Environmental Research Plan of the Federal Minister
for Environment, Nature Protection and Reactor Safety

Climate Protection

FKZ (UFOPLAN) 205 41 116

Cost-optimised Climate Stabilisation (OPTIKS)

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Commissioned by the Federal Environmental Agency

April 2008

Report Cover Sheet

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Abbreviations and Measurements

- CCS - Carbon capturing and sequestration
- CES - Constant elasticity of substitution
- EJ - Exajoule
- ESM - Energy system model
- GDP - Gross domestic product
- GJ - Gigajoule
- GNP - Gross net product
- GtC - Gigatons of carbon
- $GtCO_2$ - Gigatons of carbon dioxide
- IEA - International Energy Agency
- IPCC - International Governmental Panel on Climate Change
- PWT - Penn World Tables
- R&D - Research and development
- SRES - Special report on emissions scenarios
- t - tons
- tC - tons of carbon (1 tC = 3.667 tCO_2)
- UNFCC - United Nations Framework Convention on Climate Change
- WDI - World Development Indicators
- WEO - World Energy Outlook
- $US - US Dollars
- $US/tC - US Dollars per ton of carbon (1 $US/tC = 0.273 $US/$tCO_2$)

Acknowledgement

For helpful discussions and support in preparing the report, we are grateful to Michael Lüken, Markus Haller, Michael Jakob and Brigitte Knopf. We also thank Martin Weiss for critical comments and constructive guidance in making this report policy-relevant.

Chapter 1

Introduction

1.1 Project task

Based on the resolution of the EU Council of Ministers to avoid a warming of the Earth's atmosphere by more than 2°C compared to the pre-industrial level, it has been the mission of the research project to identify the magnitude of costs to attain such a climate protection target. The regional specification of investments and mitigation costs is highly important for the climate policy negotiations which has therefore been the central objective of the research project. In detail, the role of European climate policy in the context of globalisation shall be analysed. Moreover, the influence of international emission trade on the costs of climate change mitigation under different constellations of the post-2012 climate policy regime shall be investigated.

1.2 Preconditions

The project was started and carried out in a period of intensive external discussion and political negotiations on the Kyoto Protocol and follow-up agreements. The UN Framework Convention on Climate Change formulates the objective to stabilise the concentration of greenhouse gases on such a level that ”would prevent dangerous anthropogenic interference with the climate system” (article 2 of the Framework Convention on Climate Change). This objective is an essential basis for the international negotiation process to further develop the climate policy regime.

In order to support this process, climate policy analyses with an improved energy-economic-climate model should have been carried out within the project. The model MIND (Edenhofer et al., 2005) was available at PIK at the beginning of the project.

MIND is a global Integrated Assessment Model suited for analyses of mitigation options and the impact of induced technological change on the costs of climate policies in a cost-effectiveness mode. MIND is composed of a macroeconomic module, an energy system module and a climate module. The energy system distinguishes a fossil extraction sector, a fossil energy sector, a renewable energy sector and a remaining energy sector. Technological change in MIND has an endogenous formulation with R&D investments in labour and energy productivity, learning by doing, and vintage capital in the different energy sectors. Major mitigation options in MIND are represented by: (i) increasing energy efficiency, (ii) increasing the share of renewable energies, (iii) carbon capturing and sequestration.

In order to address the research questions posed by the OPTIKS project, further development was needed. There were two branches of model expansion. On the one hand, a more disaggregated energy system model had to be developed and integrated. This should allow to identify in more detail the technological mitigation options which will help to meet the required emission reductions of ambitious stabilisation scenarios. On the other hand, a regionalised structure which captures important regional interactions had to be developed. A regionalised model shall provide the basis for addressing the issues of international burden sharing, emissions trading, technology transfers and trade.

At PIK, preparatory work for the multi-region model (REMIND) yield experiences in modelling endogenous technological change and algorithms that solve state-of-the-art growth models numerically. Few theoretical ground is provided in modelling regional interactions in a dynamic (intertemporal) framework. The usual approach in analysing regional interactions (mainly trade-related) is to apply CGE models that, however, are limited to a recursive dynamic. The Negishi approach is an alternative, which originally is limited to a single good problem. Additional challenges arise when externalities like emissions and technological spillovers have to be taken into account.

1.3 Planning and progression

The work plan of the project was separated in two major steps: Model development and policy analysis. As mentioned above, model development was based on the existing model MIND and experiences in multi-region modeling. The modeling process, consisting of data collection, calibration and validation, was run through repeatedly. While the MIND model was advanced in terms of modeling endogenous technological change, it was limited with respect to regional interaction. Therefore, research activities were concentrated on the development of a model that is regionally disaggregated in the first phase. We developed the REMIND-S model version. While this model version allows to analyse issues of international burden sharing, technological spillovers and emissions trading, the technological options within the energy system were quite limited. In order to qualify our analyses on the mitigation costs of climate stabilisation, we focused on a disaggregation of various energy technologies in the second phase of the project. At the same time, we extended the regional disaggregation level. The product of this work - REMIND-R - is a large-scale model that is quite expensive in terms of computing time. Due to this fact, model validation took more time than expected. Consequently, project time had to be expanded to run multiple policy scenarios.

1.4 Scientific state-of-the-art

Model-based quantitative analyses are frequently used in climate policy decision-making. A number of energy-economy-climate models was developed and applied over the last decade - e.g. RICE (Nordhaus and Yang, 1996), MERGE (Manne et al., 1995; Kypreos and Bahn, 2003), FAIR (den Elzen and Lucas, 2005), DEMETER (Gerlagh and van der Zwaan, 2003). The overview of mitigation analysis in IPCC (2001) indicates that there might be at least three crucial factors in determining economic costs of climate policy strategies: 1) baseline development in the absence of climate policy, 2) the number and type of mitigation options considered in the analysis and 3) the way technological change is handled. The range of mitigation costs that the IPCC reports in the Third Assessment Report (IPCC, 2001, p. 548) for 450 ppm CO_2 stabilisation scenarios amounts to 1-4% of global GDP.

Recently, progress was made in modeling endogenous and induced technological change (cf. Löschel, 2002, Edenhofer et al. 2006). Models incorporate technological change endogenously either in the form of investments in R&D, spillovers from R&D, or technological learning processes (Grubb et al., 2002). Many applied modelling concepts with a detailed representation of energy technologies apply experience curves as a meaningful description of technological change (Grübler et al. 1999). Almost all of them are restricted to energy converting technologies and find large welfare gains from induced technological change (e.g. Goulder and Mathai 2002). This result is confirmed by bottom-up energy system models. Learning-by-doing and economies of scale within the renewable energy sector reduce the costs of meeting specific climate stabilization targets (Manne and Barreto 2004).

The energy sector is a key sector for mitigation strategies. A portfolio of different technological options and a flexible investment dynamic are crucial in transforming the energy system in a climate-friendly way. However, the integration of a ("top-down") macroeconomic system module and a detailed ("bottom-up") energy system module is only realized in a few models.

Most previous studies (e.g. Manne and Richels, 1997) interpret the climate stabilisation level requested by the UNFCC as a doubling of the pre-industrial CO_2 level - approx. 550 ppm. Climate impact studies (e.g. Hare and Meinshausen, 2004) show that the risks for irreversible climate damages is quite high when increasing the global mean temperature by more than 2°C compared to the pre-industrial level. This climate target, however, is incompatible with a stabilisation level of 550 ppm. Concentrations below 450 ppm have to be reached.

In studying the impact of climate policy instruments, a major focus is on international emissions trading. A range of different proposals for designing an emissions trading regime can be found in the literature. Heavily discussed is the question of initial permit allocation (Rose et al., 1998). Grandfathering-based regimes compete with efficiency-based regimes, with contraction & convergence and with equal per capita allocation regimes. The number of comparative studies systematically evaluating the implications of various post-2012 regime options is, however, limited. Amongst the most comprehensive analysis are the studies by Jacoby et al. (1997) and Höhne et al. (2003). Den Elzen et. al. (2005) provide an advanced regime analysis. They found that the multi-stage and the Triptych approach and, to a lesser extent, the contraction & convergence approach provide best prospects for negotiations. The weakness of their model approach, however, are missing indirect-cost effects which occur from feedbacks of the economy on the energy sector.

We present a novel hybrid model - REMIND-R - that couples a macroeconomic system module with a highly disaggregated energy system module and a reduced-form climate module. Mitigation costs estimates are based on technological opportunities and constraints in the development of new energy technologies. Most essential, technological change in the energy sector is embedded in a macroeconomic environment that by means of investment and trade decisions governs regional development. Altogether, this provides a new level of climate policy decision support and a basis for assessing future climate policy regimes. In contrast to previous policy regime analysis, this analysis considers a more advanced stabilization target and comes up with a much broader variation of regional mitigation costs based on a detailed description of the regional energy systems and trade linkages.

The main part of this report is structured as follows. The newly-developed model REMIND-R is presented in chapter 2. In chapter 3, we discuss the results from REMIND-R simulations for the reference (i.e. business-as-usual) scenario. The main focus of the report is the analysis of climate policy scenarios which are the subject of chapter 4. Three cap-and-trade systems have been selected as implementations to be analysed for a post-Kyoto regime: (I) contraction & convergence, (II) intensity target, (III) multi-stage approach. These different approaches are used to allocate the global emission reduction obligations among the regions that are necessary to reach the ambitious 2°C climate protection target. The approaches have been selected in such a way that they reflect a certain spectrum in sharing the international reduction burdens. Hence, a basis is formed for a comparative analysis of the mitigation cost structures of different policy regimes. Results from scenario runs with the global model MIND are also summarized in this chapter. Finally, by switching them off we analyse the value of single technological mitigation options (e.g. carbon capturing and sequestration, nuclear energy). Conclusions are given in chapter 5.

Chapter 2

Model description REMIND-R

REMIND-R is a multi-regional hybrid model which couples an economic growth model with a detailed energy system model (see Figure 2.1) and a simple climate model. The individual regions are linked by means of a trade module.

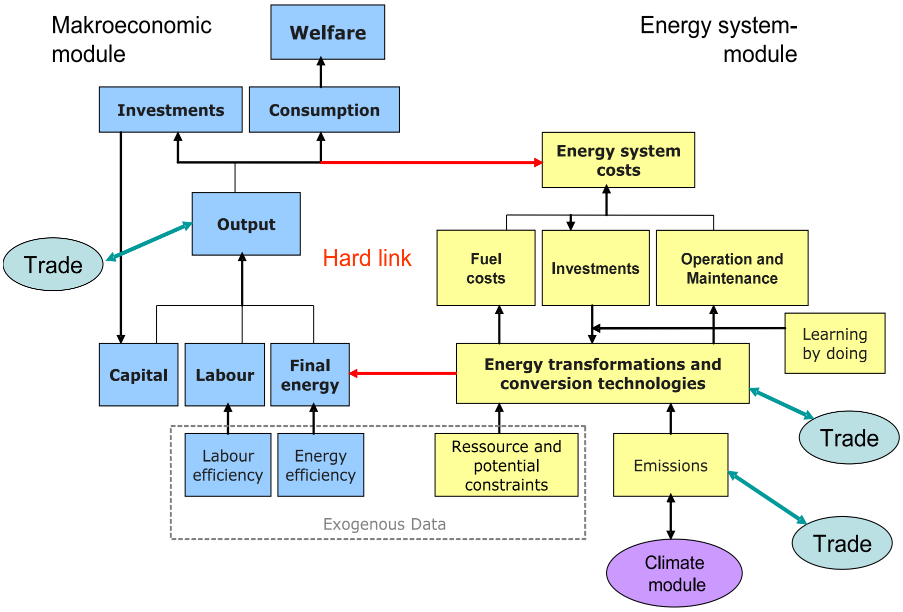


Figure 2.1: Structure of REMIND-R

The current version of REMIND-R includes nine world regions (see also Figure 2.2):

1. UCA - USA, Canada, Australia
2. EUR - EU27
3. JAP - Japan
4. CHN - China
5. IND - India
6. RUS - Russia
7. AFR - Sub-Saharan Africa (incl. Republic of South Africa)
8. MEA - Middle East and North Africa
9. ROW - Rest of the World (including Latin America, Pacific Asia and Rest of Europe).

The colours used in Figure 2.2 show whether a respective region belongs to the group of industrial countries (blue) or developing countries (green). Regions which are in a transition period (i.e. which have an average per capita income) are shown in red. Regions which are represented as ROW are shown in yellow. The decision to restrict oneself to nine regions has technical reasons. The solvability of the model could not have been guaranteed with a larger number of regions and the computing time for model experiments, that needed to be carried out several times, would have increased intolerably.

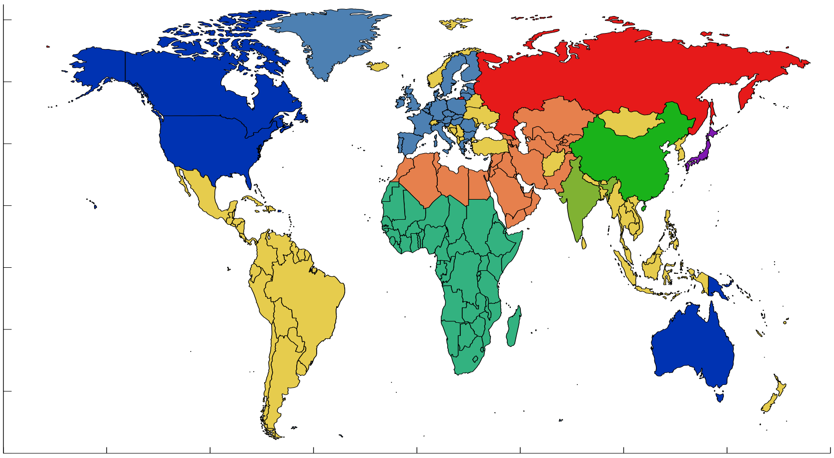


Figure 2.2: World regions in REMIND-R

Figure 2.3 shows the population development of all regions from 2005 to 2100 according to the exogenous population scenario used (WDI, 2005). World population grows from 6.6 billions in 2005 to 9.0 and 10.0 billions in 2050 and 2100, respectively. Africa and India are the regions with the largest population growth. The population number in China will still grow until about 2035 and stagnate afterwards. The regions UCA, EUR, Russia and Japan will also not crucially grow, the population number will to some extent decrease.

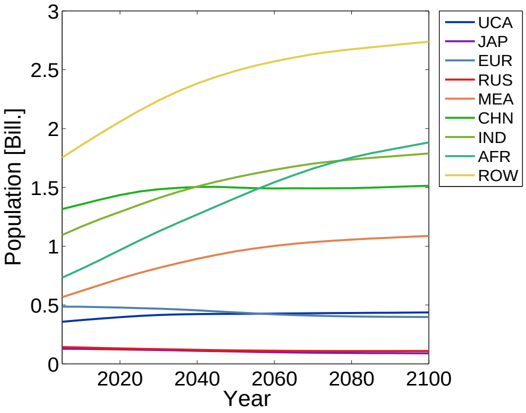


Figure 2.3: Population development

2.1 Macro-economy module

The world-economic dynamics over the time horizon 2005 to 2100 is simulated by means of the macro-economy module in REMIND-R. The time step range is five years. Each region is modelled as a representative household with a utility function that depends upon the per capita consumption. It is the target of REMIND-R to maximise a global welfare function that results as a weighted sum of the regional utility functions. REMIND-R is run in the cost-effectiveness mode when it is used for climate policy simulations, i.e. climate policy targets are integrated into the model by an additional constraint (e.g. upper bound for temperature increase). In the context of an intertemporal optimisation, a solution which is able to meet this climate target in a welfare-optimal way is searched.

The production function which determines the marco-economic output expressed as the gross domestic product (GDP) is the central element of the module. The macro-economic production function is a ”constant elasticity of substitution” (CES) function of the production factors labour, capital and end use energy. To be able to calculate this end use energy, there is a nested tree with additional CES production functions. The end use energy of the upper production level is calculated as a production function which comprises the transportation energy and the stationary used energy. These two energy types are in turn determined by means of nested CES functions. The whole tree is shown in Figure 2.4 .

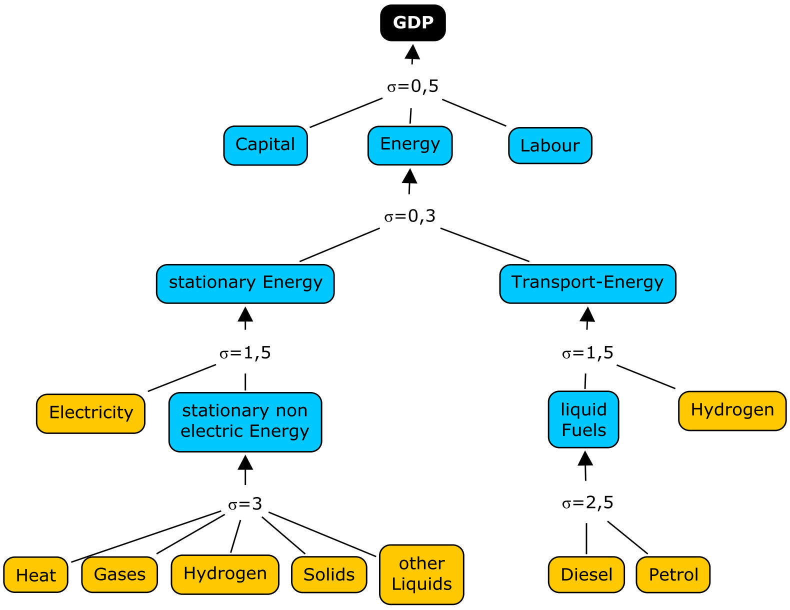
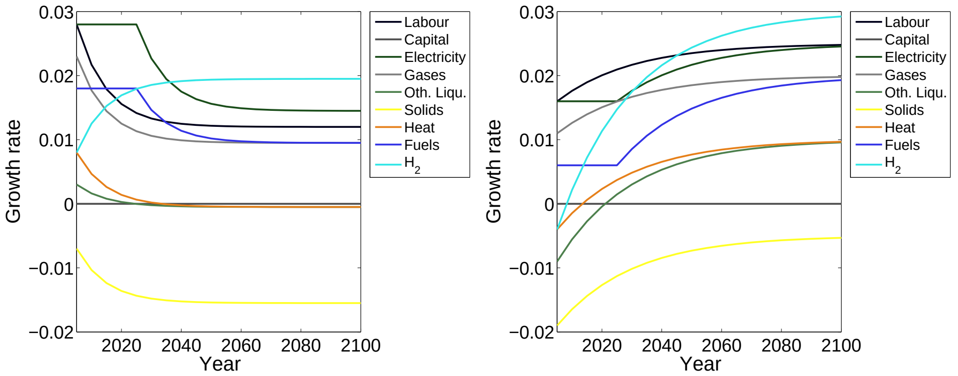


Figure 2.4: CES production structure in the macro-economic module

The CES production structure shows the substitution elasticities between the production factors of the respective levels. In general, it holds true that the substitution elasticity increases with a larger ramification. A value of 0.5 is assumed for the top level, whereas the substitution elasticity is between 2.5 and 3 for the lower levels.

The produced GDP of a region is used for the regional consumption, investments, all expenditures in the energy system and for the export of goods. The available gross national product (GNP) results from additionally considering the imported goods. An exact description of the trade module with a list of all tradable goods can be found in Chapter 2.3. The amount of investments in a region determines the change of the respective capital stock.

Endogenous R&D investments are not yet modelled in REMIND-R. Instead, exogenous efficiency changes of the individual production factors are given for all production levels. Figure 2.5 exemplarily shows the growth rates of the efficiency parameters for the individual production factors in the regions UCA and MEA. Initially, there are higher parameter values for India and above all for China. The initial values represent first best guesses supported by empirical data (PWT, 2007).



(a) UCA (b) MEA

Figure 2.5: Growth rates of the efficiency parameters of individual production factors

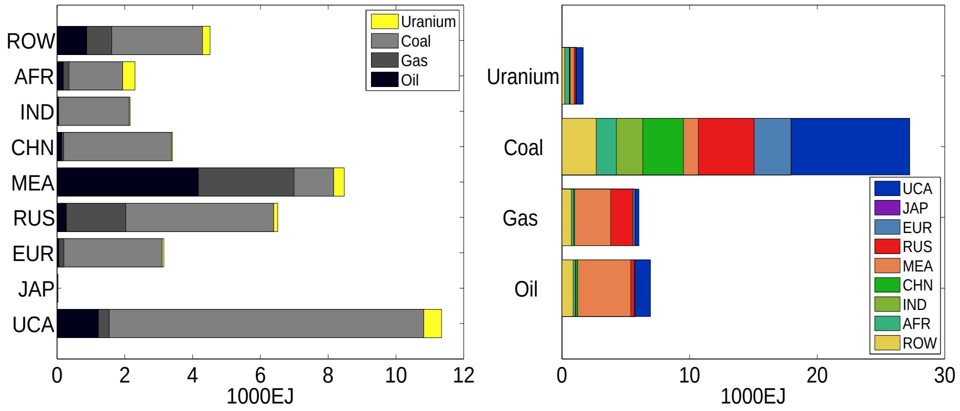
2.2 Energy system module

The energy system module (ESM) of REMIND-R comprises detailed technical and economic aspects of energy transformation. Three prerequisites need to be fulfilled to be able to transform one energy source to another:

1. Sufficient capacities need to be available that are to be built up by investments,
2. funds need to be spent for maintenance and operation,
3. sufficient primary energy sources need to be available, the provision of which is combined with fuel costs.

The financial expenses need to be covered by a budget that corresponds to the GDP, i.e. each increase in energy system costs will lead to restrictions in consumption which, according to the utility function, will lead to losses in welfare. First, secondary energy sources are produced from primary energy sources. These are transformed into final energy carriers by transportation and distribution which on their part are available on the macro-economic sector. The secondary energy source electricity takes on a special position since it will also be used for several other transformation processes. In most cases, it needs to be used - as for heat pumps - in combination with other primary energy sources. It can, however, be used alone for the production of hydrogen. In the following, the most important characteristics of the primary energy sources are explained to be able to present the connection to the secondary energy sources and their transformation options then.

Multiple primary energy sources are available in the ESM. There are renewable primary energy sources that can be used in each period without changing the costs of utilisation in subsequent periods. However, they cannot be used unboundedly. Region-specific and energy source-specific potentials are defined here. In addition, the potentials are classified into different grades which, as a result of optimisation, leads to a gradual extension of the use of renewable energy sources. This means that e.g. a gradual potential of wind power is exhausted before the next – relatively less attractive – potential will be exploited as the electricity price crosses a critical value.



(a) Countries (b) Energy carriers

Figure 2.6: Overview on reserves of exhaustible primary energy carriers

Besides, there are exhaustible primary energy sources where the costs rise with increasing cumulative extraction region-specifically and energy source-specifically. Our assumption on the scarcity of exhaustible resources is based on data from ENERDATA. Figure 2.6 shows the reserves of exhaustible primary energy carriers differentiated by energy sources and regions. Table 2.1 shows the cost parameters for the exhaustible resources. Each extraction curve for all regions and energy types starts at the initial extraction costs. The extraction costs at reserve limit are exactly met, when extraction reaches the reserve limit. The initial extraction costs and those at the reserve margin are connected by a quadratically increasing function. Extraction of the primary energy types can be extended beyond the reserve limit, but the extraction costs continue to follow the quadratic

Table 2.1: Overview on cost parameters of exhaustible primary energy carriers

	Coal	Oil	Natural gas	Uranium
Initial extraction costs [$US per GJ]	1.5	3.5	3.5	$30\frac{\$US}{kg}$
Extraction costs at reserve limit [$US per GJ]	3.5	6	6	$80\frac{\$US}{kg}$

increase. The assumptions on extraction costs of fossil resources are at the bottom edge of estimations to be found in literature.

