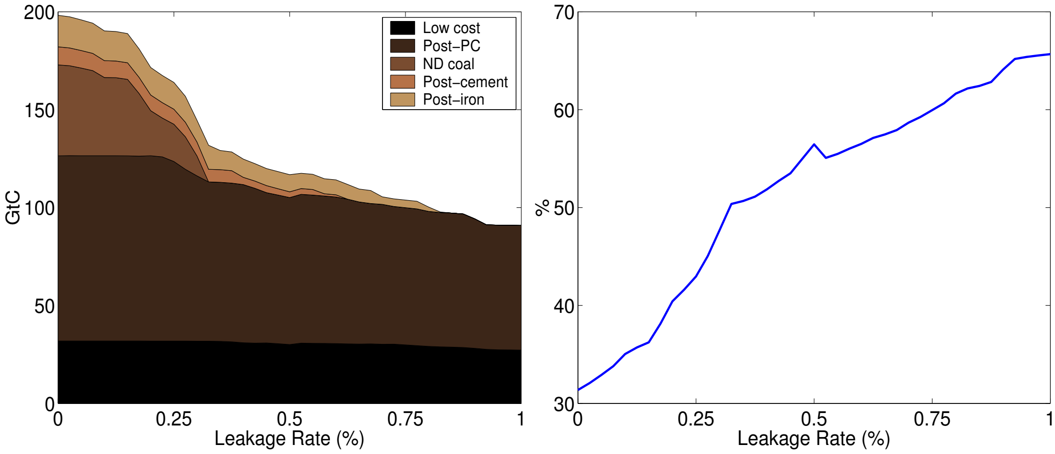
Figure 7.5: Cumulative amount of CCS and relative cumulative GWP losses until 2050 for variations of renewables learning rate and leakage rates of the sequestration alternatives. The black balls in the surfaces indicate the base case result.

by the black ball – the variations are small with respect to both parameters. Varying the learning rate over the total range, given the base case leakage rate, does not lead to large changes of the CCS amount. But if the learning rate is assumed constant there are considerable changes for variations of the leakage rate. There is a considerable non-linearity for small leakage and learning rates.

Fig. 7.5(b) shows that the relative cumulative GWP losses are sensitive with respect to the renewables learning rate, but insensitive to changes of the leakage rate. Moving from the base case towards the parameter region with low leakage and learning rate one can observe a notable decrease of the GWP losses. This region coincides with the non-linearity of the CCS amount.

This non-linearity in the cumulative amount of CCS is related to the application of carbon capture technologies. Fig. 7.6(a) shows the contribution of the carbon capture technologies to the cumulative CCS amount for the variation of the leakage rate for the base case learning rate. If the leakage rate decreases below the threshold of about 0.25% the Post-PC technology comes into use, which is the major contribution of the overall observed increase.

Fig. 7.6(b) shows the share of renewable energy production in 2050 for the variation of the leakage rate. For a leakage rate above 0.5% the renewable energy share



(a) Amount of CCS per technology

(b) Renewable share

Figure 7.6: Cumulative amount of CCS by capture technology until 2050 and renewables share of total energy production in 2050 for variations of leakage rate. The base case result is at 0.5% leakage rate.

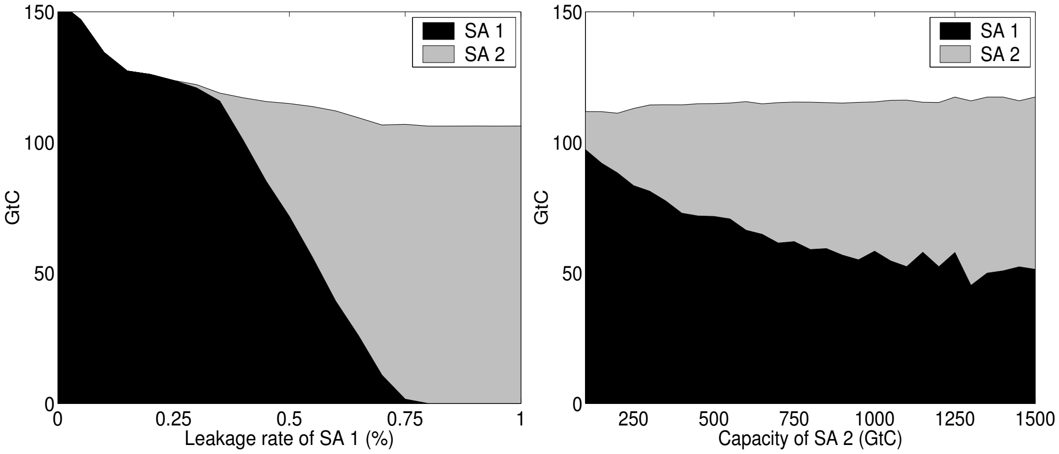
exceeds 50% in 2050. If the leakage rate is assumed to be zero the renewable share would be 31%.

Comparing the two results in Fig. 7.6 indicates that CCS and renewables are substitutes. Moreover, if the leakage rate falls below the threshold level, the Post-PC technology substitutes renewable energy sources.

7.3.2.2 Leakage Rate and Sequestration Capacity

In the following the sensitivity of sequestration alternatives SA is analysed with respect to capacity and leakage rate. Above the critique has been formulated that distinguishing SAs along geological criteria for the description of formations does not help much for the economic assessment that has to take into account assumptions about capacities and leakage rates. Therefore, the following sensitivity analysis reframes the model and distinguishes two SAs. The focus is on the ability of an SA to substitute for another, if a parameter changes that characterises one SA.

For this purpose the model *MIND1.1* is changed. In the following only two SA called ***SA 1*** and ***SA 2*** are considered that are exactly the same in every respect. The leakage rate of SA 1 and the capacity of SA 2 are varied. The fix leakage



(a) Variation of leakage rate of SA 1

(b) Variation of capacity of SA 2

Figure 7.7: Cumulative amount of CCS until 2050 by sequestration alternative for variations leakage rate of SA 1 and capacity of sequestration SA 2. The base case is not contained in the figures.

rate of SA 1 is assumed to be 0.5% and the fix capacity of SA 2 is assumed at 500GtC. Notice that the exhaustion of sequestration capacity of an SA increases the need to built pipelines for additional sequestration in that SA, which requires higher investments.

This modelling approach of SAs abstracts from geological typologies distinguishing SAs. The analysis here asks for the significance of features of two classes of SAs that represent all sequestration sites that share these features without paying attention to the geological classifications.