As for exhaustible primary energy sources, the use of fossil energy leads to CO_2 emissions, while the application of carbon capture technologies can contribute to a strong decrease of CO_2 emissions. Transformation technologies which use biomass can also be complemented by CO_2 capturing provided that they are used to produce fuels or hydrogen. Among the renewable energy sources, biomass has a special position since its fuel costs increase with the intensity of use. This complies with a biomass supply curve which, however, is only defined up to a maximum possible potential. It is assumed that the production potentials for biomass will increase until 2050 where the long-term potential of around 210 EJ is reached. It should be noted that the use of fossil energy sources and biomass will lead to further emissions (CH_4, SO_x, NO_x, etc.) that will, however, not be considered in the model.

Table 2.2 shows the transformation options of primary energy sources into secondary energy sources. Technologies that are available in the model are shown in the respective fields. A technology that appears in two fields produces joint products. For reasons of clarity, Table 2.2 only includes the most important ones. By-production is, among others, important in the refinery area since it is possible to change the composition of the output. For this reason, a number of refinery types are considered that produce the outputs in different proportions. By changing the composition of the refinery park, the output mix will also be changed. As a result, this will in particular lead to an increased processing of crude oil into transportation fuels.

The table suggests that there is a relation to energy balance equations. For each primary energy source it holds true that its consumption corresponds to the sum of the inputs of all technologies in the column. The balance equations express how these inputs are split up among the alternative technologies to produce secondary energy sources. Analogously, the production of secondary energy is the sum of all outputs of the technologies in the respective column. Due to transformation losses, the sum of all produced secondary energy sources is always smaller than the sum of all consumed primary energy sources.

		Primary energy types						
		Exhaustible				Renewable		
		Coal	Crude oil	Natural gas	Uranium	Solar, wind, hydro	Geothermal	Biomass
Secondary energy types	Electricity	PC*, IGCC*, CoalCHP	DOT	GT, NGCC*, GasCHP	LWR	SPV, WT, Hydro	HDR	BioCHP
	Hydrogen	C2H2*		SMR*				B2H2*
	Gases	C2G		GasTr				B2G
	Heat	CoalHP, CoalCHP		GasHP, GasCHP			GeoHP	BioHP, BioCHP
	Transport fuels	C2L*	Refinery					B2L*, BioEthanol
	Other liquids		Refinery					
	Solids	CoalTR						BioTR

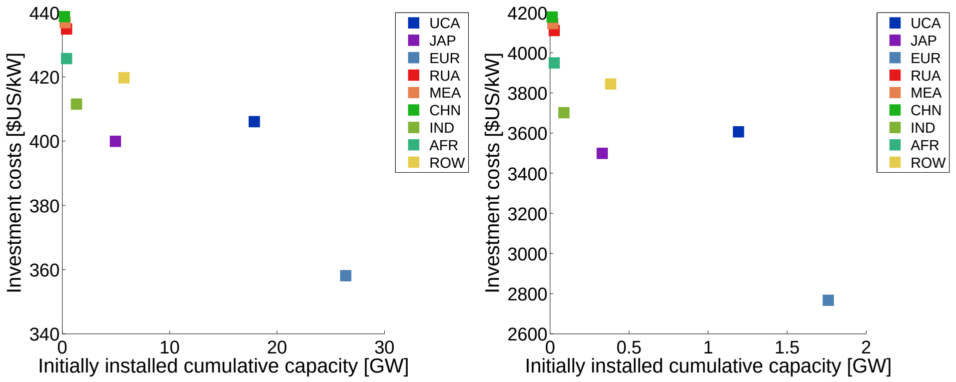
Table 2.2: Transformation technologies

Abbreviations: PC - conventional coal power plant, IGCC - integrated coal gasification combined cycle power plant, CoalCHP - coal combined heat and power, C2H2 - coal to hydrogen, C2G - coal to gas, CoalHP - coal heating plant, C2L coal to liquids, CoalTR - coal transformation, DOT - diesel oil turbine, GT - gas turbine, SMR - steam methane reforming, GasTR - gas transformation, GasHP - gas heating plant, LWR - light water reactor, SPV - solar photovoltaics, WT - wind turbine, Hydro - hydroelectric power plant, HDR - hot dry rock, GeoHP - heat pump, BioCHP - biomass combined heat and power, B2H2 - biomass to hydrogen, B2G - biogas plant, BioHP - biomass heating plant, B2L - biomass to liquid, BioEthanol - biomass to ethanol, BioTR - biomass transformation.

* this technology is also available with carbon capture and sequestration (CCS).

All technologies are considered by capacity stocks in the model. The technical transformation coefficients are assumed to be constant. However, the following modifications apply: the transformation efficiency is improved over time for fossil power generation technologies and different technology grades are considered when renewable energy sources are used. The by-production coefficients of the combined power-heat technologies (CHP) have been region-specifically adjusted to the empirical conditions of the base year.

The investment costs for each technology are the same in each region with two exceptions. Wind turbines (WT) and solar photovoltaics (SPV) are subject to the learning curve effect. ”Learning” technologies are characterised by the fact that their investment costs decrease by a certain percentage (the learning rate) with each doubling of the cumulated capacities. The learning curve effect is implemented in such a way that only some part of the investment costs can be reduced. Another part of costs is fixed (floor costs). Both, the initial values for the investment costs and the initial cumulated capacity are different between the regions (see Figure 2.7). The mode of calculation corresponds with Leimbach and Baumstark (2008, p. 11).



(a) Wind turbines (b) Solar photovoltaics

Figure 2.7: Initial conditions for the learning curves differentiated by regions
(Note: the investment costs on the ordinate represent only that part which can be reduced by learning. The floor costs amount to 1000 $US/kW for SPV and 700 $US/kW for wind)

When transforming secondary energy into final energy carriers, real transformation options are of lesser interest, but the distribution infrastructure is of particular importance. Except for hydrogen that can be used for transportation and stationary energy, each secondary energy source will be transformed into exactly one final energy carrier. Losses that occur in the distribution of secondary energy are estimated based on statistical data differentiated by region.

For each transformation technology, each region starts with a vintage capital stock which meets the statistically given input-output relations. For the fossil power generation technologies, we took into account that older generations of power plants have a lower transformation efficiency and thus higher specific CO_2 emissions.

It still has to be mentioned here that the model has no exogenous restrictions that provide maximum growth rates or maximum shares in the energy mix for energy sources or technologies. Such restrictions of the solution space can quite often be found in energy system modelling but are not justified from our point of view. Each restriction can be surmounted by innovation and investment. Furthermore, the model considers that captured CO_2 needs to be transported and compressed prior to injection. Storage is assumed to be in geological formations only. There is leakage in the process of capturing, but no leakage from sequestered CO_2. Space in geological formations is generously measured for all regions.

2.3 Trade module

The model REMIND-R calculates a pareto-optimal solution that corresponds with a global planner solution and/or a cooperative solution. With this approach, it is guaranteed that the necessary emission reductions are carried out cost-efficiently and that all trade interactions are directed at increasing welfare in general and lowering mitigation costs in particular. The emissions trading is here a significant policy instrument.

The original idea to restrict the modelled trade activities to emission trade failed due to the fact that some regions (as e.g. Japan and Europe) are not at all able to supply their existing plants with domestic resources until the end of their technical lifetime. The import of resources needs to be considered. In order to restrict the scope of regional interactions, which complicate the processes of computation and result interpretation, the following trade variables were defined:

- Coal
- Gas
- Oil
- Uranium

- Goods (aggregated output of the macro-economic system)
- Permits (emission rights)

In order to co-ordinate the export and import decisions of the individual regions, REMIND-R uses the Negishi approach (cf. Manne and Rutherford, 1994; Leimbach and Toth, 2003). In this iterative approach, the objective functions of the individual regions are merged to a global objective function by means of welfare weights. In this global model, the balance between exports and imports for each kind of goods in each period is guaranteed by adequate trade balances. The question whether the chosen trade structure is intertemporally balanced and optimal depends on how the welfare weights are adjusted. A distinguished pareto-optimal solution, which in the case of missing externalities also corresponds to a market solution, can be obtained by adjusting the welfare weights according to the intertemporal trade balances. The higher the intertemporal trade balance deficit of a region, the more the welfare weight needs be lowered to induce exports from this region to other regions. In the calculation of the intertemporal trade balances, shadow price information from the model solution of the current iteration is used. The shadow prices of the market clearing equations and/or trade balances represent the respective prices of the goods in present values.

The convergence of the Negishi algorithm is guaranteed for convex models. While REMIND-R comprises non-convexities by modelling learning curve effects, experience from a multitude of model runs provide evidence that the convergence behaviour is quite robust.

The trade pattern that will result from model runs is highly impacted by the intertemporal trade balance constraint. Each export qualifies the exporting region for a future import (of the same present value), but implies for the current period a loss of consumption. Trade with emission permits works similarly to goods trade. The emission trade allows to trade emission rights, which are distributed free of charge in the different policy regions according to different allocation rules. The revenues from the sale of emission rights prove completely advantageous for the selling regions in the way that it generates entitlements for future re-exports of permits or goods. Each unit of CO_2 emitted by combusting fossil fuels needs to be covered by emission certificates.

The representative households in REMIND-R are indifferent regarding domestic and foreign goods as well as indifferent among foreign goods of different origin. This can potentially lead to a strong specialisation and, related to the cooperative approach to solution, to rather optimistic results.

2.4 Climate module

REMIND-R integrates a simple climate model (Petschel-Held et al., 1999) that was already used for the global MIND model (Edenhofer et al., 2005) - a predecessor of REMIND. For basic model equations as well as for parameter values and initial values see Kriegler and Bruckner (2004).

The climate module considers the impact of greenhouse gas emissions and sulphate aerosols on the level of global mean temperature. The emission of sulphates is directly linked to the combustion of fossil fuels in the energy sector. The radiative forcing of both the non-CO_2 greenhouse gases and the CO_2 emissions from land use change is taken into account by exogenous scenarios. The former follows the SRES B2-scenario (model AIM), the latter combines the same scenario type with the additional assumption of frozen CH_4 and N_2O emissions after 2005. The climate sensitivity - as the most important parameter of the climate module - is set to 2.8°C.

Within the REMIND-R framework, the climate module is represented as a set of equations that restrict the welfare optimisation. The climate module allows to design climate policies based on climate targets. In contrast to policy scenarios that rely on exogenous global emission constraints, this coupled framework computes the most effective way to meet a given climate target. The applied climate model yields a comparatively sensitive reaction of the global mean temperature on emissions. Moreover, the assumption of increasing radiative forcing of non-CO_2 greenhouse gases implies additional pressure on CO_2 emission reduction in the energy sector when trying to achieve ambitious temperature targets. Consequently, the resulting emission reduction path is quite likely to meet such targets also in different model settings.

Chapter 3

Reference scenario

We start the presentation of the results of the model runs with REMIND-R with a discussion of the reference development (”business-as-usual”-scenario). In this scenario, it is assumed that climate change has no economically and socially important effects. Thus, a further world-wide increase of emissions can be assumed. A large part of the economic growth is based on the use of fossil energy sources. This reference development shall serve as a benchmark for scenarios in which climate change is sustainably confronted by climate policy.

3.1 Macro-economic development

In the reference scenario, the world-wide GDP of about 47 trillion $US [1] in 2005 will increase to 412 trillion $US in 2100. A large part of the GDP growth occurs in China and ROW. From 2005 to 2050, China increases its GDP tenfold. In the same period, the GDP of UCA increases by only 150%. Figure 3.1 shows the GDP development from 2005 to 2100 as well as the growth rates of the GDP for each region. China starts with a very high growth rate of 9.3% which will however decrease to 2.2% until 2100. India and Africa have the largest growth rates of approximately 3.6% and 2.9% at the end of the century, whereas the regions UCA and EUR have a growth rate of 1.2%.

The GDP of all regions is growing faster than its population. On world-wide average, the GDP per capita will increase between 2005 and 2100 from 7200 $US to approx. 41000 $US. The development of the GDP per capita is however quite different in the individual regions (see Figure 3.2). The per capita GDP in China and India will grow more rapidly than in other regions. The relative gap between poor and rich regions is progressively

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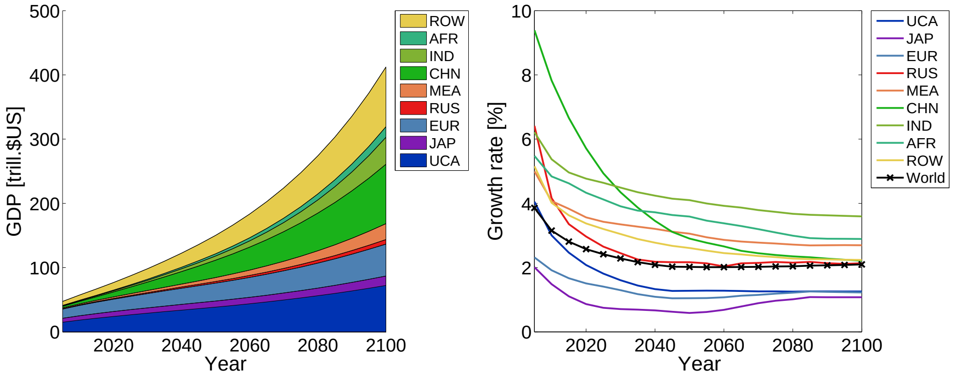
[1] Throughout this report, all relevant economic figures (e.g. GDP) are measured in constant international $US 2003 (market exchange rate).

becoming shorter, since regions with highest GDP per capita have lowest growth rates (see Figure 3.1(b)). Nevertheless, significant differences in the per capita income still exist in 2100.



(a) GDP

(b) GDP growth

Figure 3.1: Economic growth of the world regions

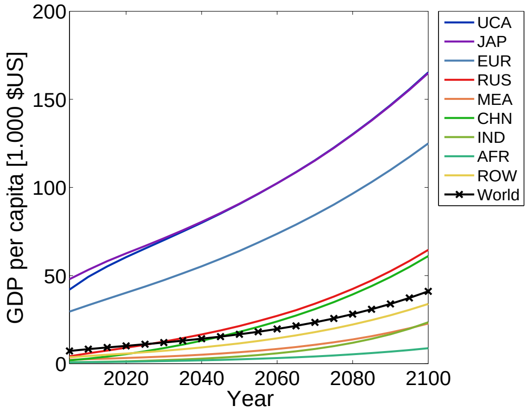
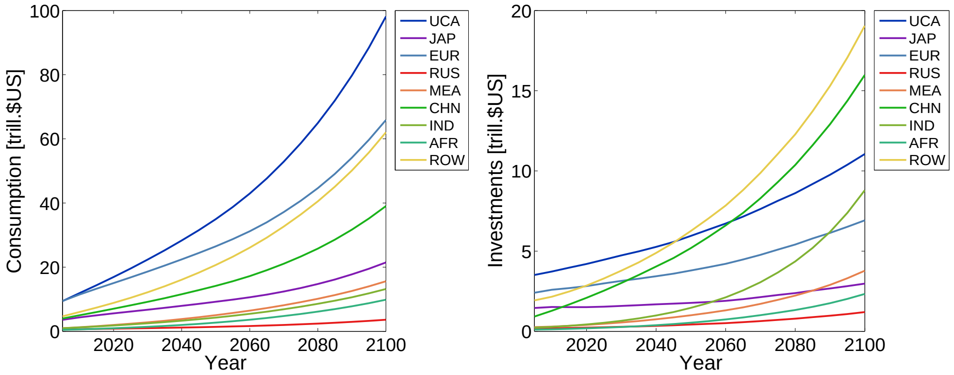


Figure 3.2: GDP per capita

Figure 3.3 shows the consumption and investment development (without investments in energy technologies) from 2005 to 2100. The most substantial increase in consumption takes place in the regions UCA, EUR, ROW and China. High growth rates in consumption can mostly be found in India and Africa. Europe and Japan slightly drop behind UCA. This is due to the initially lower growth rates in labour productivity. China's, ROW's and India's investments are growing even stronger than GDP and consumption. This is a characteristic pattern for regions which are in an economic catching-up process. UCA's investments do not increase so fast.



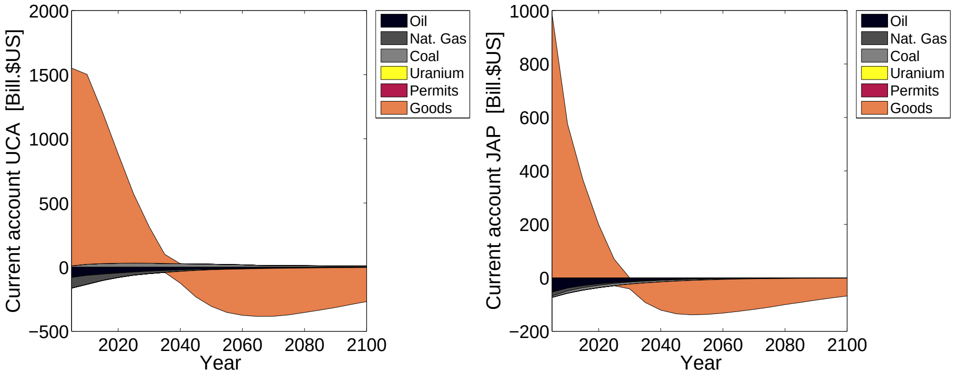
(a) Consumption

(b) Investments

Figure 3.3: Consumption and investment development

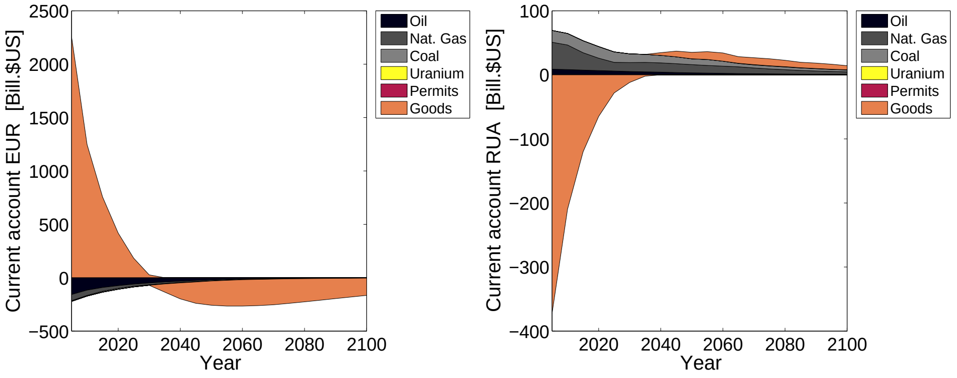
3.2 Trade

Trade (Figure 3.4 and 3.5) is presented on the basis of present values, i.e. the value of future trade amounts is subject to discounting. Despite of an increasing physical trade volume, the current account deficits/surpluses are decreasing as a rule. Net exports are shown. Negative values represent an excess of imports. The regions are characterised by different trade patterns. The trade pattern of the industrial regions UCA, Japan and EUR is mostly characterised by the dominance of goods trade. This is also true for China and India, however with a reverse sign. Whereas the industrial countries initially produce an excess of exports, the developing regions are main importers first. A large part of it might be imports of investment goods which secure a long-term growth for these regions. A third trade pattern can be observed in the regions Russia and MEA that are rich in natural resources. Here, energy trade has a large share in the entire trade. Russia exports mostly gas and MEA oil. These resource exports enable long-term imports of goods. The trade structure of Africa and ROW is similar to the trade structure of India and China, but with a higher share of resources trade in total trade. As measured by the entire trade volume, large regions like EUR, UCA and China dominate.



(a) UCA

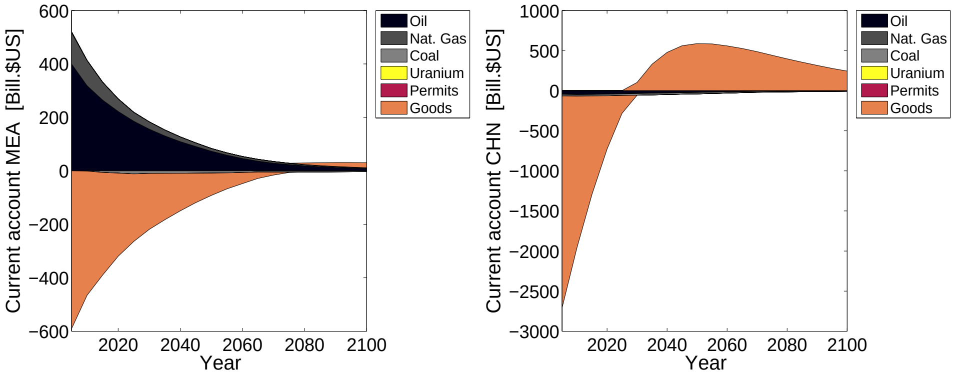
(b) Japan



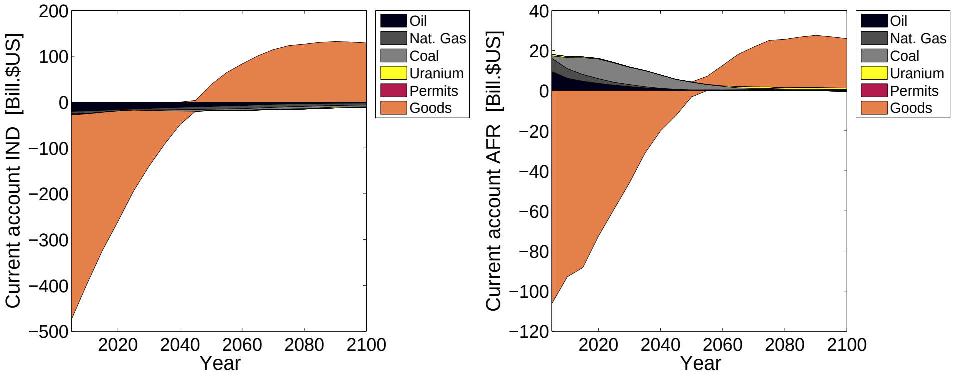
(c) Europe

(d) RUS

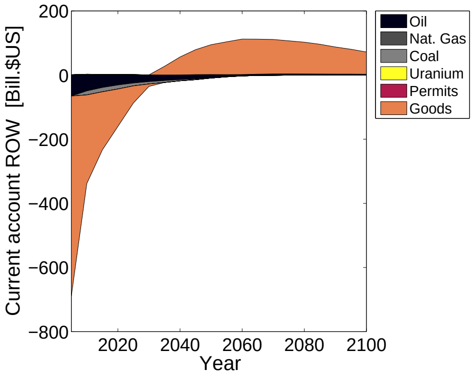
Figure 3.4: Net export in the reference scenario; part I



(a) MEA (b) CHN



(c) IND (d) AFR

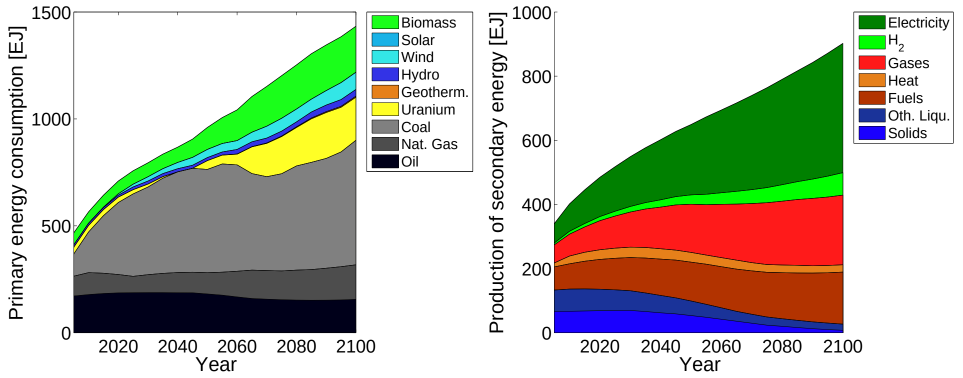


(e) ROW

Figure 3.5: Net export in the reference scenario; part II

3.3 Technology development and energy production

The development of the energy system is presented in the following. We will first present the development on the global level as the sum of results in the regions and then turn to the characteristica in the regions. Figure 3.6 shows the primary and secondary energy consumption for the 21st century, differentiated by the energy sources[2]. The primary energy consumption is increasing continuously in the next hundred years with a weakening annual increase. This is due to the population scenario, the decreasing growth of demand in the developed countries and the increasing cost of fossil energy sources. The primary energy consumption will increase from almost 470 EJ in 2005 to more than 1400 EJ in 2100.