Fig. 7.7 shows the cumulative amount of CCS until 2050 distinguished for the two SAs. In Fig. 7.7(a) the leakage rate of SA 1 is varied. The total CCS amount reacts moderately for leakage rates smaller than 0.15%. Around a leakage rate of 0.5%, which is the leakage rate of SA 2, the allocation between the two SAs shifts. This shift is considered for leakage rates of SA 1 between 0.25 and 0.75%. This shift has only moderate implications on the overall amount of CCS.

In Fig. 7.7(b) the capacity of SA 2 is varied. There is nearly no influence on the total cumulative amount of CCS, although the allocation to the two SA is adapted. The shape of this reallocation is hyperbolic in the sequestration capacity of SA 2.

If the capacity is large it does not matter much if it becomes even larger.

These results imply that the leakage rate and the investments for pipelines are important for the allocation of carbon sequestration between SAs, but the overall amount of CCS does not change much, if one SA is cancelled out, if the other SA still provides sufficient capacity and leakage rate. The sensitivity analysis shows that the leakage rate does not discretely change the order of the two SAs, which is indicated by the smooth switch. This implies that an economy would choose sequestration sites of worse environmental quality as long as the cost argument justifies this. Moreover, the allocation of CO_2 among both SAs is a mix, if a variable changes in the cumulative amounts of CCS; here this is the investments to build pipelines.

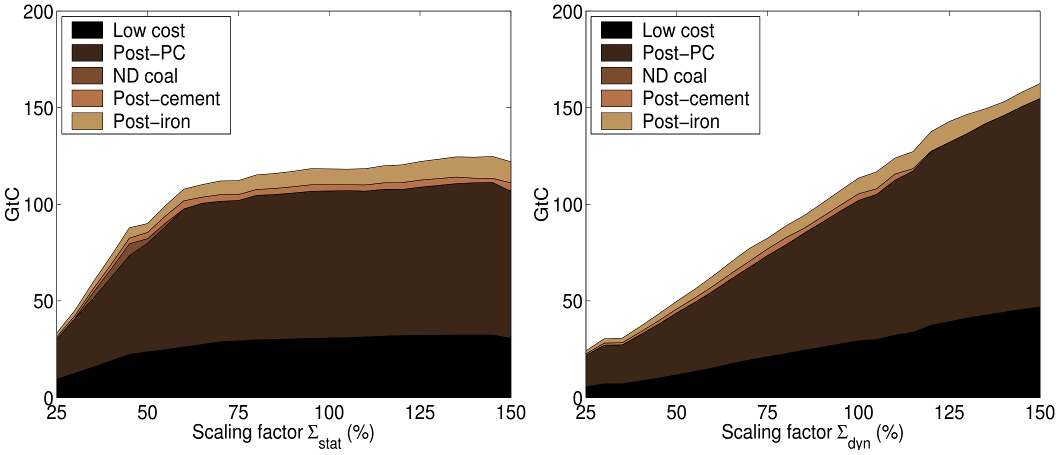
7.3.2.3 Constraints on Carbon Capture Investments

The base case result depends on the deal of flexibility of the introduction of CCS. This is in conflict with findings of the literature review on the techno-economics and geology of CCS in Ch. 5. The following sensitivity analysis focuses on the importance of the static and dynamic constraints of carbon capture, which control the flexility of CCS in the model structure. The static constraint limits the amount of total carbon that can be captured by using a technology. The dynamic constraint limits the introduction of the carbon capture technologies; see Ch. 6.2.1 for details.

The sensitivity analysis is done by introducing two scaling factors $\Sigma_{\mathrm{stat}^{\mathrm{total}}}$ and $\Sigma^{\mathrm{total}}_{\mathrm{dyn}}$ to vary the static and the dynamic constraint parameters, respectively. The constraining parameters are multiplied with the corresponding scaling factors; i.e. if the scaling factor is 100%, this implies that the base case is computed, if it is 50% the constraint parameter is only half the base case value.

In the following the sensitivity of these constraints is studied by first applying the scaling factor to all carbon capture technologies and then only on ND coal. This is done to analyse the sensitivity of the total carbon capture sector first and then to focus on the speculative ND coal technology on which the base case result mainly relies.

Fig. 7.8(a) shows the impact of varying the scaling factor of the static constraint $\Sigma^{\mathrm{total}}_{\mathrm{stat}}$. Around the base case (located at 100%) this constraint does not affect the result. The constraint becomes binding leading to a decreasing CCS amount, if the constraint decreases below 60% of the base case value. This decreasing pressure is mildly offset by applying the Post-PC technology, when the $\Sigma^{\mathrm{total}}_{\mathrm{stat}}$ is around 40%.



(a) Variation of $\Sigma_{\text{stat}}^{\text{total}}$

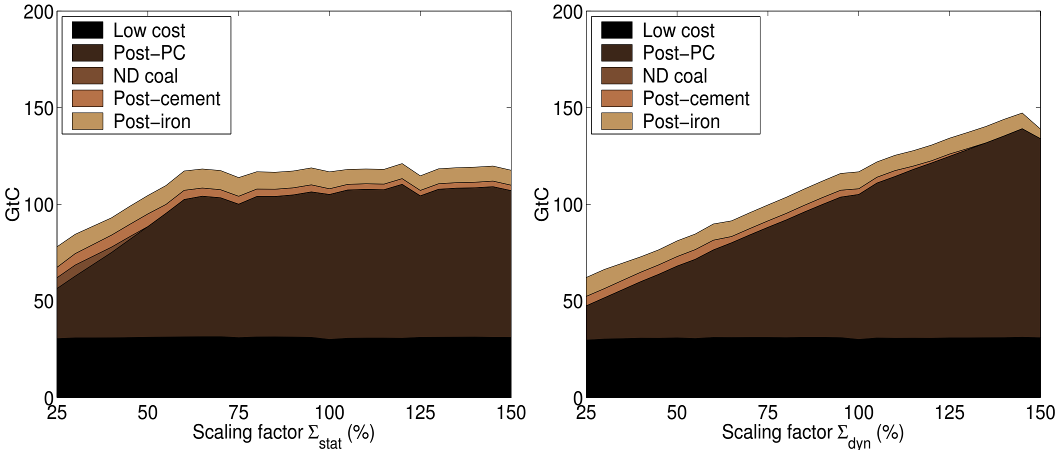
(b) Variation of $\Sigma_{\text{dyn}}^{\text{total}}$

Figure 7.8: Cumulative amount of CCS until 2050 by capture technology for variations of the constraints of the total carbon capture sector by varying the scaling factors for the static $\Sigma_{\text{stat}}^{\text{total}}$ and the dynamic constraint $\Sigma_{\text{dyn}}^{\text{total}}$. The base case is at 100%.

The dynamic constraint is more important for the cumulative CCS amount as is shown in Fig. 7.8(b). The variation of the scaling factor of the dynamic constraint $\Sigma_{\text{dyn}}^{\text{total}}$ around the base case shows considerable implications on the CCS amount. The relation is very close: decreasing $\Sigma_{\text{dyn}}^{\text{total}}$ by 10%-points leads to ∼10GtC decrease of the CCS. The relationship is very close for ND coal and Low cost, but not for Post-cement and Post-iron, since constraints are active for both technologies. The latter two technologies exhibit non-monotonous relationship with respect to the $\Sigma_{\text{dyn}}^{\text{total}}$. Different to the static constraint the Post-PC technology is not applied to offset the decrease in the other technologies.

Fig. 7.9 shows the corresponding results, if the scaling factor is only applied to the ND coal technology. Fig. 7.9(a) shows that the constraint becomes binding for $\Sigma_{\text{stat}}^{\text{ND Coal}} < 60\%$. The Post-PC and Post-cement technologies mildly offset the effect of decreasing availability of ND coal. Fig. 7.9(b) shows that the dynamic constraint is binding for the ND coal technology. Moreover, the decreasing availability is mildly offset by Post-cement but not by Post-PC. The Low cost technologies are not affected by changes of either of the constraints.

This analysis shows that the dynamic constraint, which limits the introduction



(a) Variation of $\Sigma_{\text{stat}}^{\text{ND Coal}}$ (b) Variation of $\Sigma_{\text{dyn}}^{\text{ND Coal}}$

Figure 7.9: Cumulative amount of CCS until 2050 by capture technology for variations of the constraints of the ND coal carbon capture technology by varying the scaling factors for the static $\Sigma_{\text{stat}}^{\text{ND Coal}}$ and the dynamic constraint $\Sigma_{\text{dyn}}^{\text{ND Coal}}$. The base case is at 100%.

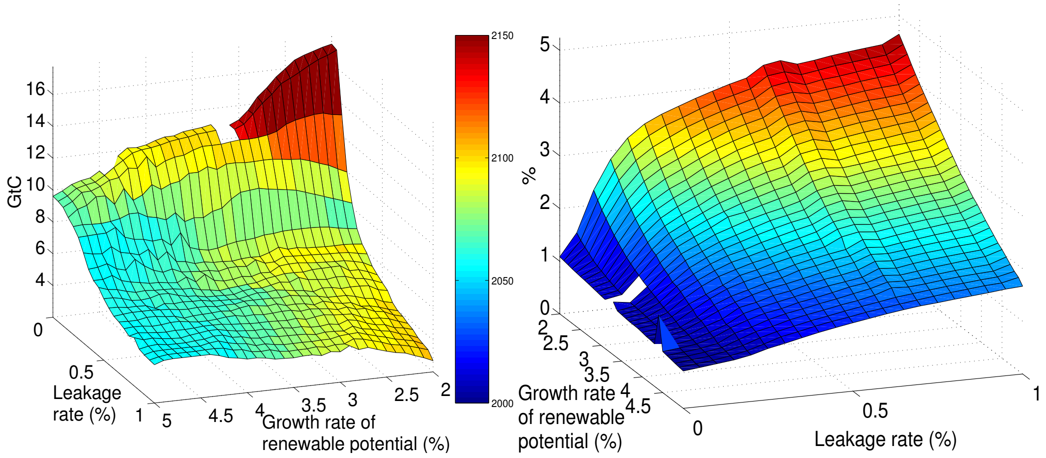
of carbon capture technologies, has considerable impact on the application of the CCS option. Moreover, the Post-PC technology is not applied to offset the reduced availability of other technologies, espec. the ND coal technology. The static constraint, which limits the overall availability of the carbon capture technologies is non-binding, if it is above 60% of the base case assumption. If it is below this level, the Post-PC technology mildly offsets the reduction of the other technologies.

7.3.2.4 Constraints on Renewable Energy Use and the Leakage Rate

In the following a constraint is introduced that limits the potential use of renewable energy sources. The reason is that the extension of infrastructures related to renewable energy technologies is subject to inertia and the need to overcome bottlenecks due to the integration of renewables into existing energy infrastructures. The quantitative importance of the sensitivity of this constraint is combined with the sensitivity of the leakage rate.

The constraint on the use of renewable energy sources is as follows:

$$E_{S,R}(t) \leq E_{S,R}^{pot}(\tau_1) \cdot e^{\gamma_{S,R} \cdot (t-\tau_1)}. \tag{7.2}$$



(a) Maximum amount of CCS

(b) Discounted GWP differences

Figure 7.10: Maximum amount and timing of CCS between 2000 and 2150 and discounted GWP losses until 2050 for variations of the constraint of potential renewable energy use and leakage rate. The colour bar only belongs to the left panel. The base case is not contained in the figure.

The realised renewable energy production $E_{S,R}(t)$ is constraint to a potential with a constant growth rate $\gamma_{S,R}$. In the initial period this constraint is $E_{S,R}^{pot} = 10EJ$. The growth rate $\gamma_{S,R}$ is varied for the sensitivity analysis.

Fig. 7.10(a) shows the maximum amount of CCS between 2000 and 2150 at the z-axis and the shading indicates the year in which this maximum is reached. Fig. 7.10(b) shows the relative discounted loss of GWP until 2050. Both figures do not contain the base base case result, since the constraint on renewable energy use is new.

The maximum amount of CCS shows a sharp non-linearity in the leakage rate; the threshold is about 0.25%. A low leakage rate allows extensive use of the CCS option. The timing of the maximum does not correspond with this threshold value. The blue area indicates that the maximum CCS amount is realised prior to 2085. This means that the constraint renewable energy use leads to a deferring of CCS activity and – not shown – prolonged and intensive use of the energy efficiency option.

The very high maxima of CCS activity that are achieved in the 22$^{\text{nd}}$ century require a low leakage rate smaller than 0.1%. In that case the economy would rely on fossil fuels augmented by CCS to obey the climate window.

Higher leakage rates imply that much less CO_2 is captured and sequestered. If the growth rate of potential renewable energy use is high the maximum amount of CCS is higher and realised earlier than for lower growth rates. The reason is that for a large $\gamma_{S,R}$ the economy could switch to extensive use of renewable energy sources in order to avoid the delayed emissions from leakage. If $\gamma_{S,R}$ is low the economy has to employ CCS over a long time, but has to limit the delayed leakage emissions in order to obey the climate window.