(a) Primary energy

(b) Secondary energy

Figure 3.6: Global consumption of primary energy and production of secondary energy in the reference scenario

The primary energy mix remains mostly based on fossil energy sources. Whereas the use of oil and gas remains nearly constant, the use of coal is strongly increasing (particularly until 2030). Coal is here particularly used to produce electricity and replaces the conversion of gas and nuclear energy into electricity. The economic attractiveness of coal is due to its lower costs, the flexible trade and the assumption that the use of coal is not subject to any regulations. There, however, will be a price increase for coal around the middle of the century that makes the use of renewable energy sources competitive. Hydro energy and especially wind energy but also geothermal energy sources will increasingly be used. The use of biomass will also increase after 2030, which is due to its increasing

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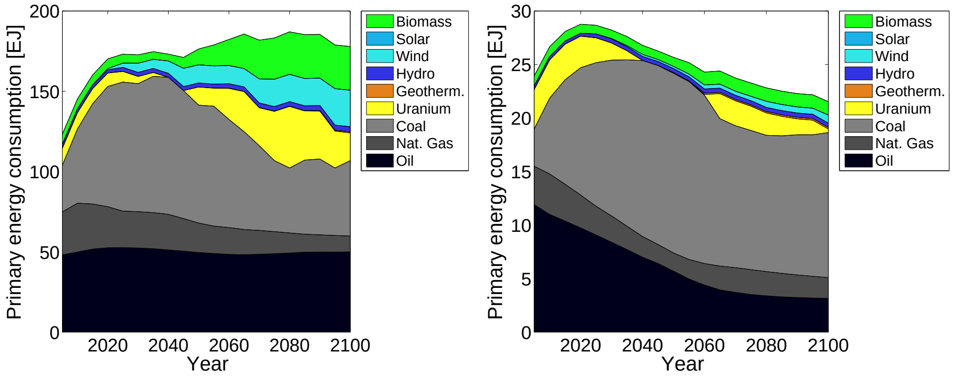
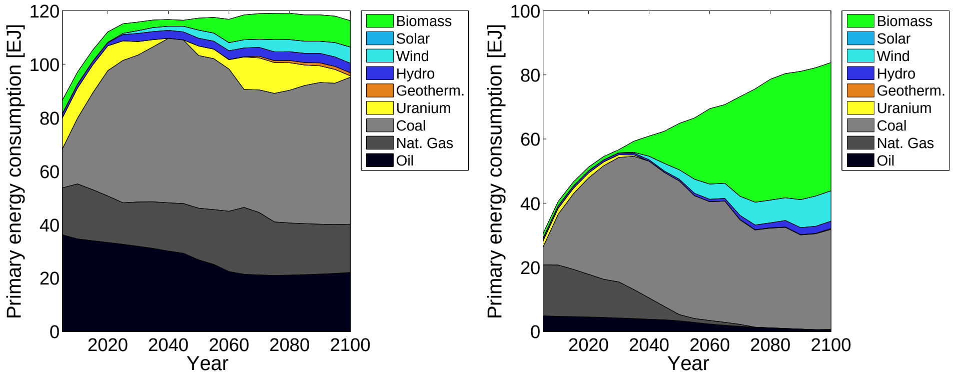
[2] The primary energy consumption of the renewable energy sources wind, solar and hydro energy is put on the same level as the related secondary energy production.

availability. Solar energy sources are not employed in the reference scenario; nuclear energy will be used as a considerable supplement for coal at the end of the century.

Figure 3.6(b) shows which secondary energy sources are produced. The secondary energy production will increase to around 900 EJ in 2100; the share of electricity will in particular increase from roughly 19% to 44%. In contrast, the use of the low-value energy sources solids and other liquids will decrease from together 42% at the beginning of the century to less than 5% at the end of the century. The use of gas will moderately increase in the mix from 18% to almost 24%, which is also true for the fuel production that will increase from 14.5% to 19%. Heat production will remain almost constant, its share will however decrease to 2.5%. Hydrogen has a share of 7.7% at the end of the century.



(a) UCA (b) Japan



(c) Europe (d) RUS

Figure 3.7: Regional primary energy consumption in the reference scenario; part I

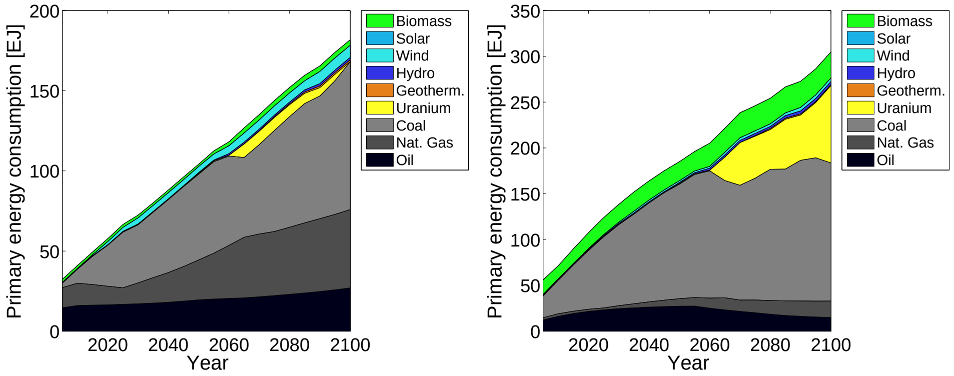
Figures 3.7 and 3.8 show the primary energy consumptions in the individual regions. A flattening trend in the developed regions (UCA, Japan and EUR) after 2020/2030 can be noticed and an even absolute decrease can be observed in Japan. The other regions show a steady growth, the absolute increase will drop in Russia and ROW and rise in India and Africa. The use of coal will increase in most of the regions in the near to mid-term, with the exception of Africa. This is also true for Russia and MEA, although there are great deposits of oil and gas. This is due to the fact that the conversion of coal into electricity is more favourable than other alternatives. The special case of Russia is quite noticeable, since biomass is used here on the large scale and is partially converted converted into gas. At the same time, Russia exports gas from geologic production without consuming it domestically. Biomass is therefore indirectly used for trading reasons, since the produced biogas itself cannot be traded. Transportation fuels can also not be traded within the framework of the model. Russia uses part of the biomass to produce fuels for domestic use.

The shares of the regions in the secondary energy production are shown in Figure 3.9. The developed regions (UCA, Japan and EUR) produce today 47.4% of the total secondary energy, while the developing regions (Africa, India, China and ROW) produce around 39%. At the end of the century, the conditions are twisted right around. The share of the developed regions will decrease to 25%, the developing regions will reach 55% then.

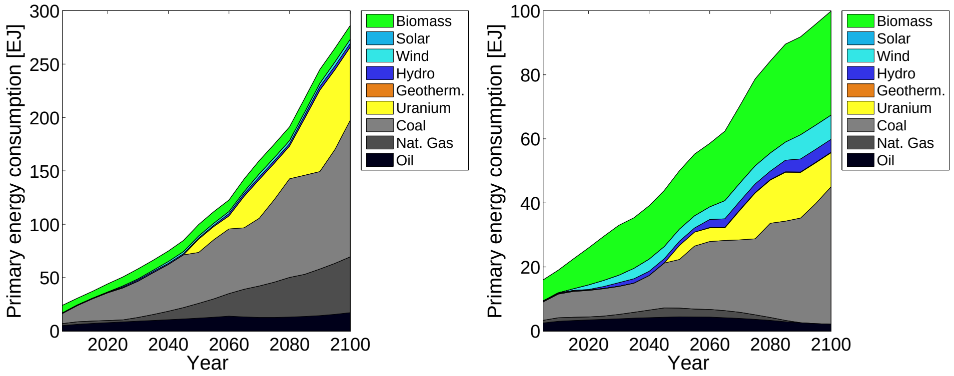
We now take a look at the development of the power generation in Figure 3.9(b), since it is one of the fastest-growing secondary energy sources. In the case of power generation, the above drawn picture is even more pronounced. At the beginning, the developed regions produce 56.5% of the total electricity, while the developing countries contribute only 31%. By the end of the century, the share of the currently already developed countries decreases to 22.5% and the share of the developing regions increases to 62%.

The question arises now which technologies can be used to convert primary energy sources into secondary energy sources. We take a closer look at the power generation mix. Power generation will increase almost linearly by approximately 3.6 EJ per year to around 400 EJ at the end of the century, it is sixfold higher compared to the base year (see Figure 3.10). The conversion of coal into electricity is the most favourable technology until 2030 (conventional power plants and those with power-heat coupling will still be built in the 21st century). It will replace all other technologies until then except for hydro energy. Apart from coal, wind and hydro energy will be used supplementary after 2030 to cover the growing need for electricity, after 2050 nuclear energy will also be used.

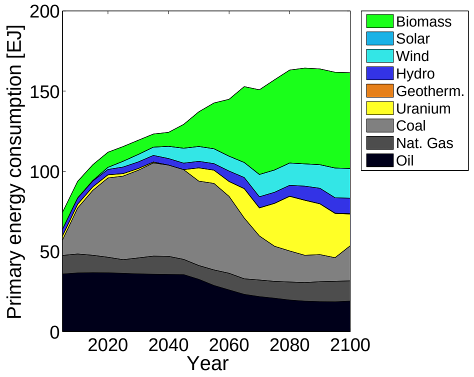
The share of coal in the electricity mix reflects how strong existing technologies will



(a) MEA (b) CHN

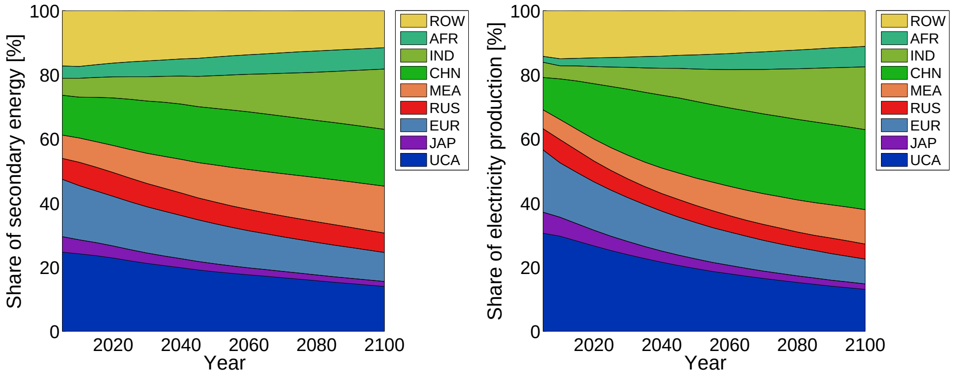


(c) IND (d) AFR



(e) ROW

Figure 3.8: Regional primary energy consumption in the reference scenario; part II



(a) Secondary energy

(b) Electricity

Figure 3.9: Regional differentiation of secondary energy production and power generation

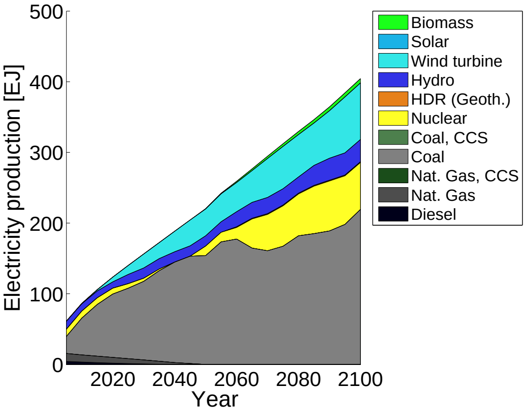
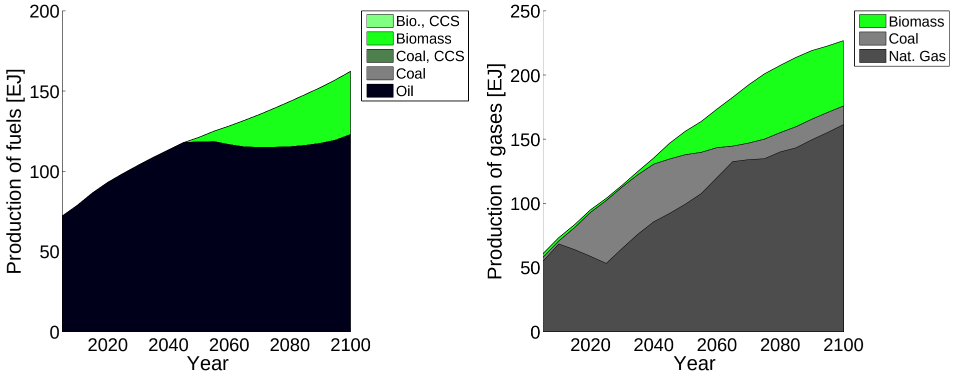


Figure 3.10: Global power generation in the reference scenario

first be replaced and how large the potential of renewable technologies is to replace coal in a climate policy scenario. The share of electricity produced with coal first also increases in all those regions which use gas (Russia and MEA) or nuclear energy (Japan and Europe) to produce electricity. In the second half of the century, the share of coal will decrease in all regions the dimension of which is however quite different. Especially Russia, Africa and UCA have great potentials in the areas hydro energy and wind energy, while these potentials are distinctly less or not at all used in China, India, Europe and Japan. The development in the production mix is due to the fact that the regions react differently on a scarcity of coal according to their potentials for renewable energy sources and/or nuclear technologies.

The secondary energy sources fuels and gases shall be examined in more detail next.

As mentioned in Table 2.2, both can be produced with biomass so that renewable source of energy is available for both energy sources. Figure 3.11 shows the respective production mixes. The use of oil is dominating in the production of fuels. The share of biomass will be growing as of 2050. While the production of oil remains static at roughly 115 EJ per year, biomass reaches a share of approximately 24% (40 EJ) in 2100. The share of biomass also increases in gas production (approx. 50 EJ in 2100). As of 2015, coal will also be converted into gas. A look at the regional distribution shows that mainly Russia, Africa, UCA and ROW convert biomass into gas and all regions, except UCA, JAP and MEA, convert biomass into fuels.

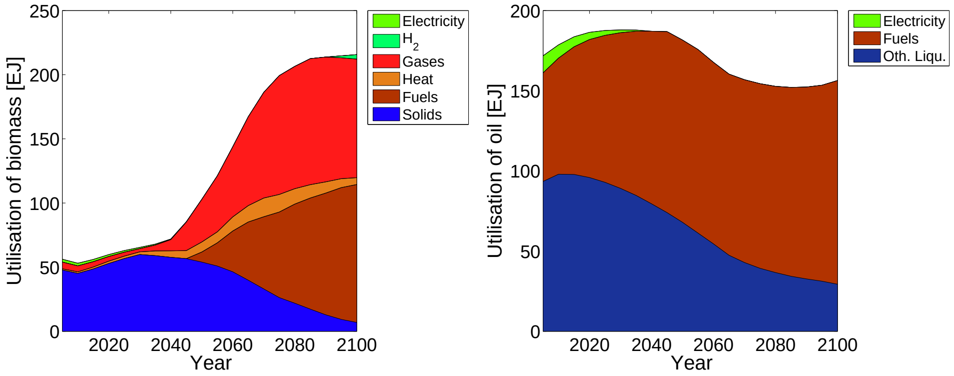


(a) Transportation fuels

(b) Gases

Figure 3.11: Generation mix for transportation fuels and gases in the reference scenario

Why do we use biomass? Biomass is today mostly used in developing countries in the form of solids. Figure 3.12 shows that this manner of use gains importance until 2030 but will almost completely run out by the end of the century. The rise at the beginning of the century mostly originates from developing regions. New scopes for the conversion into higher-value energy sources are given by discontinuing the use of solids – especially by switching to fuels and gases. The conversion into electricity, however, does not play a role. It should be noted that even in the reference scenario, the potential of biomass use will almost completely be exploited by the end of the century. A similar development can be noticed for the use of oil. The conversion of oil into fuels increases although the total consumption is almost stagnant. This increase is possible, since oil is less converted into other energy sources and does not play a role for the conversion into electricity anymore. The change of the refinery structure is at the same time economically justified, since the use of oil for transportation purposes is more profitable and the other liquids can simply be substituted.



(a) Biomass

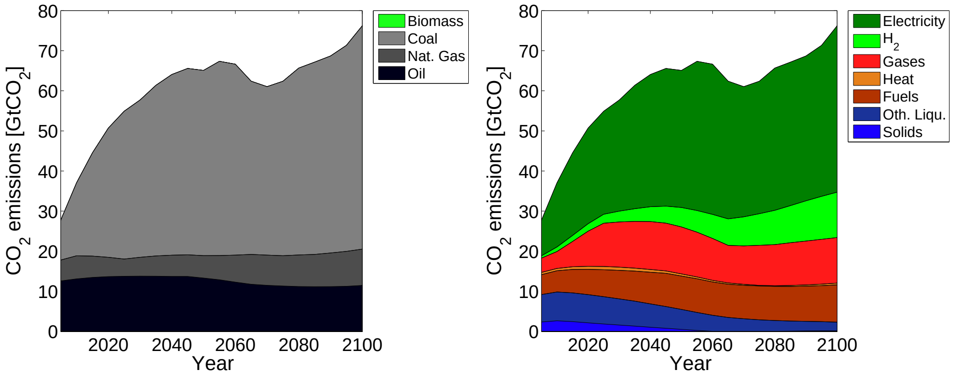
(b) Oil

Figure 3.12: Use of biomass and oil in the reference scenario

The results of the reference scenario comply with the thesis that societies with an increasing economic state of development and a continued scarcity of resources increase the production of higher-value energy sources and change to more capital-intensive production methods, especially in power production. The model shows a number of flexibilities in the conversion of energy so that it is possible to encounter upcoming scarcities by a cost-effective and adjusted technology and investment choice.

3.4 Emissions

From the analysis so far it inevitably results that there will be an increase of emissions. This is mostly due to the conversion of coal into electricity. Figure 3.13 shows the CO_2 emissions differentiated according to the use of primary energy sources and the production of secondary energy sources. The temporary lower increase after 2050 mainly results from the increased use of wind, hydro energy and nuclear energy for power generation and biomass for the production of fuels and gases. The noticeably high share of emissions from the production of hydrogen results from the use of coal as basic resource.



(a) primary energy sources (b) secondary energy sources

Figure 3.13: CO_2 emissions in the reference scenario differentiated by the use of primary energy sources and secondary energy production

The world-wide emissions amount to approximately 76 Gt CO_2 (21 GtC) in 2100 (see Figure 3.14). The increase of emissions is quite high in the early decades - with a doubling of the emissions between 2005 and 2025. The temporary decrease of the emissions around 2060 is followed by another increase.

There still remain large differences in the per capita emissions (Figure 3.15). While the industrial countries increase their per capita emissions until 2025 and keep them on a high level (18-32 tCO_2 per year) thereafter, they rise to approx. 7-11 tCO_2 in China, India and MEA. The per capita emissions rise to more than 35 tCO_2 until the middle of the century in Russia and stay above 25 tCO_2 until the end of the century. Africa remains on a consistently low level with less than 3 tCO_2 per capita.

Figure 3.16 illustrates the emission development in the four largest regions EUR, UCA, China and India. While the emissions reach their maximum around 2040 in EUR and UCA, emissions are continuously increasing in India and China. The increase will

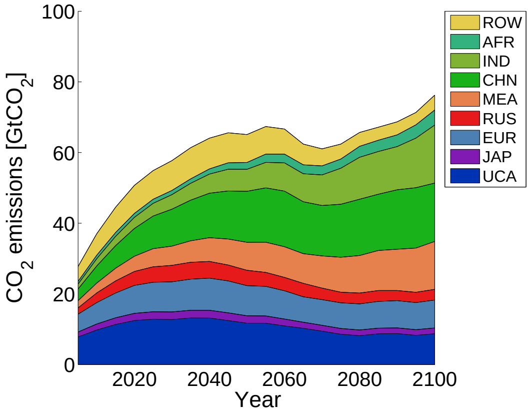


Figure 3.14: World-wide emissions in the reference scenario

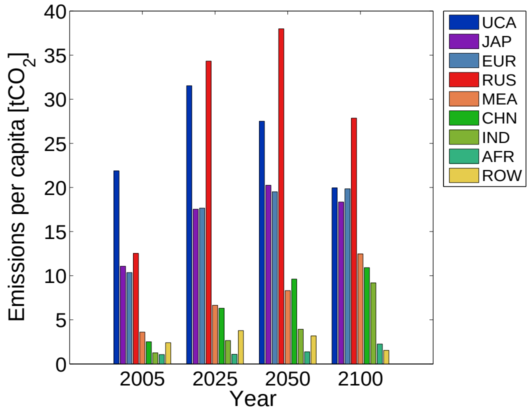
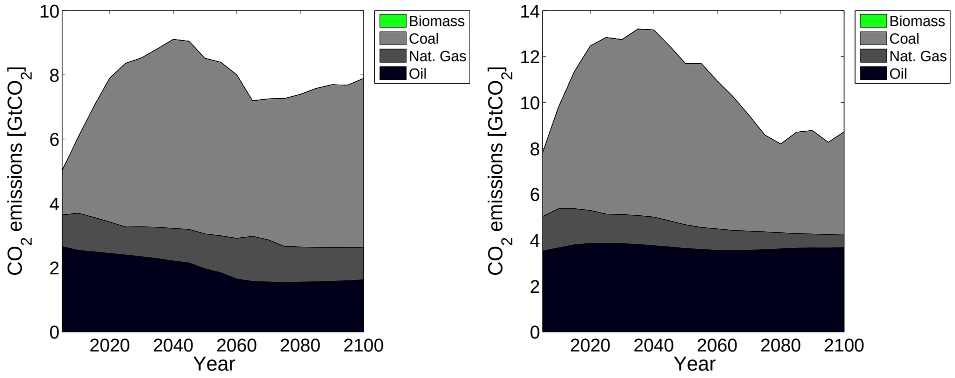


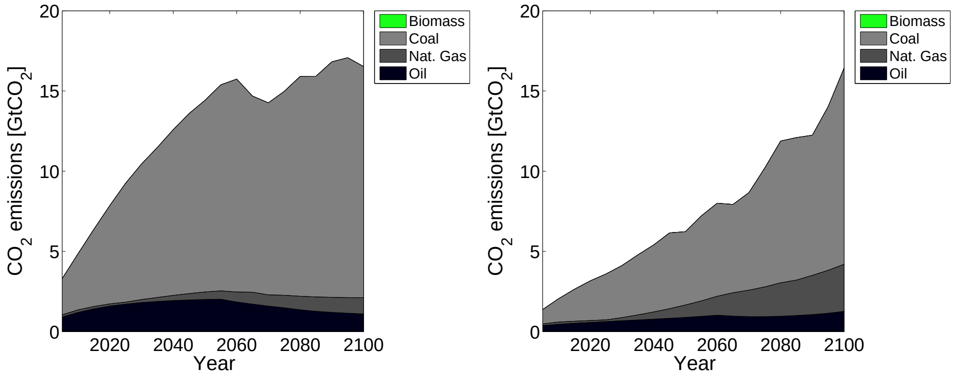
Figure 3.15: Regional per capita emissions in the reference scenario

be interrupted in China in the second half of the century when oil consumption declines. Coal is the main energy source in all regions which causes an increase of the emissions. But also the distinct reduction of the emissions around 2060 is linked to the use of coal (especially to the sharp decline in UCA). The interim reduction of the use of coal is accompanied with a temporary increase in the use of nuclear energy (cf. Figure 3.6(a)). In 2100 again, approx. 75% of the emissions in the energy sector originate from the combustion of coal (cf. Figure 3.13(a)). A share of approx. 15% and 10% is allocated to oil and gas, respectively.