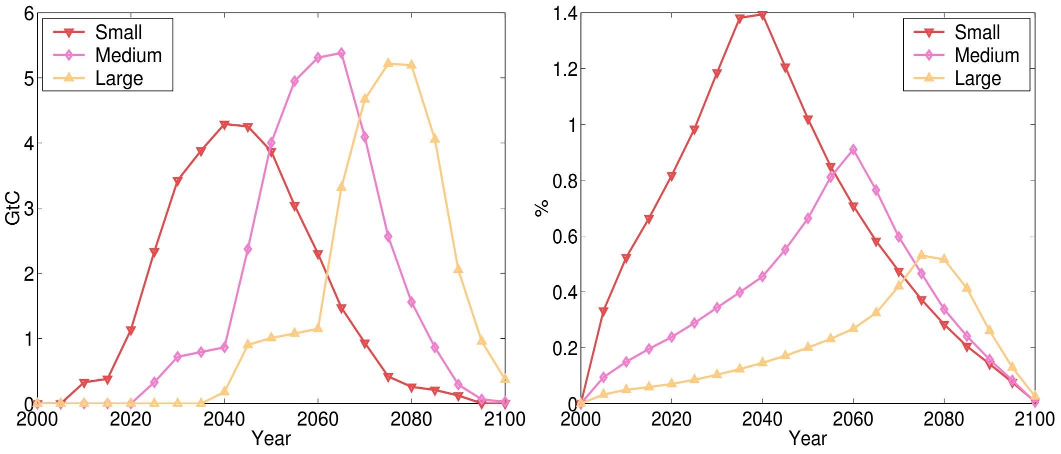
The relative discounted GWP losses are higher than in the base case result and it is highly sensitive in both parameters. As with the CCS activity there is a considerable non-linearity for low leakage rates. This is due to the potentially high CCS activity that allows higher energy production from fossil fuels that is achievable for low leakage rates. The effects becomes less significant the faster the renewable energy potential grows.

7.3.3 The Climate Window

Subject to the climate window specified so far, the endogenously determined CCS path implies that the CCS option is mainly needed in the early decades of the 21st century. The reason for this could be that the limit for CO_2 emissions is so strong that it is worth to apply CCS, since the learning process within the renewable energy technologies sector has not yet achieved sufficient cost reductions. This leads to the analysis of the CCS path for relaxed climate windows. Relaxing the climate window leads to less strict short-term emission constraints, which offers a prolonged learning period. This in turn could decrease the need for application of the CCS option.

Fig. 7.11(a) shows the CCS time paths for three climate windows of different strength. The two alternative climate windows called medium and large are specified with guardrails of 2.5°C and 0.25°C per decade, and 3°C and 0.3°C per decade, respectively.

The shape of the paths implies that CCS is a temporary option in each case. The maximum CCS amount that is realised for each climate window is between 4.3 and 5.4GtC. The inverted U-type curve is shifted in time depending on the specification of the climate window. Notice that the share of fossil energy delivered with CCS from the total fossil energy supply decreases, if the climate window is relaxed due to the growth of the economy and the energy demand.



(a) Amount of CCS (b) Relative GWP losses

Figure 7.11: Amount of CCS and relative GWP for variations of the climate window.

The short-term CO_2 emissions of the medium (large) climate window are close to the BAU scenario until 2025 (2050) as has been proposed by Wigley et al. (1996) and Manne and Richels (2004). In the case of the large climate window the emission reductions are negligible until 2020. This means that climate protection measures are deferred into the future as long as the constraints are not pressing. Climate protection strategies aiming at CO_2 emissions follow the same temporal pattern: first the energy efficiency is increased, this is augmented by CCS and learning investments in renewable energy technologies, which will be introduced at the large scale as the final measure. Relaxing the climate window means that the society will wait and will then apply a strategy with the described temporal pattern.

This leads to the assessment of the economic effects of relaxing the climate window. Fig. 7.11(b) shows the relative differences of GWP compare to the BAU scenario for the three climate windows. The peaks correspond with the maxima of CCS and decrease as the climate window is relaxed. This is attributed to two effects. First, the relaxation of the climate window leads to more efficient timing application of the climate protection strategy. Achieving the small climate window requires immediate reduction of CO_2 emissions compared to the BAU scenario, while the large climate window implies no short-term emission reductions. The second effect is related to the decreasing expenditure share devoted to energy. As the significance of the energy sector decreases, the transformation of the energy system induces less macro-economic repercussions, if it is allowed to be deferred due to a relaxed climate window.

This finding implies that CCS is applied in climate protection strategies in order to prolong the use of fossil fuels and to defer the transformation of the energy system. This feature of CCS is robust with respect to the stabilisation target of climate protection. A question that follows is whether and to what extent this depends on the climate model that is integrated into the model framework and whether more realistic representations of the dynamics of the climate system changes this finding. Moreover, it is necessary to analyse different integrations of the climate system and climate protection goals; i.e. the assessment of concentration targets and damage functions. These two issues are subject of further research.

7.3.4 Monte Carlo Analysis

In addition to the sensitivity analysis a Monte-Carlo Analysis MCA is performed. The sensitivity is able to scan a dense grid of a considerable range of one or two parameters that are varied. The MCA is a method of varying a large number of parameters stochastically and to analyse the results by applying standard statistical methods.

For this thesis an MCA is performed by varying various parameters simultaneously according to realisations of stochastic variations. The realisations are the parameter set for which *MIND1.1* computes the optimal solution. Therefore, MCA is a tool to assess the model outcome $\mathbf{y} = (y_1, ..., y_n)$ with respect to parameter uncertainties $\mathbf{x} = (x_1, ..., x_m)$, where m is the number of uncertain parameters and n is the number of model variables.

The uncertainty of the exogenous parameters is represented in the distribution functions $D_1(x_1), ..., D_m(x_m)$. From these distribution functions m_s realisations are drawn. For each realisation $\mathbf{x}_k = (x_{k,1}, ..., x_{k,n})$, with $k = 1, ..., m_s$ the corresponding model output $\mathbf{y}_k$ is computed. The model output can be analysed with standard statistical methods.

The uncertain exogenous parameters and the parameters of their normal distribution functions used in this section are given in Tab. 7.1. The parameters that have been contained in this MCA are related to the techno-economics and the macro-economic production function. Parameters considering the intertemporal

Table 7.1: Parameters for the normal distribution functions of the uncertain exogenous parameters of the Monte-Carlo analysis.