While coal is used in all regions, mainly in China, UCA, MEA and EUR, considerable amounts of CO_2 are also released by using oil and gas resources (see Figure 3.17), the latter to an increasing degree in MEA and India. Primarily in Europe, the share of emissions from the use of imported resources is quite high.

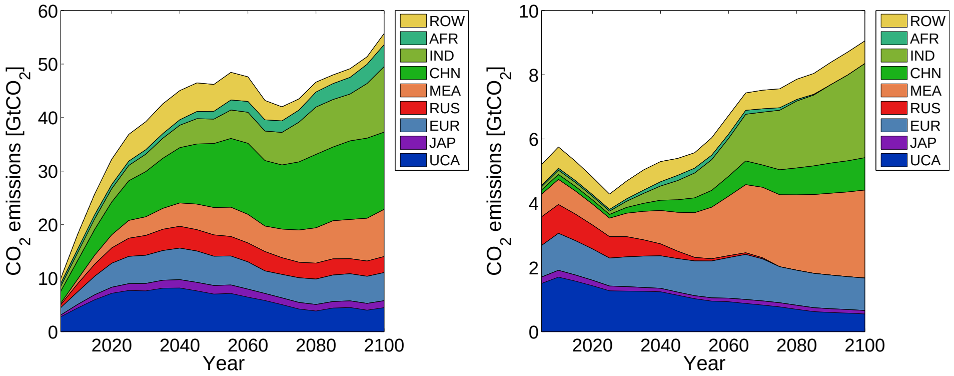


(a) Europe (b) UCA

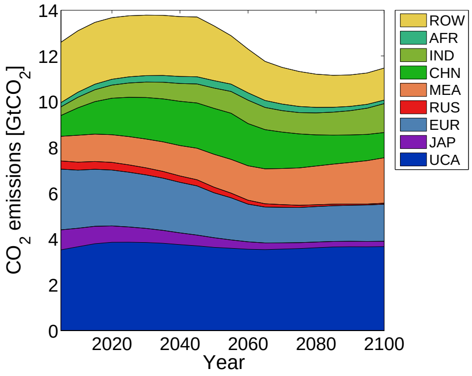


(c) China (d) India

Figure 3.16: Regional CO_2 emissions differentiated by primary energy sources



(a) Coal (b) Gas



(c) Oil

Figure 3.17: CO$_2$ emissions from fossil combustion of natural resources differentiated by regions

3.5 Comparison to WEO and SRES scenarios

We compare central figures of the reference scenario with corresponding numbers of the World Energy Outlook (WEO) and the IPCC SRES scenarios (IPCC, 2000), both on a global level. Projections of the International Energy Agency (IEA) in the WEO apply to the short term (until 2030), while we use the SRES scenarios to compare the long-term development.

With respect to the GDP development, our reference scenario assumes a growth rate until 2030 of around 3.5% per year until 2015 and 2.6% between 2015 and 2030, while the WEO is more optimistic by assuming 4.2% and 3.3%, respectively. Nevertheless, the reference scenario is not at all a low growth scenario. With respect to the GDP per capita figures, it is quite in the middle of the SRES scenarios (see Figure 3.18). Population numbers are nearly the same between the reference scenario and the WEO projections. In 2030, there is a difference of only 2.5% in the absolute numbers.

With respect to the short-term development of energy consumption, Table 3.1 summarizes WEO projections and results of the REMIND-R reference scenario. Total primary energy consumption grows faster within REMIND. The WEO projects a primary energy consumption of around 601 EJ for 2015 and 742 EJ in 2030, while in REMIND the respective figures are 645 EJ and 814 EJ. Nevertheless, the total figures are in a reasonable range (deviation of less than 10%). The difference is significantly higher with single energy carriers. This applies in particular to natural gas, coal and uranium. REMIND simulates an increase of coal use from 2005 until 2030 of almost 300%, whereas the WEO projects an increase of less than 80%. This reflects to a certain degree the property of REMIND as an optimization model which under the absence of climate policy impacts and institutional barriers favours the use of the cheapest energy carrier - which is coal. The surplus in coal consumption outweighs the minus in the use of gas and uranium. Consequently, REMIND yields also a larger production of electricity.

Under the long-term perspective, we compare GDP per capita, primary and secondary energy production and emissions of the reference case with the four SRES scenarios generated with MiniCAM.

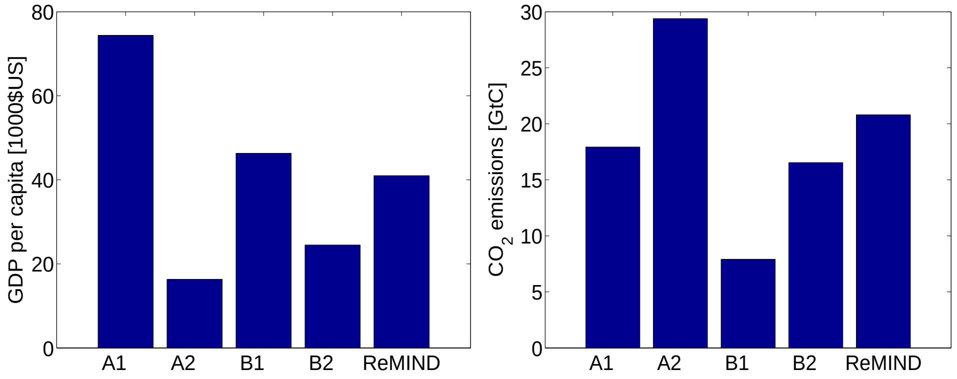
The reference scenario is for all four indicators always between the lowest and the highest value found in the SRES scenarios. We did, however, not aim at reproducing one of the SRES scenarios in particular. The GDP per capita reaches 41000 $US per capita in 2100 and is therefore close to the B1 scenario. The emissions reach 76 Gt CO_2 (20.8 GtC) which is similar to the A1 scenario. Energy production – primary and secondary – is most similar to the B2 scenario. The higher difference between primary and secondary

Table 3.1: Energy consumption in EJ (WEO projections and REMIND reference scenario)

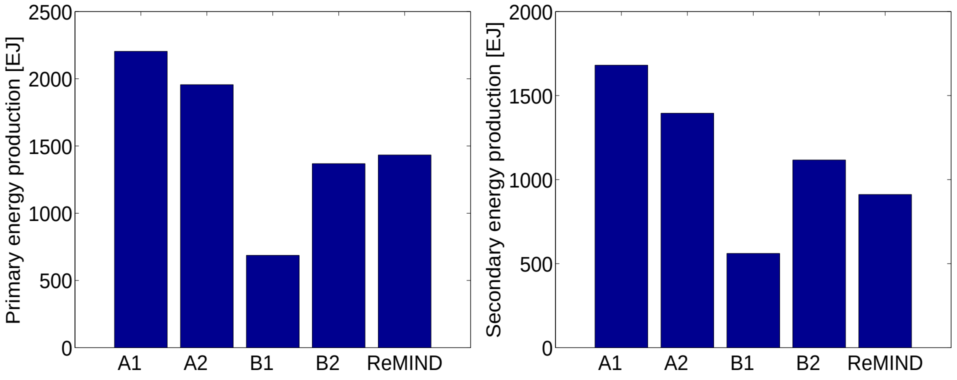
BAU	REMIND							
	Oil	Gas	Coal	Uran.	Hydro	Biomass	total	Electr.
2005	172	93	104	31	11	56	468	61
2015	184	95	269	28	10	56	645	105
2030	188	84	410	13	14	65	815	155

BAU	WEO							
	Oil	Gas	Coal	Uran.	Hydro	Bio+Waste	total	Electr.
2005	167	99	121	30	11	48	478	66
2015	198	127	167	34	14	56	601	92
2030	234	165	209	36	17	68	742	127

energy production is related to the higher conversion losses in REMIND.



(a) GDP per capita (b) Emissions



(c) Primary energy (d) Secondary energy

Figure 3.18: Comparison of basic indicators with IPCC-SRES scenarios generated with MiniCAM

Chapter 4

Model analysis of climate policy regimes

4.1 Description of the policy regimes

The target of international climate policy formulated in the Framework Convention on Climate Change is to stabilise greenhouse gas concentrations on a level which avoids dangerous climate change. Numerous model studies interpret such a stabilisation level as a doubling of the pre-industrial CO_2 level - approx. 550 ppm. Climate impact studies (e.g. Hare and Meinshausen, 2004) show that the risks for irreversible climate damages is quite high when increasing the global mean temperature by more than 2°C compared to the pre-industrial level. Following the precautionary principle, the EU Council of Ministers decided to avoid a warming by more than 2°C. This climate target, however, is incompatible with a stabilisation level of 550 ppm. Concentrations below 450 ppm have to be reached.

The following analyses are based on the 2°C target. Within each policy scenario, a global emission path has to be determined which meets the 2°C target. However, within REMIND-R, the energy-related CO_2 emissions are under the control of the decision-maker only. Exogenous scenarios are applied for the development of other anthropogenic greenhouse gas emissions (e.g. CO_2 emissions from land use change). In the current model setting (cf. section 2.4), drastic emission reductions have to be provided by the energy sector. Global energy-related CO_2 emissions need to be reduced by 50% until 2035. The atmospheric CO_2 concentration reaches its maximum at around 415 ppm in 2030.

In the analysis of how and at which costs such a reduction path can be achieved, we investigate three different designs of an international cap & trade system. In such a system, emission rights according to their reduction obligations will be allocated to the individual regions and can be traded as of 2010. The endogenously determined global emission reduction path represents the world-wide available amount of emission rights. The regional allocation follows the suggestions for a post-Kyoto climate regime below (cf. Höhne et al., 2003):

- Contraction & Convergence
- Intensity target
- Multi-stage approach

Contraction and convergence (policy scenario A)

As of 2050, the same per capita emission rights are allocated in this scenario. By determining these allocations between 2010 and 2050, there is a smooth transition of the regional shares between grandfathering and same per capita emissions. 2000 is assumed to become the reference year for grandfathering.

Intensity target (policy scenario B)

In this policy scenario, the shares of the regions on the globally available emission rights correspond to their shares in the world-wide gross product, i.e. each region receives the same emission rights per unit gross domestic product (GDP). In this policy scenario, the industrial countries are apparently provided with more emission rights than in the other two policy scenarios.

Multi-stage approach (policy scenarios C and D)

We selected a form of multi-stage approach in which the quantitative reduction obligations of the individual regions depend upon their per capita incomes. The following four stages can be distinguished:

1^{st} stage:	up to 2,000 $US per capita and year
2^{nd} stage:	up to 4,000 $US per capita and year
3^{rd} stage:	up to 8,000 $US per capita and year
4^{th} stage:	more than 8,000 $US per capita and year

Regions of the first stage are practically not obliged to any reductions. They can, however, participate in the emission trade and will be provided with certificates to the amount of their reference emissions (which are calculated in the reference scenario). Regions of the second stage will be provided with emission rights to the amount of 0.55 Gt CO_2 (0.15 GtC) per 1 trillion $US gross national product (GDP). Since a growth of the GDP can be expected as a rule, this stage comprehends an increase of emission rights for the respective regions. Regions of the third stage are obliged to stabilise their emissions, i.e.

the certificate amount last allocated in stage 2 is frozen on its level. Regions of the fourth stage have to significantly contribute to the emissions reduction. The share of global emission rights for these regions arises from deducting from total the number of certificates used for the regions of stage 1 to 3. The internal allocation between the regions of stage 4 follows again the above-described contraction and convergence approach.

In the base year, the industrial countries UCA, EUR and Japan are in stage 4. They are presumably quite promptly followed by Russia and China, while China is initially only in stage 2. MEA is initially also in stage 2, ROW is in stage 3, and India and Africa are in stage 1.

As an additional variant of the multi-stage approach, we formulated scenario D in which only those regions participate in the emission trade which are either in stage 2, stage 3 or in stage 4. Nevertheless, the regions in stage 1 keep the cap that corresponds with the above distribution key. In the presentation of the model results in the following Chapter, policy scenario A will be especially analysed in full detail. In the analysis of the other policy scenarios, we renounce in many cases to repeatedly present similar development patterns.

4.2 Model results

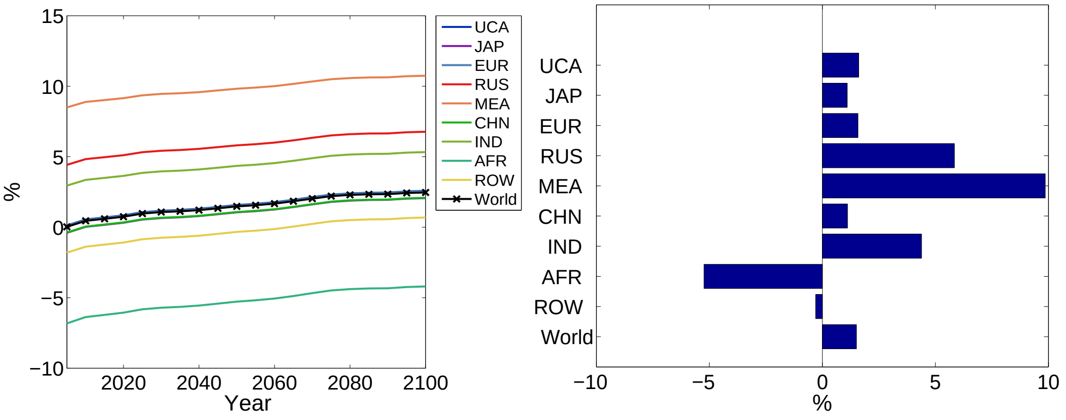
4.2.1 Policy scenario A: Contraction & Convergence

Macro-economic development and mitigation costs

Each scenario that tries to avoid an average global warming by more than 2°C by means of CO_2 emission reductions implies economic consequences for all regions. The mitigation costs are confronted with negative costs (i.e. benefits) incurred by avoiding climate damages. The latter are however not considered here, since the main target is the comparison of policy scenarios that follow the same climate stabilisation target. Similar damage costs and/or avoided damage costs between all policy scenarios can thus be assumed.

Depending on how the cap & trade system is implemented, the mitigation costs of each region can be quite different. As a measurement for the losses that a policy scenario implies for a region, we examine the consumption difference between reference and policy scenario. Figure 4.1(a) shows the change in consumption in percent from 2005 to 2100 for each region. Figure 4.1(b) shows the regional values averaged over the entire time horizon. Positive values mean less consumption and thus less welfare in the policy scenario. In policy scenario A, the average global mitigation costs are at 1.5%, at maximum approx. 2.5% with higher mitigation costs arising in the second half of the century.

The regional costs are widespread around these global values. MEA needs to deal with the highest costs - nearly 10% on average. Russia and India are also above the world-wide average. At the same time, some regions like Africa and ROW benefit in policy scenario A. Africa benefits most with an average gain of almost 5.2%.



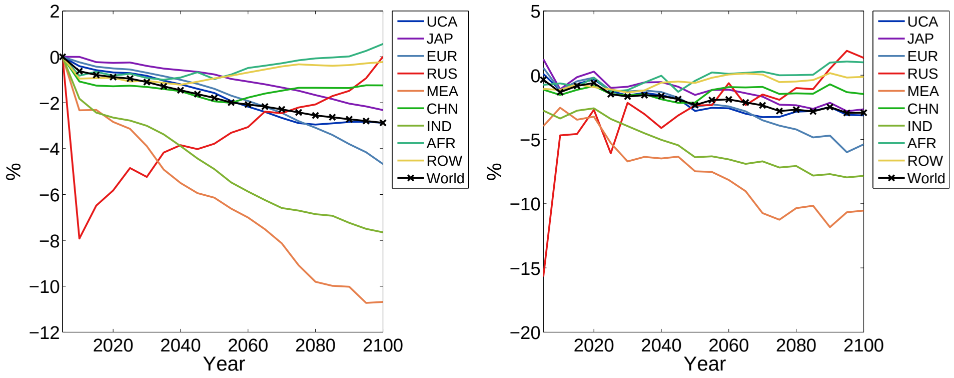
(a) Consumption losses

(b) Average consumption losses

Figure 4.1: Mitigation costs in policy scenario A

The considerable losses of MEA and Russia are mainly due to the worsened terms-of-trade (see next section). India is, over the whole century, the fastest-growing region in terms of energy consumption. In the reference scenario, most of this is delivered by fossil fuels. The long transition period towards an equal per capita allocation of permits does not favour India. Selling permits, in order to afford the import of capital in the initial periods, demands for changing the low-cost energy production based on fossil fuels from the reference scenario. India faces higher costs than China because it is provided effectively with less permits. Moreover, as of 2050, when emission rights are equally allocated per capita, the absolute volume of allocated permits is reduced drastically. On the winner side, Africa gains from emissions trading. As Africa's growth is delayed, it can sell permits without drastic restrictions for the energy production.

Figure 4.2(a) shows the GDP difference to the reference scenario for each region. The world-wide average will decrease to approx. -2.8% until 2100, while the average over time is around -1.5%. The regions MEA and India decrease their GDP stronger than the world average, while the values for Japan, Africa and ROW are distinctly above the global value. In 2020, GDP losses amount to 0.7% and 0.5% in UCA and EUR, 5.8% and 2.8% in Russia and MEA, and to 1.3% and 2.6% in China and India. Russia changes its behaviour during the century: until 2070 it decreases its GDP more and afterwards less than the world-wide average. Figure 4.2(b) shows the difference to the reference scenario regarding investments into the overall economy (without energy system investments). Again, the regions India and MEA show the largest differences, they invest notably less in the policy scenario than in the reference scenario. The other regions change their investment intensity considerably less. Russia shows less investments until 2050 and afterwards more investments in the policy scenario compared to the reference scenario. The pattern from the GDP differences is reproduced. While in the second half of the century, above all, Africa and ROW increases their GDP and/or their investments as against the reference scenario, no region gains in all periods. The GDP growth rates differ only marginally from the respective growth rates in the reference scenario (cf. Figure 3.1).



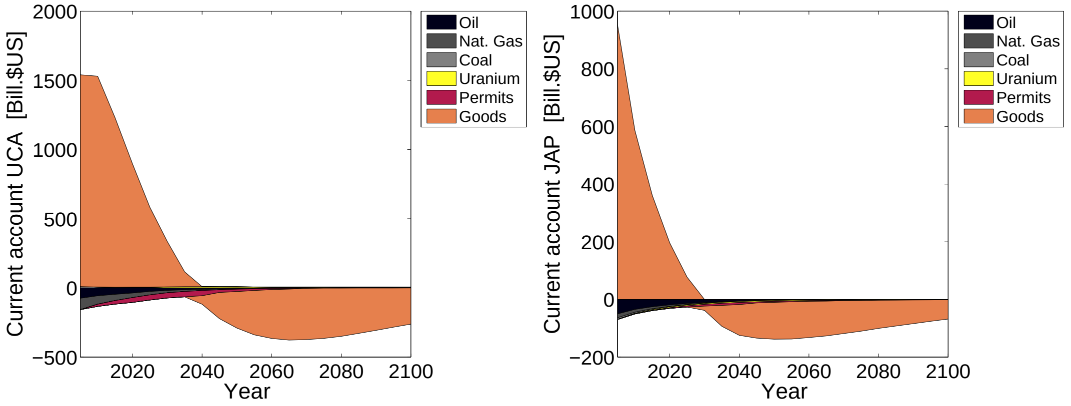
(a) GDP differences

(b) Investment difference

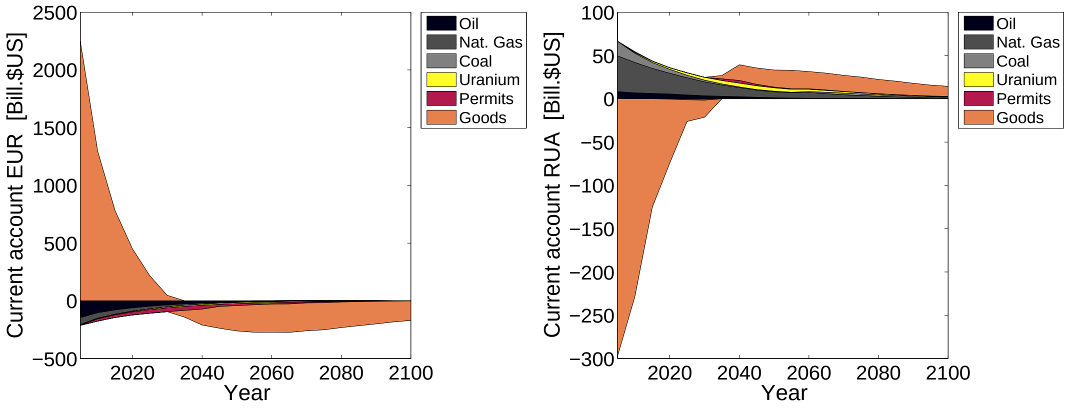
Figure 4.2: Macro-economic development in policy scenario A compared to the reference scenario

Trade

The overall trade structure also changes only marginally compared to the reference development (cf. Figure 4.3-4.4 with Figure 3.4-3.5) in most regions. However, even with a robust trade pattern, changes in the terms of trade are likely to impact mitigation costs. In the resource-exporting regions MEA and Russia, the gains from trade lower due to decreasing resource prices. The oil price, for example, is reduced to almost 50% in the long run (see Figure 4.5) compared to the reference scenario. The decrease is somewhat less for gas and somewhat more for coal. Even with only a small reduction of the trade volume, this price difference has to be compensated by less imports of goods. This limits consumption and increases mitigation costs.



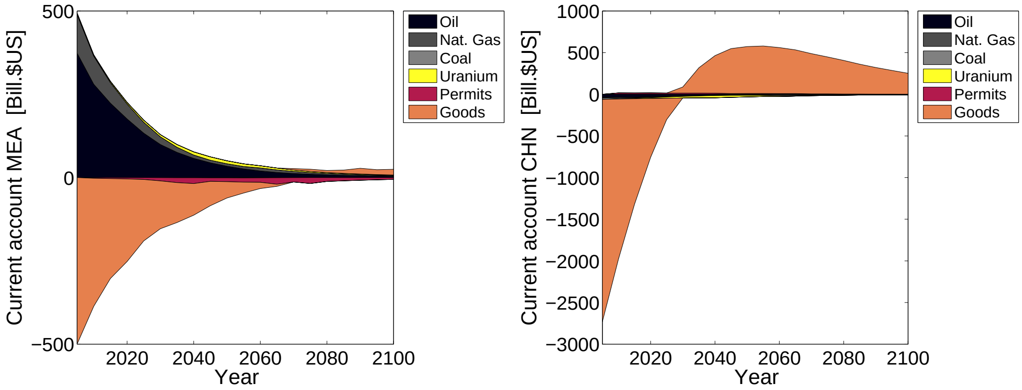
(a) UCA (b) Japan



(c) Europe (d) RUS

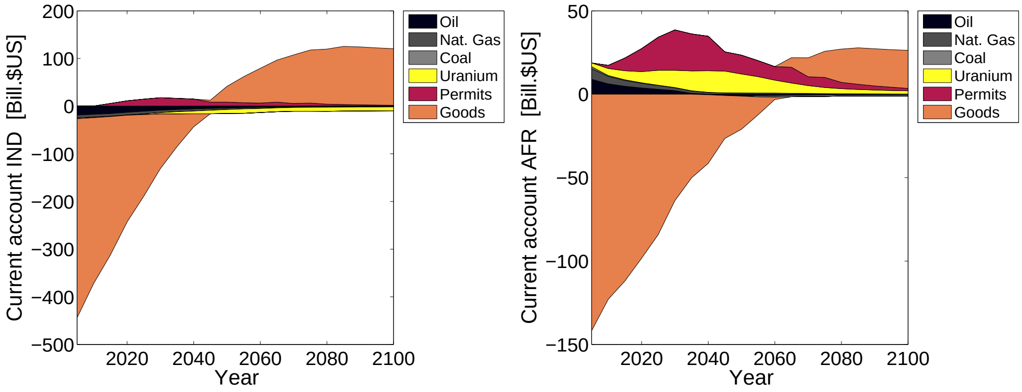
Figure 4.3: Net export in policy scenario A; part I

Another source of significant changes is the activation of emission trade. The industrial countries use the options of emission trade and buy permits in considerable amounts, this import however is on a value basis hardly visible in the trade balance. The basis for the current accounts, shown in Figure 4.3-4.4, is the present value price of permits which is in a range between 10 \$US/tCO_2 and 25 \$US/tCO_2. The nominal values, however, rise quite impressively to a level of around 150 \$US/tCO_2 (i.e. more than 500 \$US/tC) in 2050 - see Figure 4.6 - and even more than 1500 \$US/tCO_2 in 2100. This indicates a very restrictive carbon constraint. The macro-economic effect of emissions trading is slightly higher for the big sellers of emission rights - ROW and above all Africa. In return to the sale of permits, the import of goods is expanded in these regions. In addition, Africa produces significant export revenues from the trade of uranium. In contrast to the



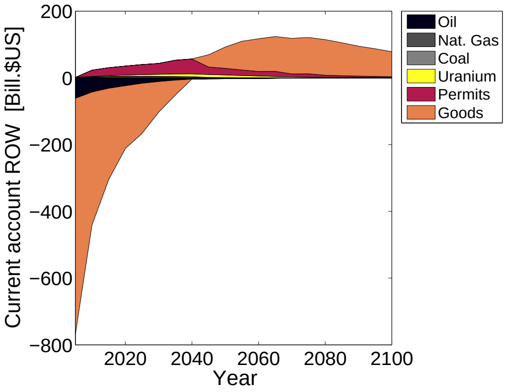
(a) MEA

(b) CHN



(c) IND

(d) AFR



(e) ROW

Figure 4.4: Net export in policy scenario A; part II

prices of fossil fuels, the price of uranium increases in the policy scenario compared to the reference scenario (by more than 200% even in the short run).

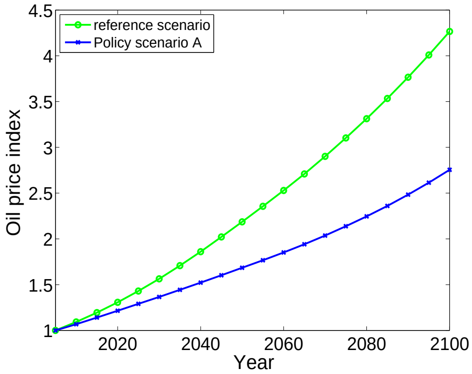


Figure 4.5: Oil price index in the reference and policy scenario A (2005=1)

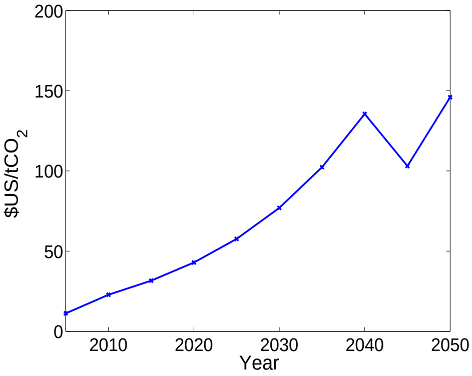
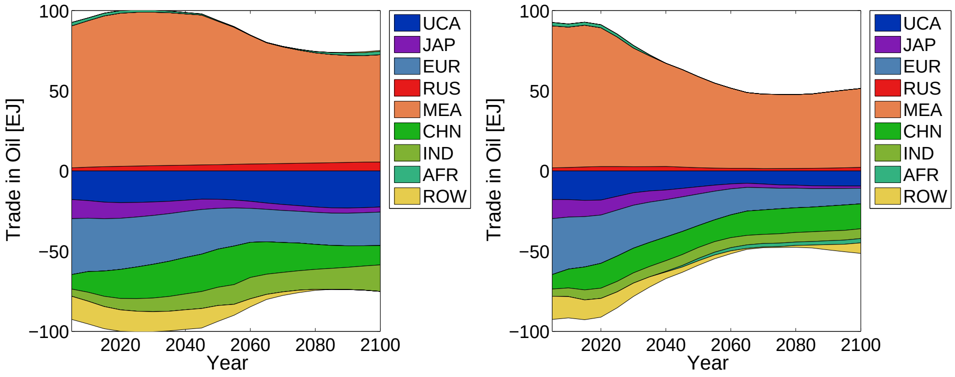


Figure 4.6: Permit price index in policy scenario A

In Figure 4.7-4.10, the resource trade (in physical units) of the policy scenario is compared with that of the reference scenario. The trade with oil decreases. Likewise, the trade of coal will first be reduced. As of 2050, CCS technology will however be applied, which will stimulate the use and the international trade of coal. The trade in coal increases monotonically between 2050 an 2100. Due to the better CO_2 balance, compared to the other fossil energy sources, the downturn in the trade of gas is significantly smaller than the trade of coal and oil. There will even be an increase in the middle of the century.

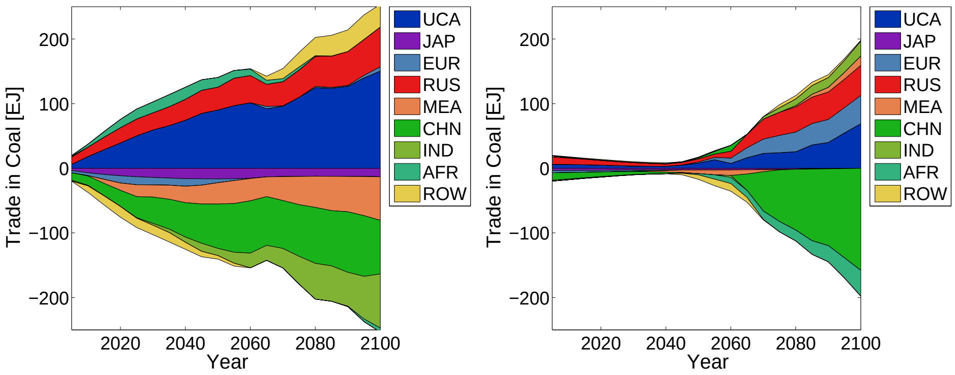
For the trade of resources, shifts in the regional shares can mainly be found in the coal and gas market. MEA's and India's shares in coal import increase in the reference scenario, but disappear in the policy scenario. China expands its import share and EUR



(a) Reference scenario

(b) Policy scenario A

Figure 4.7: Trade of oil differentiated by regions



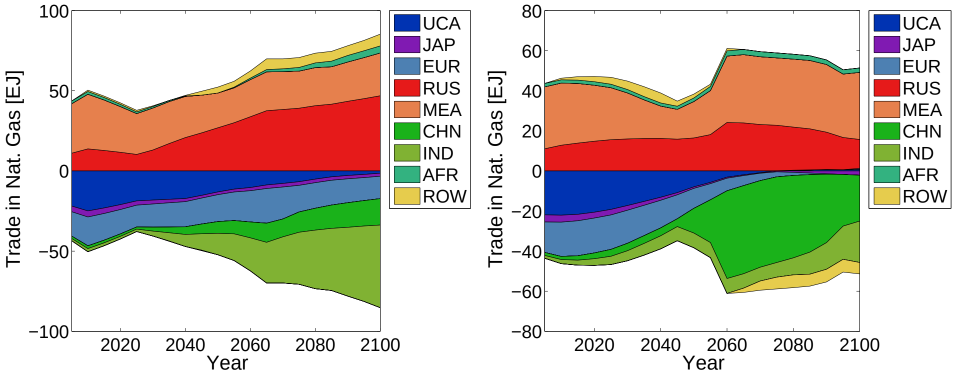
(a) Reference scenario

(b) Policy scenario A

Figure 4.8: Trade of coal differentiated by regions

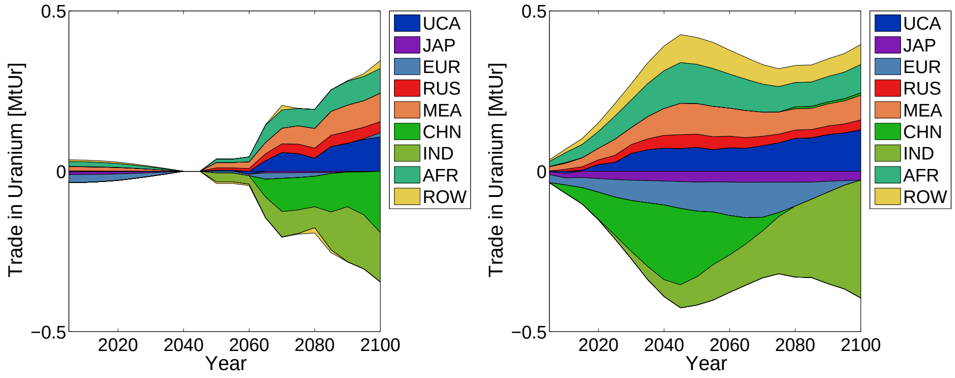
becomes an additional exporter of coal (to the account of UCA's export shares). In the gas market, Russia loses export shares in the policy scenario compared to the reference scenario. While India is the major importer of gas in the reference scenario, it does not play this role in the policy scenario and also Europe's shares in gas import decrease. In return, the imports of China are dominating. The oil market is characterized by the dominance of MEA as exporter and UCA, EUR and China as importers. The trade of uranium is intensified within the policy scenario, in particular in the short run and mid run. China represents the major importer in this period, but also EUR and India increase their import volumes. The export share of Africa is relatively high.

The trade of emissions as presented in Figure 4.11 divides the big sellers (ROW, India, China and Africa) and the big buyers (EUR, UCA and MEA). Initially, permit trading



(a) Reference scenario (b) Policy scenario A

Figure 4.9: Trade of gas differentiated by regions



(a) Reference scenario (b) Policy scenario A

Figure 4.10: Trade of uranium differentiated by regions

is concentrated on China, ROW, EUR and UCA. The entire trade volume increases to more than 5 Gt CO_2 until 2040 and decreases then to approx. 0.5 Gt CO_2 until 2100. Figure 4.12 shows which part emission trade is playing in the individual regions. As of 2030, the developing regions will sell more than 50% of the emissions rights allocated to them. This share will in fact rise up to 100% in Africa, later also in India and Russia. The industrialised countries will increasingly cover their emissions by buying additional emission rights. Already in 2030, in all industrialised countries more than half of the emissions will be covered by buying additional permits (in UCA even more than 75%). In the second half of the century, this share will even further increase, the world-wide available amount of emission rights, however, will decrease to a level of less than 2 Gt CO_2 and thus the entire trade volume will also decrease.

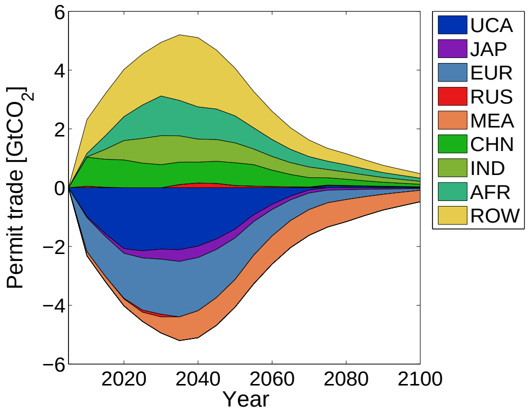


Figure 4.11: Emission trade in policy scenario A

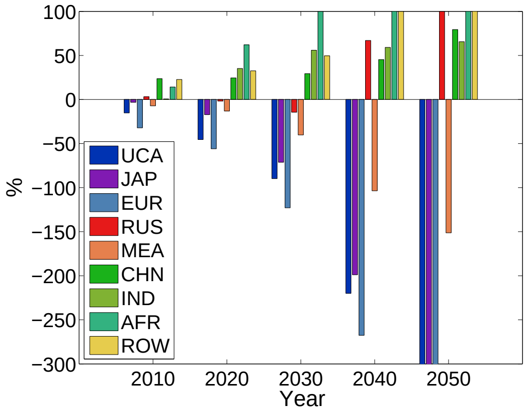


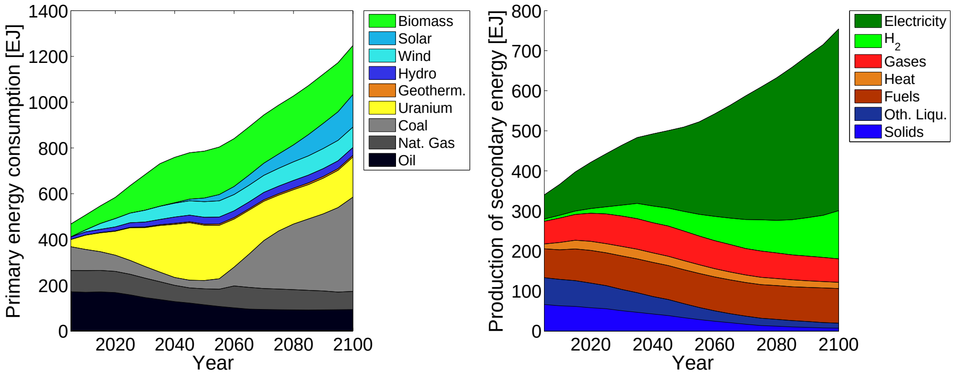
Figure 4.12: Ratio between traded and allocated emission rights

Technology development and energy production

Drastic changes in the energy system are induced by climate policy. This can be seen in many different ways in all areas. The fundamental changes can be summarised in five options for action:

1. Reduction of the entire energy consumption.
2. Immediate expansion of renewable energy technologies for the production of high-value energy carriers; expansion of nuclear energy.
3. Application of CO_2 capturing and sequestration (CCS) for the conversion of gas and coal into electricity as well as biomass into hydrogen.
4. Reducing the production of fuels and gases, since technical avoidance options are less efficient here.
5. Reducing the production of low-value energy sources solids and other liquids so that more oil and biomass is available for the production of higher-value energy sources.

In order to concretise these rough options for action, the energy system will be investigated more precisely in the following. The results are mainly discussed in comparison with the developments in the reference scenario. We start again with the global consumption of primary and secondary energy sources (see Figure 4.13 and cf. Figure 3.6).



(a) Primary energy

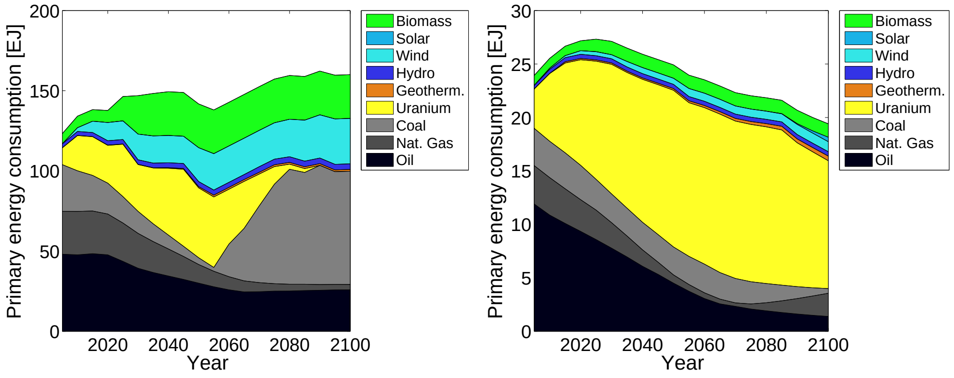
(b) Secondary energy

Figure 4.13: Global consumption of primary energy and production of secondary energy in the policy scenario A

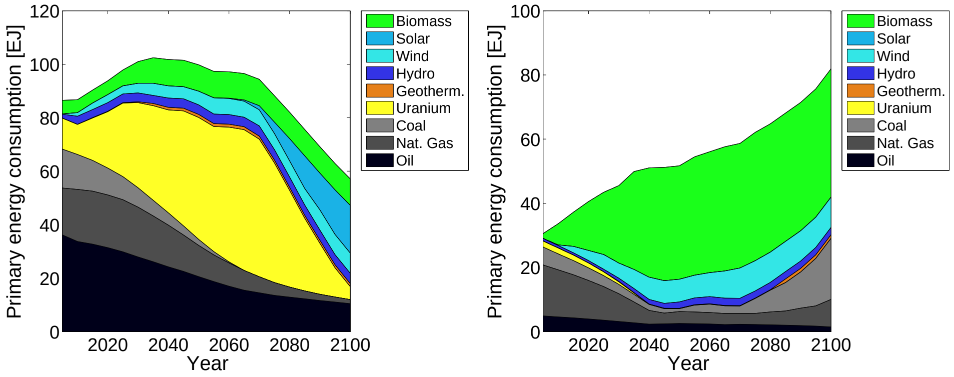
The entire consumption of primary and the production of secondary energy will be reduced. The primary energy consumption reaches now approx. 1250 EJ at the end of the century, whereas 1430 EJ were reached in the reference scenario. In the short run, primary energy consumption is increasing less first and accelerates its growth then again; this was vice versa in the reference scenario. An output of only roughly 770 EJ will be reached in secondary energy production in 2100, while roughly 910 EJ are produced in the reference scenario. This drastic reduction is due to the composition of primary energy and the balancing according to the direct method of consumption. The most obvious change in the primary energy mix (compared to the reference scenario) is the strong restriction in the use of fossil energy sources and the stronger and earlier expansion in the use of renewable energy sources and nuclear energy. As of 2040, solar energy will also play a role now. Solids and other liquids will already earlier be taken out of the system in secondary energy production. Gas, heat and fuels will be produced to a minor degree. The production of hydrogen and electricity, however, will even increase compared to the reference scenario. Similar results for electricity can be found in Weyant (2004, p. 514).

In a next step, the primary energy consumptions in the regions, shown in Figure 4.14 and 4.15, shall be analysed. The short-term increase in primary energy consumption is now lower in the developed regions (UCA, Japan and Europe). This is in contrast to an increased use of the renewable energy that can be noticed in UCA, especially regarding biomass and wind energy; the share of nuclear energy is also increasing. As of 2040, the conversion of gas into electricity and, as of 2050, the conversion of coal into electricity with CO_2 capturing will be used in UCA. Japan may rely mainly on nuclear and Europe will switch from nuclear to renewables in the second half of the century. This future development will lead to a temporary increase in the consumption of primary energy. The three regions have still in common that the decrease in the consumption of oil and natural gas can partially be compensated by the use of biomass. This is especially obvious in UCA, since a long-term biomass potential of 27 EJ was assumed here; in Europe, this figure amounts to only 10 EJ and to only 1.5 EJ in Japan. Solar energy is used in Europe as of 2065.

The consumption of primary energy will increase in the next decades in all other regions. There are especially great differences between China and India on the one side and Russia, Africa, ROW and MEA on the other side. Russia, Africa, ROW and MEA have high potentials in renewable energy sources that they are going to exploit to a high degree. MEA will employ its huge potential of solar. Russia has high potentials in biomass which actually allows them to discontinue the use of gas and to export it instead. Coal is also hardly used in Russia but is exported. In Russia and Africa, part of the biomass is even used to produce hydrogen. For both regions (as well as for all other regions), it is possible to produce fuels and gases with biomass, however it is not possible to export them. This is



(a) UCA (b) Japan



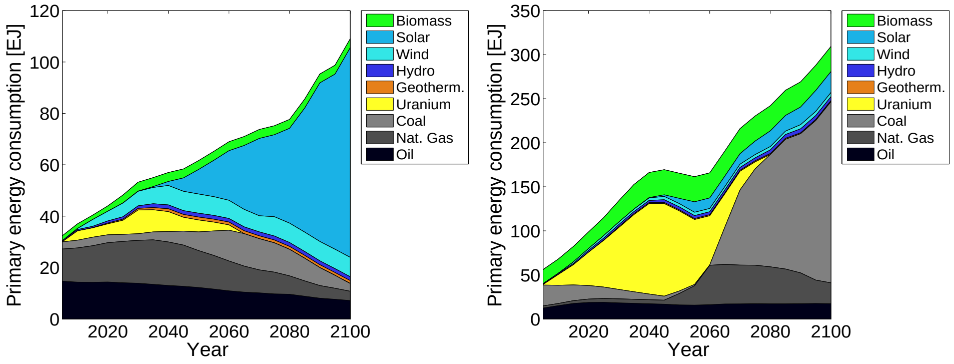
(c) Europe (d) RUS

Figure 4.14: Regional primary energy consumption in policy scenario A; part I

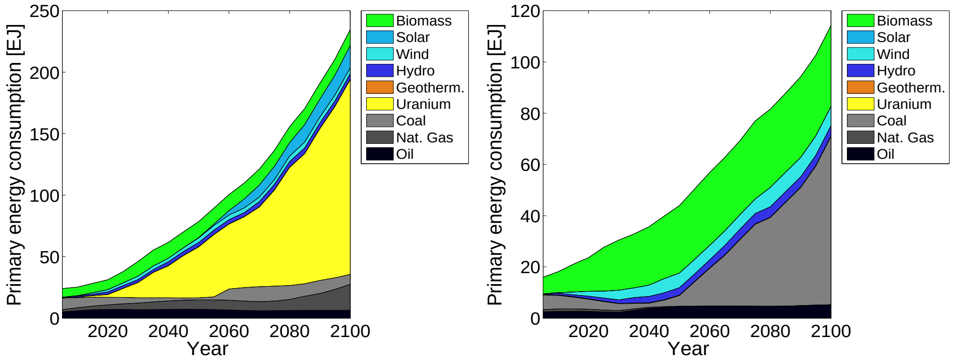
due to the fact that the current version of the model does not allow to trade any secondary energy carrier. The potentials of renewable energy sources in Russia, Africa and ROW are so high that the use of nuclear primary energy sources is not necessary.

India and China, however, have considerably less potentials in the area of renewable energy sources so that another strategy is effective here. The use of nuclear energy will first be expanded in both countries. Like in the developed countries, CO_2 capturing in coal-fired power plants will be used as of 2050 in China. CO_2 capturing will in addition be used in gas-fired power plants however already as of 2040. The necessary gas and coal will be imported. Only at the end of the century, wind energy and solar energy will considerably be used in China and India.