Parameter	α_L	α_E	σ_A	$\kappa_{fr,l}^{mult}$	K_F^0	K_{fr}^0
Unit	none	none	none	none	tril.$US	tril.$US
Mean	.02	.015	.4	2.	6.	5.
Variance	1.5e-5	1.5e-5	5.e-3	7.5e-2	1.	.75
Parameter	$\varphi_{cap,lc}^{stat}$	$\iota_{cap,lc}$	$\varphi_{cap,ndc}^{stat}$	$\iota_{cap,ndc}$	$R_{sequ,saon}^{max}$	$R_{sequ,saof}^{max}$
Unit	none	$US/tC	none	$US/tC	GtC	GtC
Mean	.06	98.	.2	156.	2.5e+3	1.e+3
Variance	2.e-4	100.	1.5e-3	750.	2.19e+5	3.5e+4
Parameter	χ_3	ι_{ren}^0	λ_{ren}	$\lambda_{leak,saon}$	$\lambda_{leak,saof}$	λ_{pipe}^{min}
Unit	GtC	$US/kW	none	none	none	1000km
Mean	3.5e+3	7.e+2	.15	5.e-3	5.e-3	.15
Variance	5.e+5	2.25e+4	1.e-3	1.e-6	1.e-6	1.5e-3

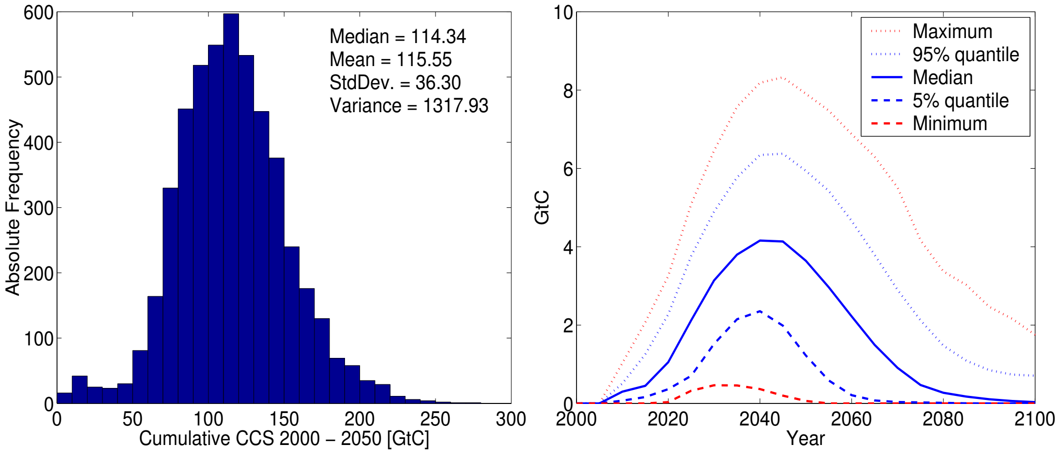
social welfare function and the climate system are not varied.

The means of the distribution functions are the same as in the base case. The variances of the distribution functions are based on *ad-hoc* assumptions. There are two reasons for this. First, the distribution functions of parameters have not been derived from estimation procedures. Second, the parameters for speculative technologies can not be derived from estimations because data is not yet available.

The sample of exogenous parameters has been drawn using the Latin-Hypercube method as is described in Flechsig et al. (2004, Ch. 6). The sample size contains 5000 realisations of parameter sets.

The results of the MCA are summarised in Fig. 7.12. The histogram in Fig. 7.12(a) shows the frequency distribution of the cumulative amount of CCS until 2050. The summarising statistics are given within the figure. The median and the mean are approximately equal and are located within the most frequent bin that ranges from 110 to 120GtC. The standard deviation is 36.3GtC, which indicates that 66% (95%) of all cases in the sample are characterised by a cumulative amount of CCS between 77 and 150GtC (43 and 185GtC) until 2050.

Fig. 7.12(b) shows quantiles of the time path of CCS until 2100. These time paths indicate that CCS is to a greater or lesser extent a temporary solution for all the parameter variations contained in the sample. No run in the sample shows a qualitatively different behaviour than that of the base case: the CCS path increases



(a) Histogram of cumulative CCS

(b) Time path of quantile

Figure 7.12: Results of the Monte-Carlo Analysis.

in the short-term, reaches a maximum around the middle of the 21st century and decreases afterwards. The maximum CCS amount in 2100 is less than 2GtC.

In the sample used for the MCA the feature of CCS being a temporary option is stable within the model framework *MIND1.1*. The variation of CCS implied by the assumed distribution function is quite large. However, CCS is an option that would be demanded over the next decades.

7.4 Comparison of Results

In the following the results computed with *MIND1.1* are compared with the results of other studies. The comparison is limited to studies that compute global CCS time paths for the 21st century. It has two main foci. First, the time path of CCS is compared and discussed. Second, the results are compared with respect to the leakage rate.

The time path of CCS is mainly characterised by the year the technology is introduced first, the pace of introduction and the maximum amount achieved over the time horizon that is studied. The path derived by WBGU (2003) and that computed with *MIND1.1* introduce CCS in the first half of the century at a fast pace, reaches a maximum around the middle of the century and fades out until 2100. The

Table 7.2: CCS time paths of several studies. Source: see footnotes.

	EW98[a]	DEW90	MS04	R04
Model type	ESM	ESM	Hybrid	Hybrid
Model horizon	2095	2095	2200	2100
Climate goal	Conc.	Conc.	Conc.	Conc.
Climate constraint	550	550	450	550
BAU GWP (tril.$US)				243.
BAU Energy (EJ)	1950.		1070.[b]	1921.
BAU CO_2 (GtC)	24.	22.3	14.5	28.
Options[c]	CFRD	CFRD	CFRS	CFRS
First CCS	2020	2020	2040	2040
Max. amount (GtC)	9.	3.1	4.9	8.9
Cum. CCS (GtC)	335.	111.		243.

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[a] The studies are EW98 $\hat{=}$ Edmonds and Wise (1998); DEW99 $\hat{=}$ Dooley et al. (1999); MS04 $\hat{=}$ Mori and Saito (2004); R04 $\hat{=}$ Riahi et al. (2004).

[b] This is final energy.

[c] If an option is available, it is indicated by a letter. The letters indicate C $\hat{=}$ carbon capture and sequestration; F $\hat{=}$ fossil fuel substitution; R $\hat{=}$ renewable energy technologies; S $\hat{=}$ factor substitution; D $\hat{=}$ demand reduction of energy.

Monte-Carlo analysis and most of the sensitivity analysis undertaken with *MIND1.1* indicate that such path is robust against variations of exogenous model parameters. Imposing constraints on the potential of renewable energy technologies long term increasing CCS amount, if the leakage rate is sufficiently small.

Other studies compute CCS time paths, where CCS is introduced during the second half of the century and increase the CCS activity steadily until the end of the century. Four such studies are summarised in Tab. 7.2, of which none doe take into account leakage. The entries of the table are mainly the same as in Tab. 4.9. The bottom three rows indicate (i) the first year of introduction of CCS (First CCS); (ii) maximum CCS reached and (iii) the cumulative amount of CCS over the 21^{st} century.