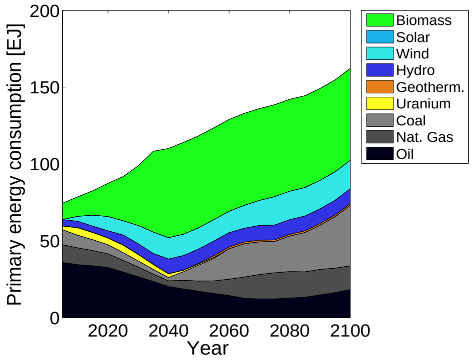
Power generation (see Figure 4.16) shall now be analysed in more detail. Compared to the reference scenario, it can be observed that electricity generation is even higher in



(a) MEA (b) CHN



(c) IND (d) AFR



(e) ROW

Figure 4.15: Regional primary energy consumption in policy scenario A; part II

2100. It will reach 480 EJ. The secondary energy mix, however, does not include the entire amount of generated electricity, since a small part of it is now used to produce hydrogen; see below.

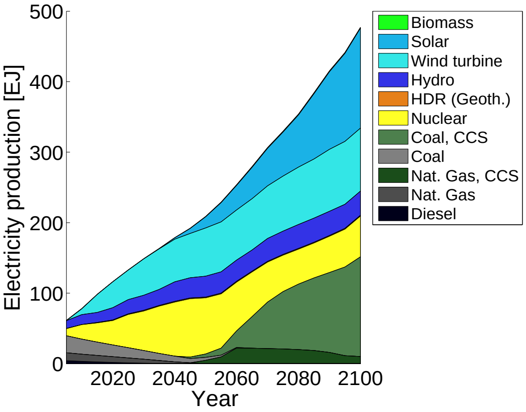
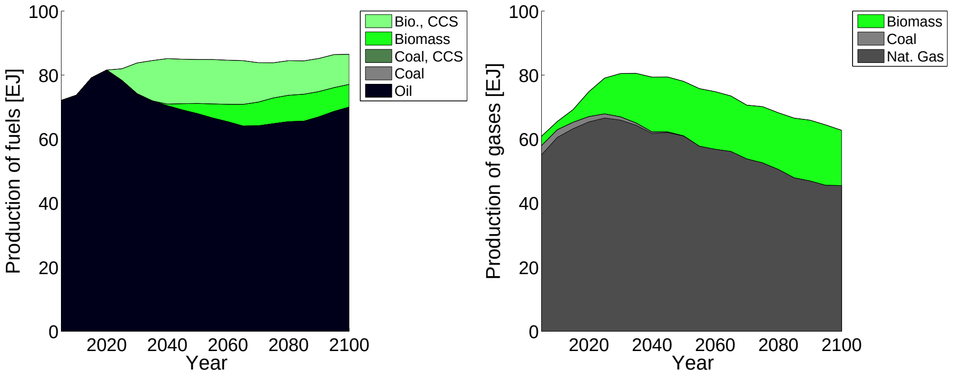


Figure 4.16: Global electricity production in policy scenario A

Expectedly, the use of wind, solar energy and water power is especially noticeable in the power generation mix. The earlier expanse of these alternatives is especially remarkable. This also applies for nuclear energy. By the end of the 21st century, the share of renewable energy sources will be 56%. In the area of fossil energy sources, it can be observed that gas is slightly used for power generation; the emission restriction, however, demands CO_2 capturing. Coal will even on the long-term not be excluded from the electricity mix. It is burnt in power plants according to the so-called oxyfuel method. This technology actually provides the most thorough capture technology, since only roughly one percent of the produced CO_2 will be released into the atmosphere. Alternative approaches that capture CO_2 in coal-fired power plants will not be used, since the remaining emissions of approximately 10% are too high.



(a) Transportation fuels

(b) Gases

Figure 4.17: Generation mix for transportation fuels and gases in policy scenario A

The generation mixes for fuels and gas will be investigated next (see Figure 4.17). The use of both is essentially reduced compared to the reference scenario, but the use of the fossil resources without any capture and sequestration remains high. The long-term restriction of fuel and gas production can only partially be held up by the partial switch to biomass. Here, emphasis should again be put on the fact that gas is now also used for power generation with CO_2 being captured. This opportunity cannot be provided for oil, since there are no CO_2 capture technologies for oil-based transportation fuels, and oil it is not going to be used in efficient combined cycle power plants.

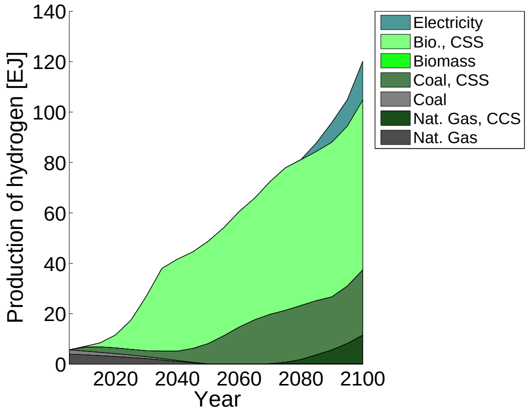
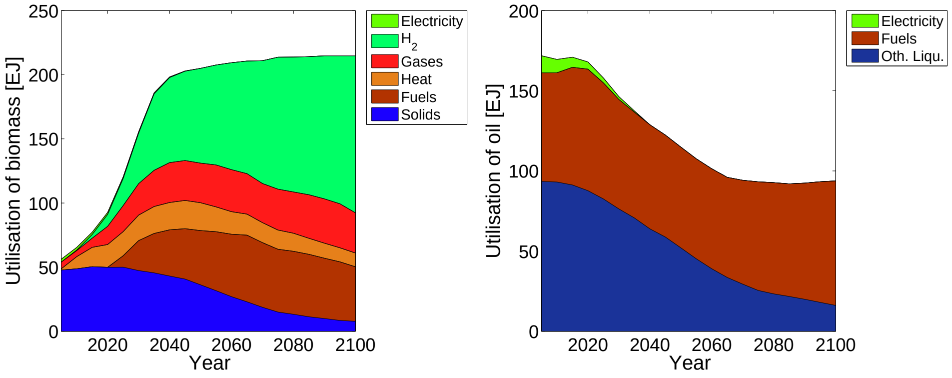


Figure 4.18: Global production of hydrogen in policy scenario A

We now take a look at the generation of hydrogen in Figure 4.18. Various opportunities to generate hydrogen are employed. Biomass is preferred in Russia, Europe, ROW, China and UCA, while in all other regions biomass, coal and later gas is used. These technologies will be supplemented by electrolysis in MEA. The extension of the capacities to generate hydrogen from biomass, gas and coal is exclusively done with CO_2 capturing.

Next, the use of biomass and oil is shown in Figure 4.19. Compared to the reference scenario (cf. Figure 3.12), biomass is more strongly used and the entire potential available will be exploited as of 2040. The conversion into solids will less strongly be practised, since biomass can be converted into a large number of other secondary energy sources the use of which is more valuable. Biomass is further processed into fuels, heat, gases and hydrogen but will not be used to be converted into electricity since there are other opportunities - as discussed above - for this kind of usage. The use of oil will be drastically restricted, especially the conversion into other liquids will be limited. This loss will partially be compensated by the conversion of biomass into fuels. Alternatively, on the basis of the macro-economic production function, fuels can be substituted by hydrogen and other liquids by gases. Despite these opportunities for cushioning, the reduction of



(a) Biomass

(b) Oil

Figure 4.19: Use of biomass and oil in policy scenario A

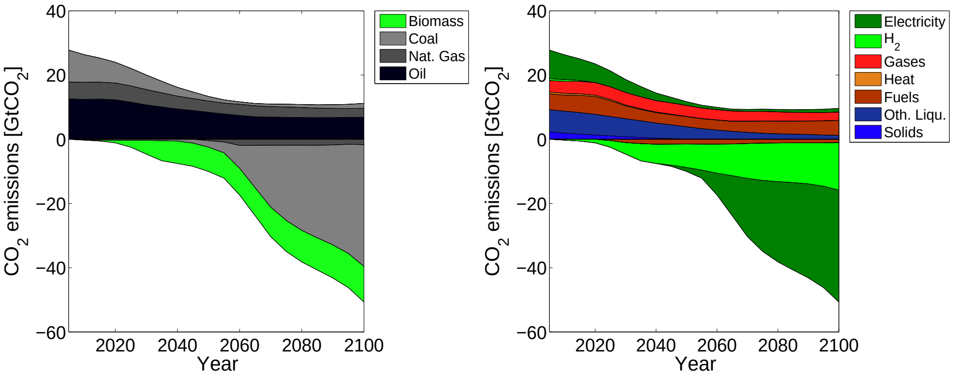
oil consumption is a severe restriction that is caused by the technological impossibility to cost-effectively capture CO_2 at the means of transportation.

It is to be summarised that the energy production, compared to the reference scenario, is much lower and that the structure will be modernised in a speedy manner. The low-value energy sources quickly lose their shares, while power generation will maintain its absolute share and hydrogen is gaining importance. On the part of the generation of individual secondary energy sources, the changes are quite obvious. The electricity sector, in particular, offers several opportunities to avoid CO_2 emissions. The avoidance options in the electricity sector will be used in temporally and regionally different ways. Thus, Russia can completely abandon nuclear energy and large parts of fossil energy sources. The other regions draw on renewable energy sources, fossil combustion technologies with CO_2 capturing and nuclear energy. Besides the electricity sector, CO_2 capturing plays part in producing hydrogen. In the electricity sector, this alternative is only adopted for coal and gas and not for biomass.

For the production of the other secondary energy sources, less technical opportunities are available to reduce CO_2 emissions. Therefore, they are first economised where they can most likely be abandoned. If this is not possible, the scarce biomass will be used. This primary energy source would vanish from its traditional role as supplier of solids and would become a supplier for gases and fuels. Biomass - in contrast to the other renewable sources - has many uses, but will not be used for power generation. The model is limited here, since neither biomass nor the produced secondary energy carriers can be traded. Possible differences in the price of fuels between the regions cannot be compensated.

Emissions

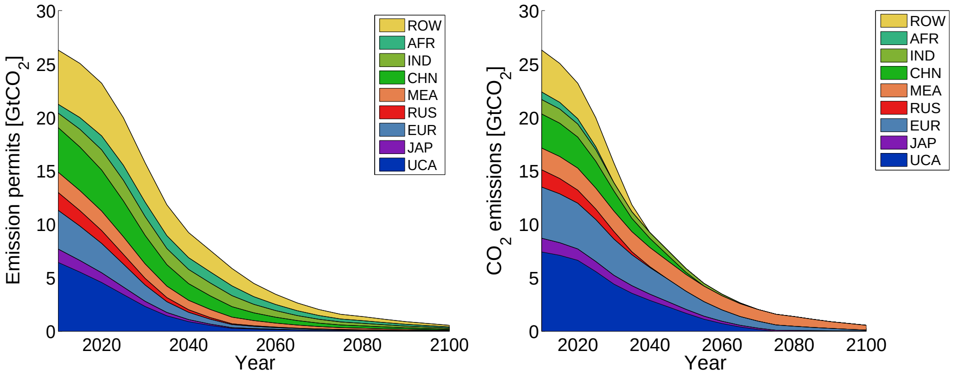
Emissions follow a completely contrary course compared to the reference scenario. Figure 4.20 shows emissions on the positive side and CO_2 capturing on the negative side. It can quickly be seen that the share of oil in the entire remaining emissions is highest. Total emissions from fossil fuels stay above 10 Gt CO_2 until the end of the century. Most of these emissions are neutralized by CCS technologies in combination with the use of biomass (green area in Figure 4.20(a)). The emissions are most rapidly decreasing for electricity (see Figure 4.20(b)), but in this area a lot of CO_2 capturing is done, especially when using coal. In this scenario, more than 40 Gt CO_2 would be captured in 2100.



(a) Primary energy sources (b) Secondary energy sources

Figure 4.20: CO_2 emissions in policy scenario A differentiated by the use of primary energy sources (left) and secondary energy production (right)

Figure 4.21 shows the permit allocation and the actual emissions development. The pursued stabilisation scenario requires a fast and drastic decrease of emissions of all regions. Reductions are most drastic between 2025 and 2050. Global emissions have to be reduced in 2050 by almost 73% and 78% related to the year 1990 and 2005, respectively. The permit share of the developing world regions and ROW increases drastically. In the case of a missing emissions trading market, the industrialised world regions would need to decrease their per capita emissions to around 5% of today's level by 2050, MEA, China and ROW to 20-25%. India and Africa could still increase their per capita emissions. For both regions it is however obviously more favourable not to increase their own emissions and to sell the allocated emission rights profitably. Taking emission trade into consideration, the reductions are lower in the industrialised countries. Figure 4.22 shows that the respective per capita emissions would need to be reduced by approx. 20-35% in 2025 and



(a) Permit allocation (b) World-wide emissions

Figure 4.21: Permit allocation and emissions in policy scenario A differentiated by regions

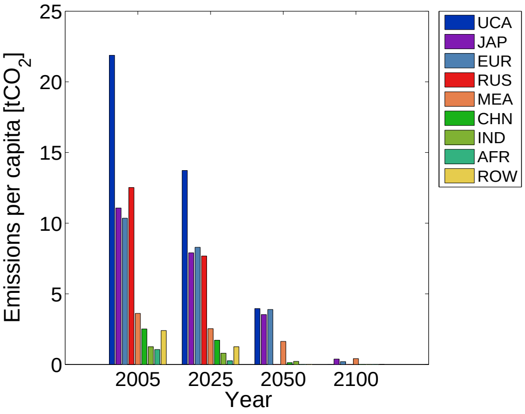
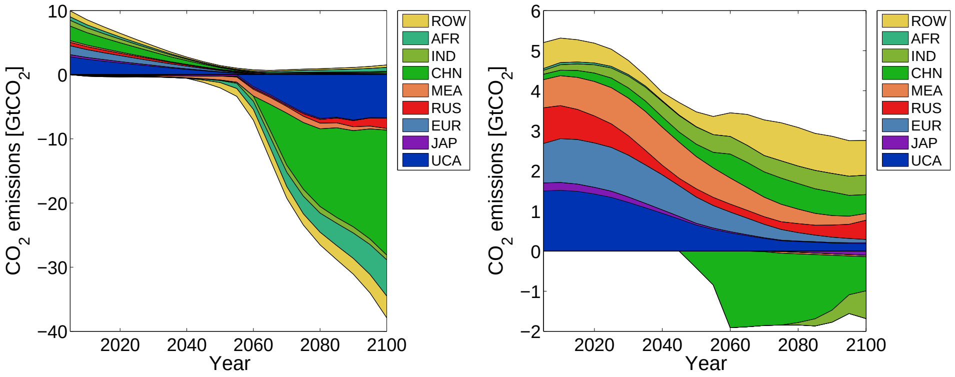


Figure 4.22: Per capita emissions in policy scenario A

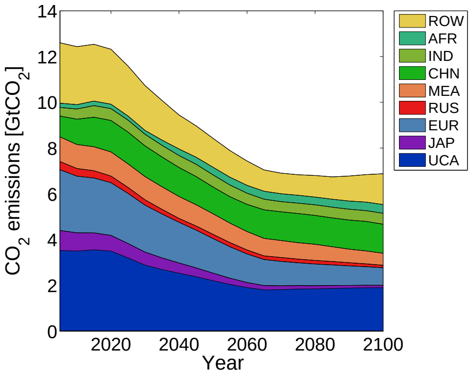
by approx. 70-80% in 2050. Moreover, all regions need to reach per capita emissions of less than 4.5 tCO$_2$ per year in 2050, in 2100 even less than 0.7 tCO$_2$.

In order to cover the energy demand in the long term despite emission restrictions, CCS-technologies are increasingly used in many regions, especially in China and UCA. In Figure 4.23 it becomes clear again that CCS-technology is mainly applied for the use of coal but also for the use of gas (areas in the negative range show again the emission amount which is avoided by using CCS-technology).



(a) Coal

(b) Gas



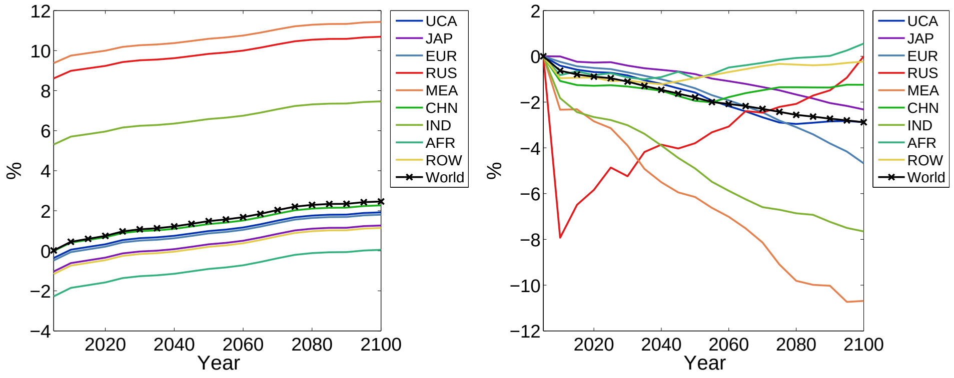
(c) Oil

Figure 4.23: CO$_2$ emissions from combustion of fossil resources differentiated by regions

4.2.2 Policy scenario B: Intensity target

Macro-economic development and mitigation costs

Policy scenario B produces in principle a different picture for mitigation costs than policy scenario A. Although the global average loss in consumption is the same, the regional distribution of costs is quite different. Figure 4.24(a) shows the consumption losses of each region for the period 2005 to 2100, Figure 4.25 the average mitigation costs. First, it can be noticed that Africa is not so clearly the only region to still benefit from the policy scenario. At least for the short term, negative mitigation costs can also be found in other regions (in particular in Japan and ROW). The consumption losses of UCA, EUR and China are slightly lower than the global average. Moreover, all industrialised regions have lower costs in policy scenario B than in policy scenario A. The regions MEA and Russia have further on higher costs than the world average, but also India bears high costs. Figure 4.24(b) shows the difference in the GDP of the regions. It is noticeable that this value, in contrast to the difference in consumption, does hardly change compared to policy scenario A. This primarily means that we deal with a pure allocation effect which determines the revenues from the emission trade. But beyond this, it has only little influence on the development of production and income.



(a) Consumption losses

(b) GDP differences

Figure 4.24: Consumption losses and GDP differences in policy scenario B (compared with the reference scenario)

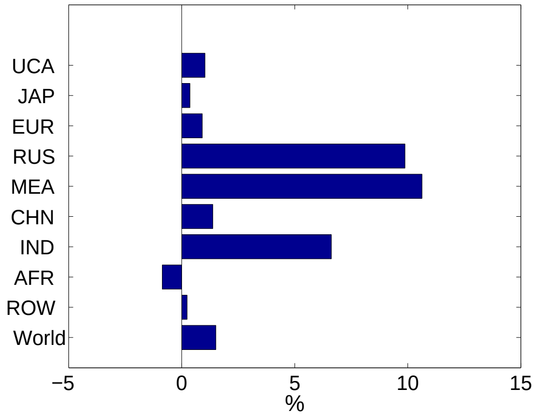


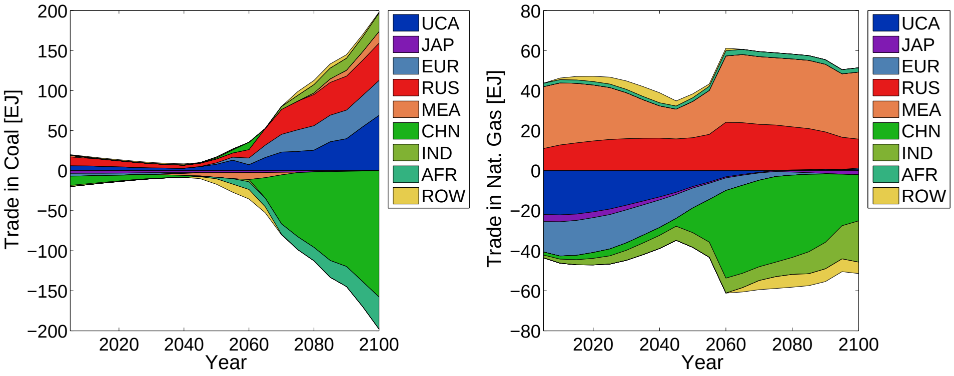
Figure 4.25: Average mitigation costs in policy scenario B

Trade

Due to the lower provision with permits compared to policy scenario A, the revenues of the developing regions from the emission trade are much lower or disappear completely in policy scenario B. These regions reduce in turn their imports of goods (up to 15% in India and ROW and up to 30% in Africa).

The trade flows on the resource market (see Figure 4.26) are almost the same as in policy scenario A. Emissions trading enables all regions to follow the same strategy in the energy sector (including the trade of energy sources) as in policy scenario A.

However, in contrast to the other policy scenarios, the distribution of emission rights according to GDP enables the industrialised countries not only to reduce the share of imported carbon certificates but even to sell their emission rights in a significant order. Initially, Japan, EUR and UCA represent big sellers in the permit market (see Figure 4.27). On the other hand, all developing regions (in particular MEA and China) and Russia are buying permits. MEA remains the largest importer of emission permits, while China and ROW become major sellers of permits in the mid and long term. The peak in emissions trading of nearly 5.5 Gt CO_2 appears already in 2010. The yearly trade volume decreases fast to 2 Gt CO_2 in 2030, and thereafter more slowly to 0.5 Gt CO_2 in 2100.



(a) Coal

(b) Gas

Figure 4.26: Trade of resources in policy scenario B

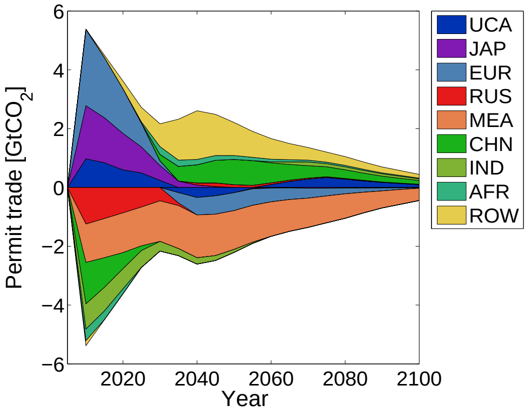


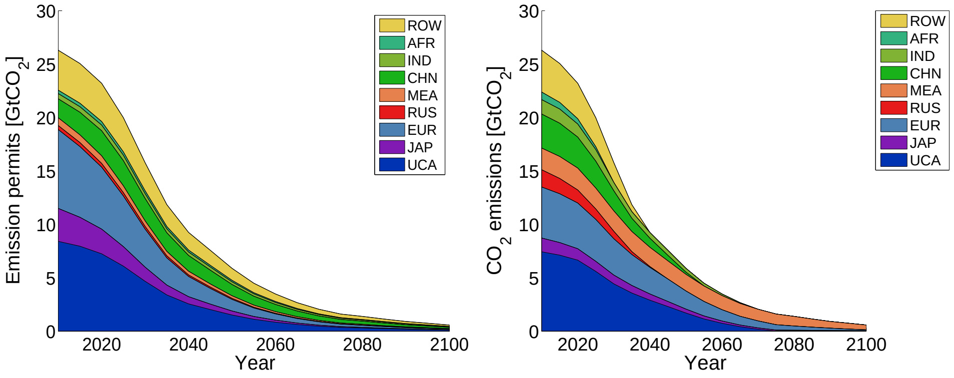
Figure 4.27: Emission trade in policy scenario B

Technology development and power production

The technological development in policy scenario B is the same as in policy scenario A. This is due to the properties of an efficient market that generates the same allocation of scarce goods independent of the distribution of the emission permits among regions.