These studies differ not only with respect to the qualitatively different CCS time path in the 21^{st}. The CO_2 emission mitigation strategy computed with *MIND* is a sequence of employing several options. Although there are considerable overlaps, there is a temporal shift in the emphasis on the various options. The models cited above have in common that the options are extended steadily in order to close the gap between the BAU emissions and the emissions that are consistent with the climate stabilisation constraint. This means that the extension of CCS activities is combined with the extension of the other CO_2 mitigation options; see also Pacala and Socolow (2004) for discussion of that point. The different dynamic behaviour of *MIND* compared with the other models requires a more in depth analysis. The constraints on utilisation of particular options seem to be a good starting point for such discussion.

Next, the results are compared with respect to the leakage rate and the question which rate leakage should not exceed in order to make CCS an option of choice. The result with *MIND1.1* has been that CCS is chosen temporarily depending on the availability and characteristics of alternative options. The leakage rate becomes a sensitive parameter, if the alternatives are limited or exhibit a bad performance; espec. potential of renewables. Under particular circumstances – like low leakage and learning rate – CCS is a longer-term solution. If the alternatives are provide poor characteristics and the leakage rate is high, then it is optimal to wait with CCS in order to have it available, when the value of carbon has grown to very high levels.

Ha-Duong and Keith (2003) assess the global implications of leakage on CCS activity and undertake a sensitivity results with *DIAM*, which is a model based on marginal cost functions of mitigation and damage; see Ch. 2.7.2. The marginal damage function describes the mitigation costs as a percentage GWP depending on the atmospheric CO_2 concentration. The function is characterised by a rapid increase from 2% at 550ppmv to 6.5% at 625ppmv.

Four leakage rates are assumed (0%, 0.1%, 0.5% and 1%). In each case the level of mitigation is 99% in 2150, but the mitigation level in 2050 is 17% for 1% leakage and 23% for 0%. In each case the CO_2 concentration remains below 529ppmv. This means that the availability of save sequestration sites increases the emissions in the near term. CCS will be applied after 2050. In 2150 it is not used in the case of 1% leakage rate. It reduces the emissions mildly (6%) for 0.5% leakage rate and highly (38 – 47%) in the case of low leakage rates of 0 – 0.1%. This implies that CCS being a long term option requires sufficiently low leakage rates.

Dooley and Wise (2003) use an ESM and asses the significance of different leakage rates (0, 0.1, 1%) and three atmospheric CO_2 stabilisation constraints (450, 550 and 650ppmv). The computations are done in two steps. First, the CCS time paths are computed with zero leakage, which gives rise to 100, 200 and 340GtC cumulative CCS until 2100 for the three stabilisation constraints. Second, the corresponding CCS paths are assumed exogenously for the leakage variants. Then the model computes the solution with the additional assumption of the exogenous CCS and leakage time path. This means that the CCS time path does not change, if leakage is taken into account.

The result is that for 550ppmv and 0.1% (1%) leakage the allowed CO_2 emissions are reduced by 0.2GtC (2GtC) at the end of the 21st century. This increases the costs of CO_2 emission mitigation. In the case of 450ppmv stabilisation and 0.1% leakage the mitigation costs are increased by 15%. In the case 550ppmv and 1% the mitigation costs increase by 67%. The authors conclude that high leakage rates would induce considerable costs. However, it has to be pointed out that the CCS path would have been change in order take account of the delayed emissions.

The sensitivity analysis of this chapter pointed out that the importance of leakage rates for the CCS time path and the reduction of GWP losses depends on the characteristics of all other options. This is due to the substitutive relationship between CCS and other options. A high leakage rate defers the application of CCS to later periods because the marginal return of a ton of carbon increases as the economy grows. Early CCS would induce delayed emissions that have to be taken into account in latter periods. If an alternative is available, then the negative impact of delayed emissions is reduced.

7.5 Discussion of Results

The results computed with *MIND1.1* confirm the assumption done in *MIND1.0*, where an exogenous path of CCS has been assumed. Endogenous determination of CCS results in a temporary utilisation of that option within an CO_2 emission mitigation strategy. The reduction of economic losses are temporary by reducing the peak of the inverted-U shaped time path of economic losses. The overall economic effect is small.

Testing the robustness this result provides two different pictures that are related to two types of model parameters. The first type of parameters describes features of a part of a model like learning or leakages rates. The second type of parameters is related to constraints of varying control variables.

1. ***Type 1 Parameters*** Variations of these parameter result in small changes of the CCS path – except the intertemporal elasticity of substitution IES –

and the corresponding reductions of economic losses induced by the climate protection goal.

- Variations of the leakage rate do imply a non-linear effect on the CCS path for low leakage rates by applying the high cost Post-Coal technology also, but the changes changes of the reduction of economic losses are not as sensitive.
- Variations of macro-economic RD&D parameters reducing the energy demand lead to linear changes of the cumulative amount of CCS until 2050 by reducing and deferring the maximum amount of CCS. Parameters characterising the intertemporal welfare function show a different sensitivity. Variations of the discounting rate leads only to small changes of the CCS amount. However, the IES exhibits a considerable non-linearity of the CCS amount, that is related to changes of the investment dynamics during the transition of the world economy towards the long-run growth path.
- Reframing the characteristics of sequestration alternatives SA show that variations of parameters specific to one SA alter the allocation of between the SAs, but the absolute amount does not depend on that.

This result is confirmed by a Monte-Carlo analysis varying such parameters.

2. ***Type 2 Parameters*** Variations of these parameters show different impacts on the climate protection strategy, depending whether the related constraints are binding or not.

    - Constraints on the introduction of CCS technologies do not lead to changes of the major CCS technologies. This implies that the constraint is binding.
    - Constraints on the maximum utilisation of CCS technologies do not lead to changes around the base case. This means that the constraint is not binding.
    - Introducing a constraint on the potential supply of renewable energy has considerable implications on the time path path of CCS, the reduction of economic losses and the sensitivitity of the leakage rate. The economic

losses become much higher and the type 1 parameter leakage rate becomes a highly sensitive. Since the delayed emissions have to be taken into account the model shows a complex sensitivity with respect to variations of the renewable constraint and the leakage rate. Most notably, low leakage rate ($<0.1\%$) induce high and prolonged CCS activity.

These findings point on the importance of the dynamics of energy systems and possible constraints on the introduction of new technologies. Although this finding has been observed in other studies, the main emphasis in techno-economic studies and CO_2 emission mitigation assessments is on parameters of the first type. But for the assessment of the overall systems performance parameters of the second type limiting the flexibility of energy systems seem to be more important.

Chapter 8

Conclusion and Further Research

The final discussion of this thesis contains two main subjects. First, the option of CCS is assessed (Ch. 8.1) and second directions of further research are identified (Ch. 8.2).

8.1 Assessment of the Option

The main guiding question of this thesis has been whether CCS is an option to buy time. This question is embedded in discussions regarding sustainable economic growth, introduction of new technologies and the choice between several mitigation options. Answering the question has to take into account economic and technology transitions.

Today, the world economic system depends heavily on fossil fuels. In the past they supported economic growth. Since the increase of the energy productivity has been lower than the increase of labour productivity and population, the demand for fossil fuels increased and so did the CO_2 emissions.

Fossil fuels are still plentiful in order to support economic growth over the 21st century and beyond. When they become exhausted, the energy system would be mature for a transition towards renewable energy sources. However, emitting the carbon underground into the atmosphere would lead to dramatic and persistent changes of the world climate that are expected to lead to considerable damages, if the ability to adapt to such changes turns out to be limited. One alternative to climate change adaptation is macro-engineering of the earth's radiative balance. The outcome of such measures is uncertain and there are serious doubts on the possibility that a political mechanisms could be implemented to find a decision at the international level.

Since adaptation and macro-engineering are risky options, emission mitigation – espec. CO_2 emissions – is the only alternative to deal with climate change. Reducing the emissions through population control or long-term reduction of economic growth appears questionable on ethical and political grounds and additionally could be counterproductive because technological change is decelerated. Technological options offer the possibility to circumvent the use of these options.

The technological options address the CO_2 emissions from the energy demand and supply side. Reducing the growth of energy demand reduces the growth of CO_2 emissions, but it would turn out to be too costly, since in the long run the energy consumption has to increase because otherwise the energy prices would persistently increase and thereby reduce economic growth shifting expenditures towards energy. Increasing energy supply without increasing CO_2 emissions can be achieved either by employing renewable energy source pre-maturely or by capturing the produced CO_2 from fossil fuel use and to sequester it in geological formations.

The technological options are intertemporaly related to another. The near-term reduction of fossil energy supply leads to increasing prices and due to the limited potential for substitution the energy expenditures increase. This gives the incentive to introduce renewable energy or CCS technologies. The relative costs and long-term dynamics – espec. leakage and learning – determine the timing and extent of employing both technologies.

If renewable energy technologies are the only possibility, the economy has to suffer considerable costs and macro-economic disruptions in the mid-term, when renewables are introduced at a rapid rate. These are reduced through learning investments that reduce the investment cost prior to the rapid introduction of renewables.

If CCS is considered an available option the costs and macro-economic disruptions can be reduced and deferred because CCS allows the prolonged use of cheap fossil fuels. This makes CCS an option to buy-time. Although fossil fuels will be replaced by renewables at some time in the future, the relative costs temporarily favour the use of clean fossil fuels with reduced CO_2 emissions. The forgone learning in renewable energy does not outweigh the additional costs of CCS.

The extent and timing of the CCS option requires an appropriate modelling framework. The *MIND* model framework used in this thesis is a hybrid model integrating an economic growth model of the Ramsey-type with an energy system model and a climate system model. The use of a hybrid model that integrates these various systems is suggested by the complex problem at hand and justified by the dynamics and feedbacks between the systems.

The CO_2 emission mitigation options are related to investments and their social optimal timing and extent is computed by maximising an intertemporal social welfare function. Although this function is subject to various points of critique it takes into account issues of intergenerational equity.

The use of CCS and the other options depends on assumptions of various exogenous model parameters. The extensive sensitivity analysis undertaken in this thesis revealed that the property of CCS being an option to buy time is robust for a broad range of parameter values. It turns out that the potential to introduce renewable energy technologies is highly important for the use of CCS. Imposing such a constraint reduces the ability to switch to alternative energy sources giving features of CCS like the leakage rate a higher significance. The more constrained renewable energy sources are the more sensitive are the results regarding the extent and the welfare impact of CCS with respect to parameter variations of the CCS technology. For tight constraints on renewables and low leakage rates can make CCS even an option that is used throughout the 21^{st} century.

However, CCS is still a speculative technology. There is only some experience with the technology components that CCS requires and there is only one CCS project – Sleipner – that is exclusively undertaken due to a CO_2 tax. It is questionable at which time low cost capture technologies for large industrial facilities will be commercially available and at what rate they could be introduced.

Since both – renewable and CCS – are speculative technologies with respect to the large scale integration into the existing energy system, more experience has to be gained by undertaking (relatively) small scale projects. As long as the experience is not reliable for a large-scale change of the energy system increasing the energy productivity is a robust strategy, but it is becoming more and more expensive.

Macro-engineering and adaptation require experiments at the planetary level that seem to risky. However, adaptation has to be undertaken in order to deal with climate change that is already present and up to the level that can not be avoided any more. Macro-engineering remains a highly dubious option, that – nonetheless –

should be further investigated in order to be prepared, if all other options turn out to be flawed.

8.2 Further Research

8.2.1 Validation of Economic Models

Economic models for the assessment of public policy issues like CO_2 emission mitigation should reproduce a set of predefined empirical facts. There are at least two levels of such standards. First, a model reproduces a set of stylised facts qualitatively and quantitatively. Second, a model reproduces a set of economic time series data.

Such quality standards are important for the reliability of economic models that form the basis for policy advice. A first consequence of that research has been to improve the endogenous growth model part of *MIND* in the future; see Edenhofer et al. (2004b). Moreover, this research seems useful to enhance the understanding of the dynamics of economic transition processes.

A serious problem with respect to validation of economic models is that it requires large computational capacities. The model validation environment *MOVE* introduced in this thesis has to compute the optimal solution of a model about 100 times in order to converge to an optimal set of parameters. Improvements of optimisation algorithms are expected for large scale solvers, but not for solvers that search for the optimal set of three or five parameters. Therefore, new mathematical methods that reformulate the nested optimisation problem would be highly useful for this branch of research. Otherwise the problem could only be solved by the use of computing power and time.

8.2.2 The Decentralised Economy and Policy Instruments

The *MIND* model computes social optimal solutions. However, the economic system in reality consists of decentralised economic agents coordinating their decisions on markets. It is questionable whether the policy variables of a social optimal solution would induce the equivalent behaviour in a corresponding model of a decentralised economy, if learning effects are considered.

The problem is that computable general equilibrium models are inherently weak in representing decentralised coordination of intertemporal allocation problems and additionally, if learning effects have to be taken into account. This is due to the increasing number of markets that have to be considered, when several periods are taken into account.