Emissions

The permit allocation is quite different between policy scenario A and policy scenario B (compare Figure 4.28(a) with Figure 4.21(a)). The latter allocates permits proportional to the regions' share on global GDP. Until 2050, the share of permits allocated to the developed world regions amounts to more than 50%. In this period, the larger part of cumulated emission permits is allocated, which additionally favours the developed regions. Despite the differences in the permit allocation, the emission trajectory and the regional structure of actual emissions is nearly the same (compare Figure 4.28(b) with Figure 4.21(b)). This is consistent with the already mentioned correspondence of the GDP paths and dynamics of the energy systems between both scenarios.



(a) permit allocation (b) World-wide emissions

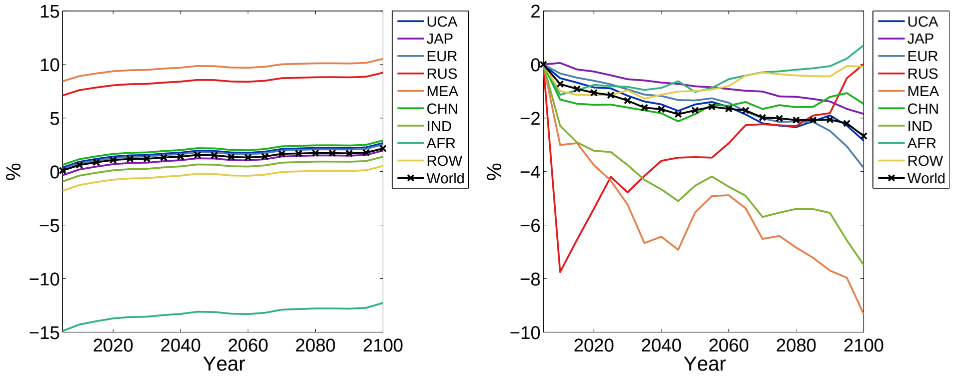
Figure 4.28: Permit allocation and emissions in policy scenario B differentiated by regions

4.2.3 Policy scenario C and D: Multi-stage approach

Macro-economic development and mitigation costs

Figure 4.29(a) shows the consumption differences between policy scenario C and the reference scenario for each region for the period 2005 to 2100. Again, MEA and Russia need to bear the highest mitigation costs. As distinct from policy scenario A and especially from policy scenario B, Africa benefits even stronger from a distribution of emission rights with a multi-stage approach. This is due to the fact that Africa is the region with the lowest per capita income and thus, by the assumed allocation rule, gets even more emission rights than in policy scenario A. As Africa can substitute easily away from the baseline use of fossil resources, an excess of permits results, which can be sold profitably. This also applies to India which faces quite low consumption losses.

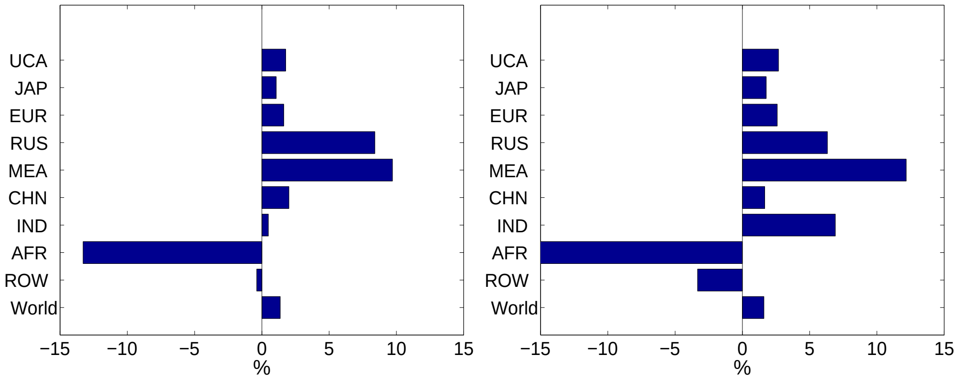
Only small deviations compared to policy scenario A can be found for the differences in the GDP (Figure 4.29(b)).



(a) Consumption losses (b) GDP differences

Figure 4.29: Consumption losses and GDP differences in policy scenario C compared with the reference scenario

As a variant of the multi-stage approach, emission trade in policy scenario D is restricted to those regions that are found either in stage 2, stage 3 or in stage 4. Above all, this means that Africa and India will be excluded from emission trade for a long time. Thus, potential sellers of emissions rights are omitted. Consequentially, China, Russia, Africa and ROW benefit from higher shares and/or higher prices on the less liquid emission market. All other regions will be confronted with a rise of the mitigation costs compared to policy scenario C (see Figure 4.30). On the one hand, India will lose due to the missing revenues from the emission trade and is not compensated by higher prices



(a) Policy scenario C

(b) policy scenario D

Figure 4.30: Average mitigation costs in policy scenario C and D

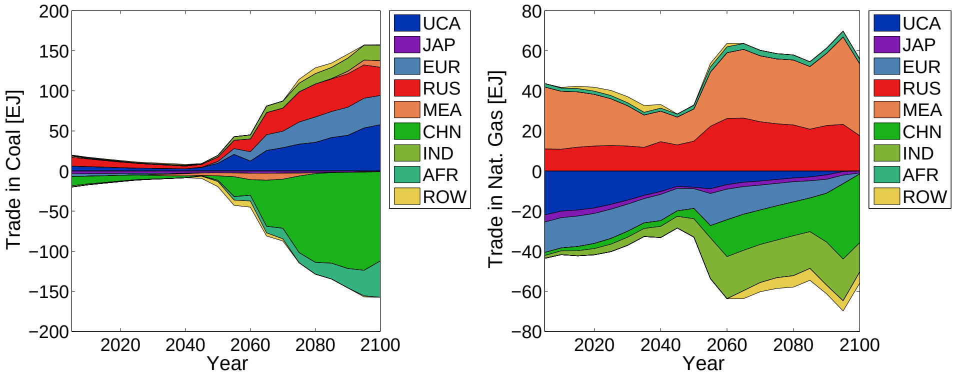
for permit exports later on as it is the case for Africa. On the other hand, UCA, EUR, Japan and MEA will lose due to the necessity that they need to invest more into domestic emission reduction measurements immediately.

Trade

In policy scenario C, the trade structure represented by the current account is quite similar to those in policy scenario A and B. There are slight differences on the resource market (compare Figure 4.31 with Figures 4.8 and 4.9) and larger differences on the permit market (see Figure 4.32).

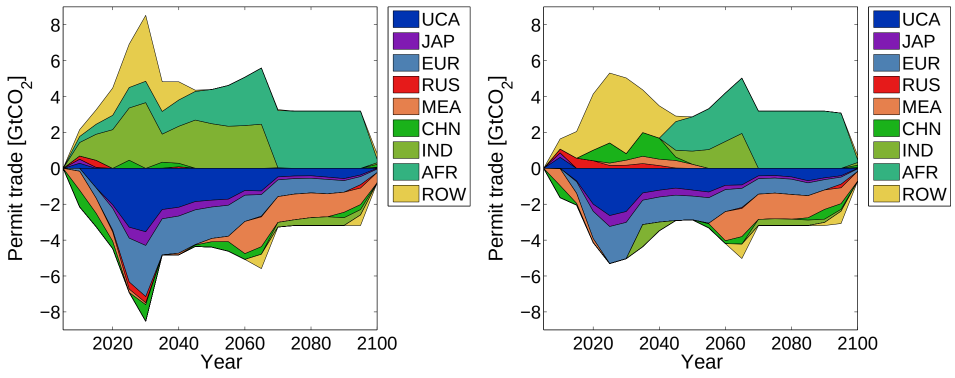
China reduces slightly its import shares on the gas market in the second half of the century in favour of India and EUR. Altogether, the trade in fossil resources is initially somewhat lower than in the policy scenarios A and B. This depends on the permit allocation which cannot be equally compensated by emissions trading as within the other policy scenarios. As a result, there are less permits available in the beginning, but more permits later on. The initial shortage in permits is even more significant in policy scenario D. Hence, the decrease of resources trade is more distinct in policy scenario D.

The strongest changes can again be found on the permit market. Although the distribution of roles between emission right purchaser and seller remains (except for China which temporarily purchases permits), there is a considerable shift of shares on the sellers' side. In policy scenario C, China's export shares are neglible. Since Africa will raise its per capita income quite slowly (true for all scenarios), it will remain below that stage of the multi-stage approach until the end of the century where substantial emission reductions will become necessary. This is also true for India until 2070. The resultant amount of emission rights for India and Africa restricts on the one hand the allocation of emission rights to other regions and results on the other hand in a quasi monopolistic position of Africa in the sale of emission rights after 2070. In the short to mid term, India dominates the export of emission rights. ROW plays its role as major exporter of permits until 2050 only.



(a) Coal (b) Gas

Figure 4.31: Trade of resources in policy scenario C



(a) policy scenario C (b) policy scenario D

Figure 4.32: Permit trade in policy scenarios C and D

A slightly different situation, again on the seller side, emerges from policy scenario D (see Figure 4.32(b)). Since India and Africa will participate in the emission trade only as of about 2035 and 2045, respectively, only a restricted amount of permits is available for sale on the international emission market. Russia, MEA and especially China join the emission export market in the short to mid term which is dominated by ROW. Africa again dominates in the second half of the century.

A striking feature of the multi-stage scenario is the existence of double peaks in permit trade - the first one around 2025/2030, the second one around 2065. These peaks correspond with the transition of ROW and India, respectively, from stage 3 to stage 4. The first peak in policy scenario C amounts to 8.4 Gt CO_2 which is far above the maximums in policy scenarios A and B.

Technology development and energy production

Policy scenario C differs from the scenarios A and B, since the allocation of energy carriers is not the same any more. The policy scenario is more than only a redistribution of burdens and benefits of the global mitigation effort. The energy system exhibits another development path that is compatible with the overall climate change mitigation objective of not increasing the global mean temperature by more than 2°C.

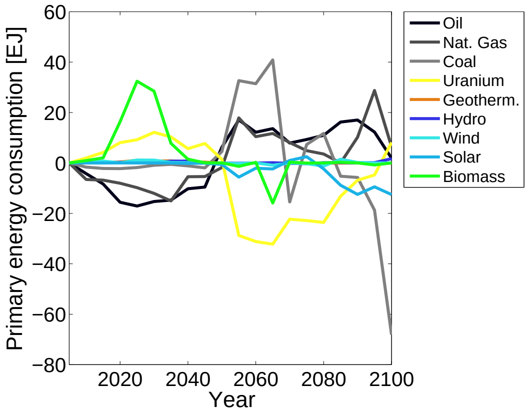
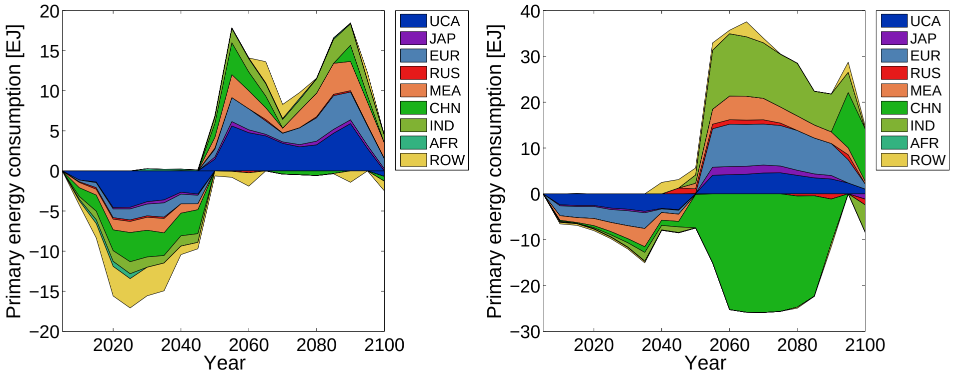
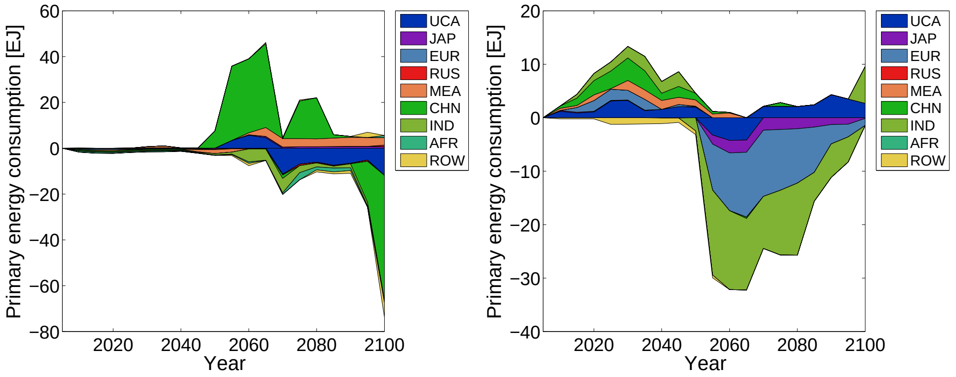


Figure 4.33: Net differences of the global primary energy consumption between policy scenario C and policy scenario A
(Positive values indicate a higher consumption in policy scenario C)

Figure 4.33 shows the absolute differences between policy scenario C and policy scenario A for the different primary energy sources. In the short run, less oil and gas is used in policy scenario C that is substituted by an increase in the use of biomass and uranium. During the second half of the 21st century the development twists to the opposite: more oil, gas and coal is employed, but the use of uranium is reduced. This pattern corresponds to the changing path of global emission permits (see next section).



(a) Oil (b) Natural gas



(c) Coal (d) Uranium

Figure 4.34: Differences in the consumption of primary energy carriers between policy scenarios C and A differentiated by regions
(Positive values indicate a higher consumption in policy scenario C)

Figure 4.34 shows the differences between the two policy scenarios for some primary energy carriers differentiated by regions. While oil shows a clear pattern of reallocation in time, we observe a different distribution between the regions for gas in the 2nd half of the century. China reduces its gas consumption favouring all other regions. In Figure 4.34(c), however, we see that China increases its consumption of coal. The use of uranium shows mainly a temporal redistribution, but the reduction of uranium use is most emphasised in India and Europe.

Next, we turn to policy scenario D. Figure 4.35 shows the differences to policy scenario A in the same manner as Figure 4.33. While global primary energy consumption is similar to the unrestricted multi-stage policy scenario, the regional pattern is changing again. The most important difference is that India and Africa use more coal in the near to mid term and the MEA region reduces solar significantly in the long run, but uses uranium instead.

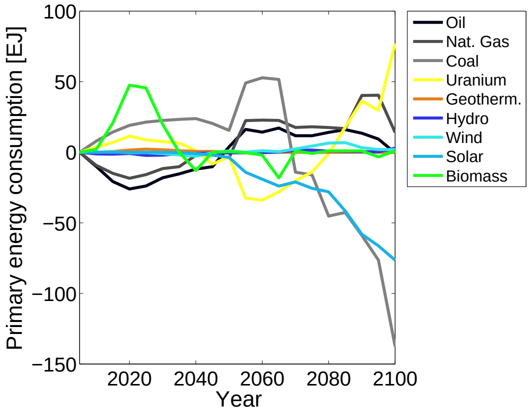
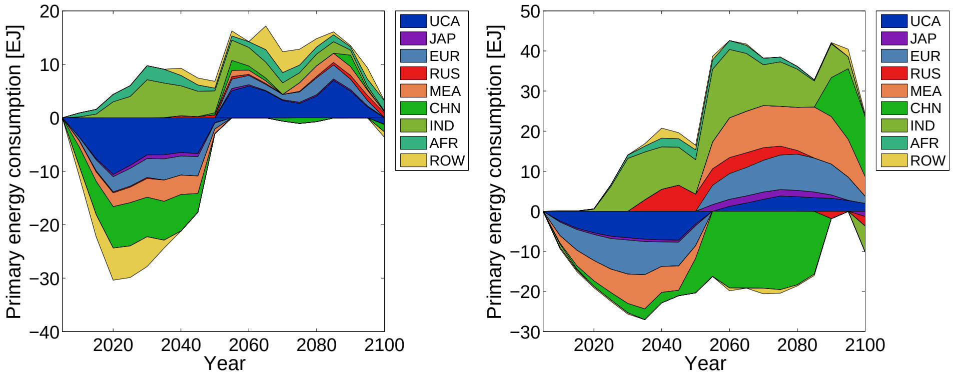


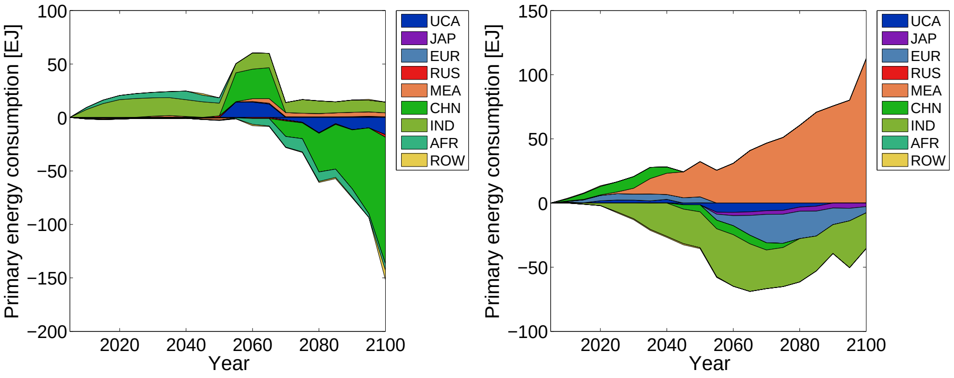
Figure 4.35: Net differences of the global primary energy consumption between policy scenario D and policy scenario A
(Positive values indicate higher consumption in policy scenario D)

The switching of MEA from solar to uranium has significant impacts on the overall allocation of uranium shown in Figure 4.36(d). The increase in demand by MEA crowds-out the deliveries to EUR and especially India, which need to reduce their demand. India, in turn, substitutes uranium by increasing its demand for coal in the short run; see Figure 4.36(c). Another interesting result is that now the interregional conflict for oil and gas is increased as indicated in Figures 4.36(a) and 4.36(b), respectively. In the short run, the demands for gas and oil are increased in some regions like India at the expense of other regions like the developed regions and MEA.



(a) Oil

(b) Natural gas



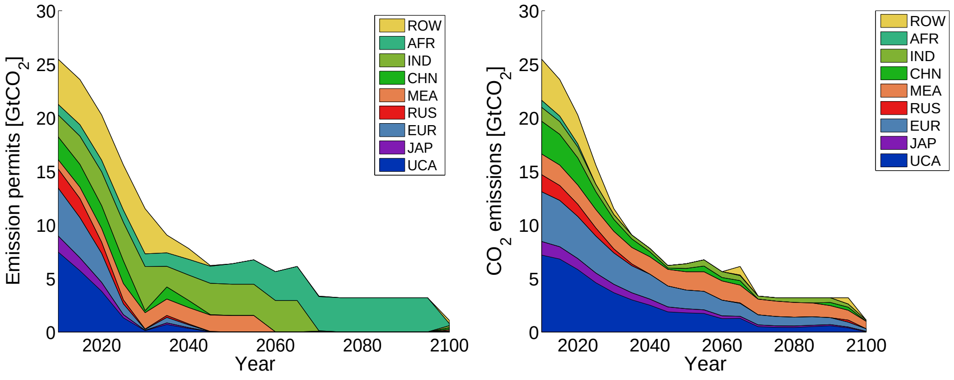
(c) Coal

(d) Uranium

Figure 4.36: Differences in the consumption of primary energy carriers between policy scenarios D and A differentiated by regions
(Positive values indicate a higher consumption in policy scenario D)

Emissions

The permit allocation in the multi-stage scenario (see Figure 4.37(a)) is featured by a fast increase of the developing regions' permit share. Already in 2030, UCA, EUR and JAP are allocated with less than 10% of global permits (while provided with 50% in 2010). Moreover, in contrast to policy scenario B, policy scenario C (see Figure 4.37(b)) comes up with regional emission reduction paths which differ from policy scenario A. Globally, less emissions are produced in the short term, but more in the long term. The most demanding reduction phase, which is between 2025 and 2040 in policy scenario A and B, is brought forward (between 2015 and 2030; in policy scenario D (see Figure 4.38) even between 2010 and 2025).



(a) Permit allocation

(b) World-wide emissions

Figure 4.37: Permit allocation and emissions in policy scenario C differentiated by regions

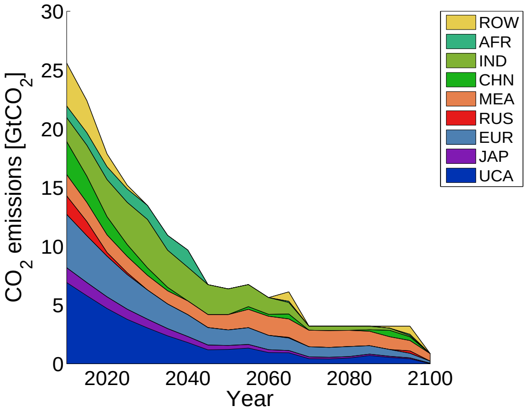


Figure 4.38: Emissions in policy scenario D

Whereas policy scenario A and B imply full flexibility in allocating global emission permits over time, policy scenario C and D imply predefined amounts of permits for the stages 1 to 3. This, on the one hand, results in a rather discontinuous profile of global emissions, and on the other hand, yields a higher amount of permits to be allocated in the second half of the century[1]. In order to meet the climate target, the latter has, obviously, be compensated by a lower level of emission permits in the first half of the century. In a first instance, the multi-stage scenario is more restrictive, resulting in slightly lower welfare than policy scenario A and B. Global average consumption losses are, however, slightly lower in policy scenario C.

The most remarkable difference between policy scenario C and policy scenario D is the emission level of India. While India contains its emissions in the former in favour of selling permits, it increases emissions in the trade-restricted case (even in periods when it is allowed to trade). There is some kind of lock-in effect. India uses domestically the permits which initially cannot be traded, and consequently builds an energy system that is partly based on fossil fuels. At the same time, potential buyers of permits have to restructure their energy system away from fossil fuels, thus reduce the demand for permits in the long term.

4.3 Comparison of policy regimes

In the following Chapter, a comparative analysis is carried out for the investigated policy regimes. The comparison of the mitigation costs and the resulting incentive effects for different regions are the focus of this analysis. Implementation issues are not discussed here. Beyond the selection of policy scenarios, there will be no discussion about equity aspects that play an important part in the international negotiation process.

All policy scenarios pursue the same stabilisation target. Regarding ecological efficiency (i.e. its contribution to climate stabilisation), they are almost equal. They are remarkably different in terms of permit allocation. Table 4.1 specifies the change of emission permits in 2020 and 2050 compared to the emissions in 1990. Figures differ for nearly all regions, especially in 2020. The high implicit reduction requirements for Russia are a bit misleading due to the structural break in the Russian economy after 1990.

On the global level differences are small. But still, the global emission path of the different policy scenarios is not identical. This indicates inefficiencies in the distribution of emission rights. This effect, which applies to the multi-stage scenario, is however marginal here. Global average mitigation costs measured as consumption losses relating

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[1] The model does not allow to allocate and trade negative emission permits.