Therefore, the assessment of policies addressing long-term policy issues like technological change and CO_2 emission mitigation could be improved considerably, if equilibrium solvers are developed that could solve such models. Issues that could be resolved are related to the efficiency of policy instruments like taxes, emission caps and direct subsidies in order to support learning investments.

8.2.3 The Decentralised Economy and the Capital Market

The *MIND* model implicitly assumes a perfect capital market. This assumption is questionable and considerable research in theoretical and empirical economics has been devoted to this issue. It is well known that imperfect capital markets do not necessarily lead to social optimal solutions; see e.g. Stiglitz and Weiss (1981).

The issue of imperfect capital markets is important for at least three reasons:

1. Energy related investment decisions usually regard two financial needs: upfront investments and fuel costs. It seems reasonable that facilities with a higher fuel efficiency demand require higher investment costs that are offset by lower fuel costs. If an investor is confronted with a financial constraint on a credit rationed market – i.e. he does not get the financial means he would demand at a given interest rate – he would tend to invest in less energy efficient facilities or use old facilities for a longer time. Moreover, since various energy supply technologies exhibit different cost structures regarding capital and fuel costs, it is reasonable that imperfect capital market could lead to biases in investments.

2. The literature on empirical findings regarding the returns on R&D expenditures revealed that imperfect capital markets tend to increase the interest rate of such investments. A related field is the financing of exploration and development projects in the oil and gas industry that also require large up-front investments with uncertain return rates. It would be worth to gain insights into the implications on energy demand and supply technologies.

3. Energy markets are known to exhibit emphasised investment cycles and price variations that are considered to be related to the high investment costs as well as leads and lags of down-stream and up-stream facilities. Morishima (1992) related these cyclical trends to the problem of financing investments through capital markets.

Such effects could have implications on the business as usual scenario as well as on policy scenarios, but the significance is already unknown. CO_2 emission mitigation policies might be considered as second best problems with imperfect capital markets and it seems worth to consider possibilities to overcome these imperfections.

8.2.4 Energy Systems and Technology Disaggregation

The *MIND* model assumes a single good energy. This is a highly stylised assumption considering the different forms of energy, conversion technologies and end-uses. As has been already pointed out this leads to considerable problems regarding the integration of various carbon capture technologies.

The heterogeneity of energy opens different potentials for the CO_2 emission mitigation strategies in different sectors. For example, the housing sector is considered to be a sector with a significant potential for efficiency improvements of end-use energy of low-temperature heat. Different to that the electricity supply sector seems to be important for fuel switching including renewable energy technologies as well as CCS. The transportation sector might apply a switch towards fuels produced from biomass.

This suggests the disaggregation of the energy sector in order to represent several energy carriers, conversion technologies and end-uses. Disaggregation of the energy supply sector has to be combined with the disaggregation of the energy demand sectors. Energy supply and demand sectors exhibit different structural dynamics that should be addressed for long-term policy issues.

Modelling various energy supply technologies in hybrid type models is highly advanced, while the representation of the demand sectors is at a less sophisticated level. There are different approaches to model several energy demand sectors. The one applied in models like *MERGE* is to use a nested CES function and to combine end-use energies in a particular CES composite; i.e. electric and non-electric energy form a CES composite that is combined with capital and labour in order to produce aggregate economic income. An alternative is to develop a multi-sectoral growth model with several competing production sectors like agriculture and industry, which are related to one another by input-output relationships and supplying goods to the household sector. A less sophisticated approach is to advance the nesting structure of a macro-economic production functions in order to represent several types of energy that are combined with several types of capital that represent end-uses.

A related research task is related to the functional specification of production functions. The discussion about the elasticity of substitution and the separability of production factors showed that the CES production function might be problematic, since energy is not separable from labour and capital. Using translog production functions could gain new insights into the interaction of growth and distribution, if an essential production function is (temporarily) scarce.

8.2.5 Technology Dynamics: Diminishing Returns and Innovation

The point for further research addresses the problem of modelling energy technologies in energy system models ESM as well as hybrid models. As has been pointed with respect to renewable energy sources and CCS technologies there are investment projects with different productivity depending on location, technical characteristics and factor prices.

In *MIND* the renewable energy technologies are characterised by constant full load hours and investment costs that decrease with experience. It has been pointed out that different locations provide different full load hours although the investment costs are more or less the same. However, it is assumed that renewables can be extended without taking into account the differences of spatial location.

The carbon capture technologies in *MIND1.1* have been disaggregated to represent several technological options and that the low cost technologies can only capture a limited share of all CO_2 emissions. If more CO_2 shall be captured, less productive technologies have to be used. The temporary utilisation of CCS exhibits a pattern that the low cost technology is used first for the longest time and the less productive technologies enter the portfolio later and for a shorter period.

It is a promising task to disaggregate the renewable energy sector also in order to take account for the varying characteristics of different locations. On the one hand favourable locations are a scarce good and the availability of locations implies constraints on renewable energy technologies, which can be overcome if they pay off. On the other hand, early opportunities for inducing learning investments would be less costly and as the technologies move down the learning curve they act as pioneer projects that make locations profitable that won't pay off otherwise; e.g. on-shore wind is a preceding off-shore wind.

Disaggregation of the renewable energy sector along these lines offers the possibility to model the dynamics of endogenous technological change and the relation to climate policy in a more appropriate way. It seems reasonable that a small increase of the price of carbon pushes some projects over the break even point of profitability. The modelling approach introduced in this thesis, given that there are no learning effects, would push the entire renewable energy sector over the break even, which would lead to a sharp switch of the investments. The learning effect induces learning investment prior to the extensive use of renewables; i.e. the learning effect smoothes the investment path.

A way to deal with this problem is to introduce sharp constraints on the introduction or potential use of renewables. This straight forward approach leads to time paths of the energy mix that seem realistic, but it does not pay attention to the fundamental problems of innovation and diminishing productivity that characterise renewable energy sources. The concept of diminishing returns, although broadly discussed with respect to the dynamics of exhausting fossil fuel deposits, has not yet entered the modelling of energy systems, when it comes to renewable energy sources.

The essence of the problem has been forestalled by David Ricardo who focused on growth and distribution in an economy with a scarce factor that is essential for production. He concluded that growth – induced by increases of the labour productivity – would be limited and income distribution would shift towards the owners of the scarce factor because the rising relative price. As Schumpeter pointed out, this rent income – characteristic for an unsustainable economy – is the incentive for innovation because it could be appropriated by an innovator. The innovator needs financial means in order to prepare market introduction and to build up production capacities. Therefore, technology dynamics should be modelled as the contradiction between diminishing returns and innovation with a particular emphasis on financial institutions.

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