Table 4.1: Percentage difference between allocated emission permits (2020 and 2050) and emissions in 1990

	2020			2050		
	Scen. A	Scen. B	Scen. C	Scen. A	Scen. B	Scen. C
UCA	-19%	+29%	-32%	-95%	-73%	-100%
JAP	-18%	+108%	-25%	-94%	-67%	-100%
EUR	-34%	+39%	-35%	-93%	-74%	-100%
RUS	-45%	-84%	-52%	-97%	-96%	-100%
MEA	+95%	-24%	+38%	-33%	-74%	+64%
CHN	+45%	-12%	-20%	-63%	-60%	-100%
IND	+190%	-18%	+387%	+59%	-61%	+351%
AFR	+197%	-25%	+149%	+108%	-69%	+334%
ROW	+19%	-13%	+2%	-61%	-73%	-100%

to the reference scenario are between 1.4% and 1.5% for the policy scenarios A, B and C. Policy scenario D is most expensive with 1.6%. Global GDP losses are of the same magnitude. [2]

Figure 4.39 provides an overview of the average regional mitigation costs for the four investigated scenarios. Policy scenarios A and C have a similar cost structure for UCA, JAP, EUR, MEA and ROW. While the C&C scenario is more beneficial for Russia and China, Africa and India benefit significantly from the multi-stage scenario. Policy scenario B has the smallest range in regional mitigation costs. But at the same time, it is also a scenario of extremes (see Table 4.2). For many regions, it is either the most favourable or the worst scenario. It is most favourable for industrialised countries. The developing regions, on the other hand, need to bear significant mitigation costs. In the light of the distribution of the historical responsibility for the climate problem, this could be a heavy burden in future climate negotiations. Policy scenario D is acceptable for few regions, but for most it is not. Altogether, the restriction made to the global emission trade system has a relatively high price.

As a robust result, it turns out that the variance of mitigation costs is higher between the different regions than between the different policy scenarios. From the regional point of view, it should be noted that the region MEA has to bear the highest costs in all scenarios (always more than 9%). The reconstruction of the global energy system reduces

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[2] In general, regional GDP losses differ from regional consumption losses. This is due to the effects of international trade.

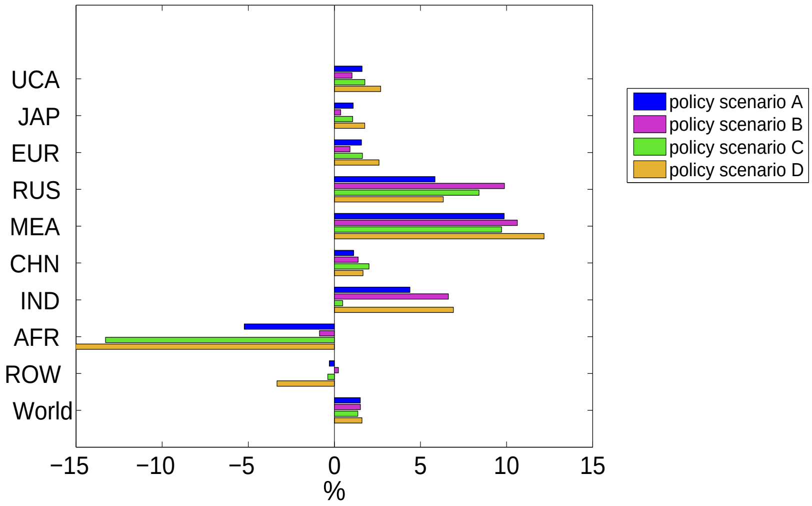


Figure 4.39: Average mitigation costs

part of the possible rents of this region whose revenues are to a large part derived from selling fossil resources. This is in a slightly milder form also true for Russia (always more than 5%). For the three developed regions UCA, Japan and EUR, the costs over the different scenarios develop according to a fixed pattern. The highest mitigation costs among this group can be found in UCA, they are slightly lower in Europe and they are lowest in Japan. Beside the different base level (highest per capita emissions in UCA), the growth pattern is also reflected in this relation according to which the region UCA will grow most rapidly among these three regions. For all three regions, policy scenario B is the most favourable one (average mitigation costs amount to 1% or less). For China, the lowest costs arise in policy scenario A, however, variance of costs between the scenarios is relatively small. The contrary holds for India, where all scenarios but the multi-stage scenario C are quite expensive. Africa benefits in all policy scenarios, most remarkably in both multi-stage scenarios (more than 10% consumption gains).

The regional mitigation costs are once again listed in detail in Table 4.2. Green figures show the most cost-effective policy scenario for the respective region, red figures those scenario which is the most expensive one for the region.

With regard to the technological development in the energy sector, similar patterns arise in the different policy scenarios. Six options to avoid climate change were identified:

1. Lowering the entire energy consumption.
2. Modernising the output structure of secondary energy carriers.

Table 4.2: Consumption losses in %

(Note: green and red figures label the most cost-effective and most expensive policy scenario, respectively)

	Pol. scenario A	Pol. scenario B	Pol. scenario C	Pol. scenario D
UCA	1.61	1.03	1.77	2.68
JAP	1.09	0.37	1.06	1.77
EUR	1.58	0.91	1.63	2.59
RUS	5.84	9.88	8.40	6.32
MEA	9.86	10.63	9.71	12.18
CHN	1.11	1.38	2.01	1.66
IND	4.39	6.62	0.49	6.91
AFR	-5.23	-0.86	-13.29	-16.11
ROW	-0.30	0.24	-0.38	-3.33

3. Reduction of fossil fuel derived transportation fuels and gases.
4. Use of renewable primary energy sources.
5. Use of nuclear energy.
6. Application of CCS for the use of gas, coal and biomass.

Table 4.3 gives an overview about the utilisation of different mitigation options in the energy system according to their priority in the temporal course. The weights are attributed according to policy scenario A and B. The reduction of primary energy consumption is important in the beginning and becomes less prominent in the long run; modernisation of the secondary energy carrier production becomes more and more important with time especially through the increasing shares of electricity and hydrogen instead of other liquids and solids. The reduced production of fuels and gases derived from fossil fuels also becomes more important with time; partially the use of fossil fuels is substituted by the use of biomass. The use of renewables is not uniform across energy sources. While biomass, wind and hydro are already meaningful in the short term, solar energy sources start to play a prominent role only in the long term. Nuclear power is important in the near to mid term, but disappears as mitigation option in the long term. Instead, CCS technologies gain importance over time. Hence, the energy system demonstrates a high degree of flexibility to deal with the carbon scarcity imposed by the climate change mitigation objective.

Table 4.4 summarises the intensity with which the options are employed in the regions. It shows an impressible diversity. The reduction of primary energy consumption is most important in the developed countries and MEA, but it is not so important in the developing regions. There, the modernisation of the secondary energy mix is much more important,

Table 4.3: Overview of mitigation options employed in policy scenarios A and B
(+ used weakly ++ used intensively +++ used most strongly)

	Short term	Mid term	Long term
Reduction of primary energy	+++	++	+
Modernisation of secondary energy	+	++	+++
Reduction of fossil derived fuels & gases	+	++	++
Wind & hydro	+	++	++
Solar			+++
Biomass	++	++	+++
Nuclear	++	++	
CCS		++	+++

Table 4.4: Overview of options employed in policy scenarios A and B differentiated by regions
(+ used weakly ++ used intensively +++ used most strongly)

	UCA	Japan	EUR	Russia	MEA	China	India	Africa	ROW
Red. primary energy	++	+++	+++	+	+++	+	++	+	+
Modern. secondary en.	++	+	++		+++	+++	+++	+++	++
Red. fuels & gases	+++	++	++	+++	++	+	+++	+	++
Wind & hydro	+++	+	++	+++	++	++	+	+	+++
Solar		+	++		+++	++	++		
Biomass	+++	+	++	+++	+	+	+	+++	+++
Nuclear	++	+++	++		+	+	+++		
CCS	++	+		+	+	+++	+	+++	++

that is only of medium or low importance in the developed countries. The reduction of fossil fuel derived transportation fuels and gases plays a significant role in UCA, Russia and India. The application of renewables depends mainly on the assumed potentials, but solar is special in that. Solar is only applied in regions that have low potentials in the other renewables or would need to import resources. Nuclear is very important in Japan and India. CCS is surprisingly most important in China and Africa. However, it should be mentioned that these results are quite sensitive and often alternative strategies could be followed by the regions without significantly increasing mitigation costs (see sect. 4.5).

The analyses in the previous sections make it obvious that the allocation of emission rights has neither a significant influence on the development of the global mitigation costs nor on the development of regional energy systems. This result is in accordance with economic theory and with experiments with the model MESSAGE-Macro (cf. Nakicenovic and Riahi, 2003, p.24), which emphasize the separability of efficiency and equity. The investments in transformation technologies will not be changed by the distribution of emission certificates. This perfectly fits with policy scenarios A and B.

This separability theorem is well-founded for statistical cases and perfect markets. There are, however, assumptions in the present model that are in contrast to the conventional approach (i.e. compliance of the theorem cannot be expected offhand):

1. In principle, the model is dynamic, terms-of-trade effects can change the trade flows.
2. Trade is restricted; secondary energy sources cannot be traded.
3. The power generation technologies wind turbines and solar photovoltaics are characterised by learning curve effects.

In particular, trade restrictions in policy scenario D prevent this scenario to meet the separability theorem.

4.4 Comparison with *MIND*

We summarise the most important results from the *MIND* model that were presented in the first report for the OPTIKS project. This summary serves as a reference point to compare this model with the REMIND model. We will first refer to the assumptions and then turn to the results.

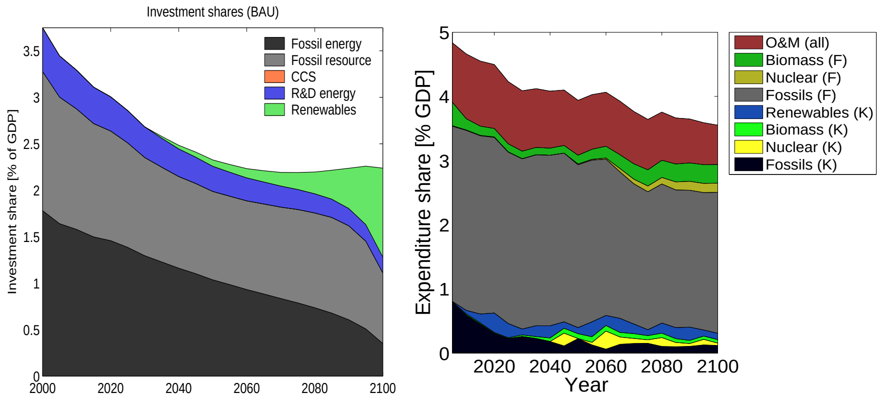
Both models – *MIND* and REMIND – are built in the same tradition. A Ramsey-type growth model was hard-linked with an energy system model and a climate system model. However, the original *MIND* model was a very simple model:

1. There is only one region representing the world, compared to nine regions in REMIND. Hence, there was no need to represent trade in goods, energy or emission certificates.
2. There is only one final energy carrier in *MIND*, compared to eight in REMIND.
3. In *MIND*, there is a single alternative back-stop technology that was available without any physical limits. In REMIND, a great number of renewable energy carriers are modelled explicitly and each of them is restricted in differing grades in order to consider the scarcity of attractive opportunities.
4. There are only two primary energy sources in *MIND* compared to nine in REMIND; e.g. biomass and nuclear energy are explicitly represented in REMIND, whereas production of the latter was part of an exogenous scenario in *MIND*.
5. There are only two energy transformation technologies, instead of 70 in the REMIND model. Hence, the dynamics of investment paths are much more detailed and complex in REMIND.

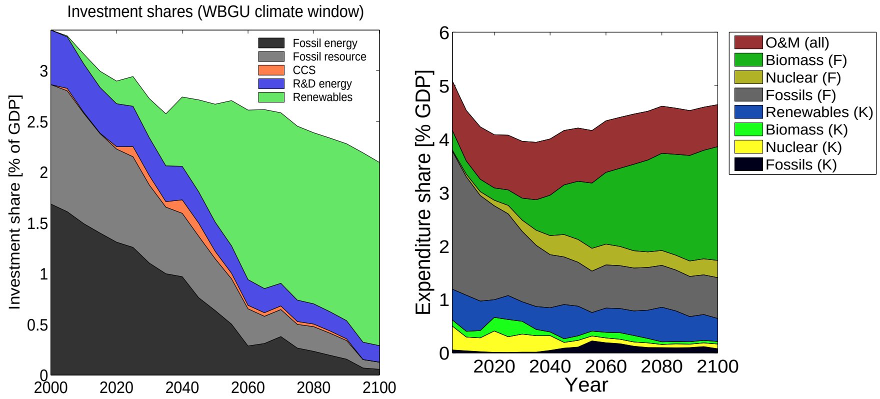
This means that we introduced a number of bottlenecks and flexibilities into the model's structure. On the other hand, *MIND* was triggered by endogenous biased technological change that is exogenous in REMIND. The new model structure does not consider endogenous changes of the labour and energy productivity induced by specific RD&D investments. This altogether limits the comparability of both models.

With respect to the results, we want to revisit the figures on the energy-related investment structure, the primary energy production and the prices of CO_2 emissions certificates. Note that the two model structures are not exactly comparable. O&M costs are not considered in *MIND*; in the graphs below, we do not disaggregate this position according to the energy types.

The sum of investments and fuel costs – expressed in expenditure shares – are roughly of the same order of magnitude for both models. In the two reference (BAU) scenarios



(a) *MIND*, BAU (b) REMIND, BAU

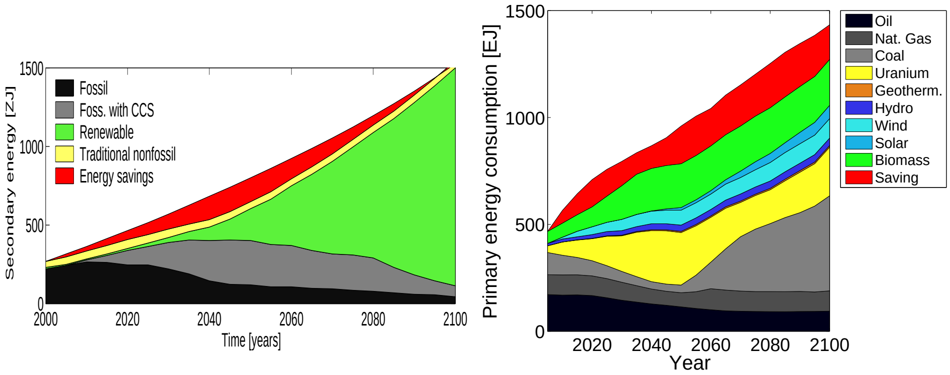


(c) *MIND*, WBGU (d) REMIND, policy scenario A

Figure 4.40: Comparison of investment shares between *MIND* and REMIND policy scenario A

(Note: The letter in parenthesis for the REMIND scenarios indicates whether the position represents capital investments (K) or fuel costs (F))

they are decreasing over time (see Figure 4.40). Furthermore, the share of the fossil energy sector is roughly the same in the beginning and is dominating in both models in the reference scenario as well as significantly decreasing in the policy scenario for both models. However, there is a number of differences in the details regarding magnitudes and structure. First, the expenditure share in the REMIND model is not a monotonously decreasing function in the policy scenario as it was the case in the *MIND* model. Second, the investments in renewables are much lower in REMIND in the mitigation case, which is mainly due to the constraints on potentials. However, in REMIND, renewable invest-



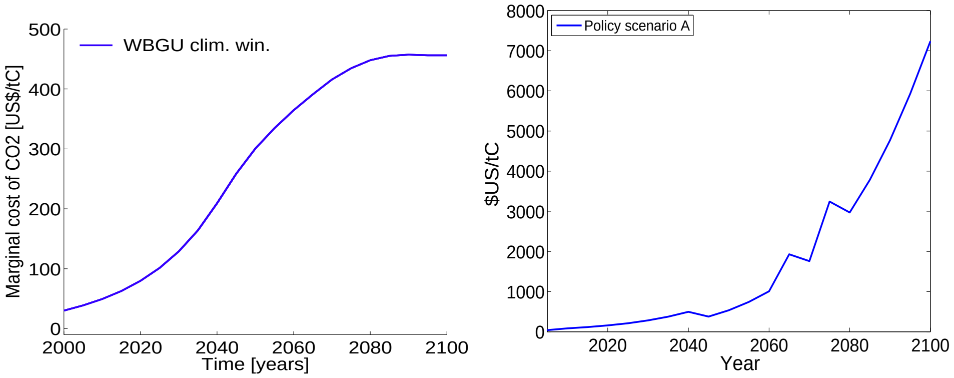
(a) *MIND* (b) REMIND

Figure 4.41: Comparison of primary/secondary energy production between *MIND* and REMIND policy scenario A

ments are launched earlier in the BAU cases. Third, the fuel costs for biomass are very high in REMIND. This is mainly due to the exhaustion of the overall potential, which induces very high rents. Also, nuclear fuels are increasing significantly in prices as climate protection goals are imposed; the uranium price increases by a factor of 25 until the end of the century. This leads to a reversal of the expenditures structure for nuclear electricity: fuel costs get more important than capital costs.

Regarding energy production in the policy scenarios, we find very different results. The use of fossil primary energy carriers in REMIND is declining from the very beginning (see Figure 4.41(b)), but it was slightly increasing by applying CCS based technologies in *MIND* (see Figure 4.41(a)). In REMIND, the use of fossil fuels (especially coal) is increasing in the second half of the 21st century, when it is augmented by the use of CCS. *MIND* was mainly relying on renewable energy sources, which are much lower in REMIND. Energy savings are now more important and not only temporary; biomass gains importance; nuclear energy serves as a near to mid term option. Differences in the energy mix of both models are due to the above mentioned differences in model features. In particular, in *MIND* the renewable energy sources were modelled as back-stop technologies – i.e. the potential is unlimited, whereas nuclear technologies were not considered as an option. Moreover, the single region approach imply unrestricted tradability of energy carriers.

The prices of CO_2 emission permits computed with the two models are very different; see Figure 4.42. In *MIND*, the price of CO_2 permits increased from 35 \$US per tC (around 10 \$US/tCO_2) in a logistic pattern to 450 \$US per tC (around 120 \$US/tCO_2) until 2080.



(a) *MIND* (b) REMIND

Figure 4.42: Comparison of CO_2 permit prices between *MIND* and REMIND policy scenario A

REMIND, instead, starts with prices of about 40 \$US per tC (11 \$US/tCO_2) that increase exponentially to nearly 7500 \$US per tC (2000 \$US/tCO_2) in 2100 at a rate of about 5.7%. The reason is that the implied emission constraint in REMIND is tighter, that the potentials of the renewable and biomass energy sources are constrained and that secondary energy carriers derived from renewable primary energy carriers cannot be traded. The high carbon price is needed to keep low-cost fossil energy from reentering the market.

4.5 Analysis of mitigation options

In the analyses of the previous section, it turns out that the use of different technological options is the optimal policy. In contrast to the global model MIND, the more advanced model REMIND simulates higher shares of nuclear energy and use of coal based on CCS technologies. Risk aversion and a lack of social acceptance may restrict the use of both technologies. Investing in risky technologies can only be justified if their option value is high. The option value can be interpreted as a measure of substitutability. We determine the option value as the difference in the mitigation costs between a policy scenario that allows to employ the relevant technological option and a policy scenario that switches it off or fixes it to its utilisation level in the reference scenario.

Based on the contraction & convergence scenario (see section 4.2.1), we defined two additional scenarios which restrict the use of CCS technologies and nuclear energy technologies.

4.5.1 No-CCS scenario

In this scenario, the application of CCS technologies either in combination with the use of coal and gas or in combination with the use of biomass is completely switched off. In consequence of switching off CCS, the energy consumption will be reduced significantly. This, above all, applies for the long-term. In 2100, primary energy consumption in the No-CCS scenario is almost 30% lower than in policy scenario A, which however is partly due to the different composition of the primary energy (a lower share of fossils means that in terms of secondary energy the energy consumption is reduced to a smaller degree). The remaining gap is filled mostly by solar energy and nuclear energy (see Figure 4.43). There is a reduction of global electricity production compared to policy scenario A in the last 20 years of the century only. It amounts to less than 10%. While alternatives exist for the electricity production, the drop out of CCS technologies has a more drastic impact on the transport fuel sector and on the production of hydrogen (see Figures 4.44(a) and 4.44(b) compared to Figures 4.17(a) and 4.18). Oil consumption is indirectly affected as shown by its significant reduction in transport fuel production. The missing CCS option reduces negative emissions from biomass use. They have to be compensated by reducing emissions from consumption of oil.

The option value of the CCS technology is quite high. Mitigation costs increase by more than 1% globally as well as in most regions (see Figure 4.46). UCA, EUR, Japan, Russia and MEA face highest additional mitigation costs, while AFR and ROW benefit. The drop out of CCS technologies increases the permit prices significantly. This improves

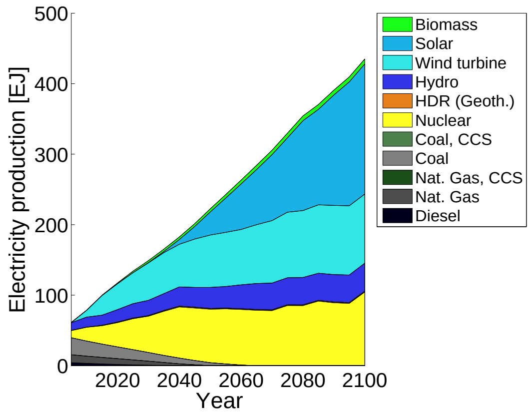
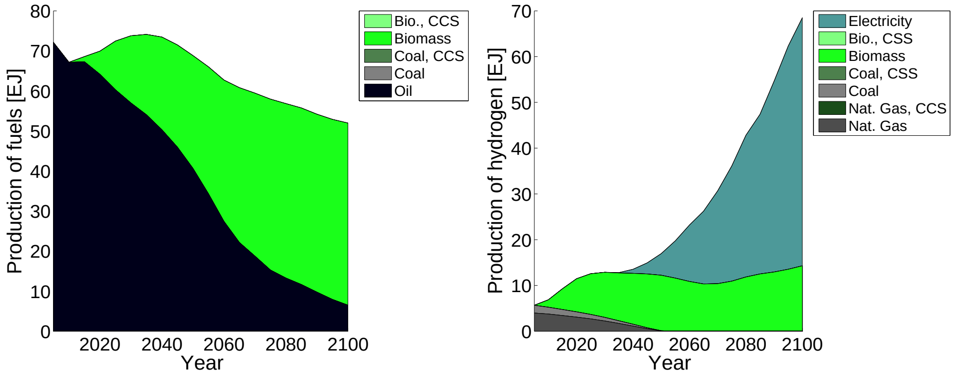


Figure 4.43: Global power generation in the No-CCS scenario



(a) Transportation fuels

(b) Global production of hydrogen

Figure 4.44: Transport fuel sector and the production of hydrogen in the No-CCS scenario

the terms of trade of Africa and ROW.

4.5.2 Fixed nuclear scenario

In this scenario, the use of nuclear energy is fixed to the amount that is used in the reference scenario. The reduction in energy consumption is less drastic than in the No-CCS scenario. The total electricity production, however, is quite similar (see Figure 4.45). Investments in CCS technologies (gas, coal, biomass) and solar technologies are brought forward, but cannot completely be compensated for the missing nuclear option. Other renewable energy technologies (wind and hydro) fill the gap in the short term. In the mid term (2030-2060), coal with CCS gains additional shares. Altogether, doing without additional nuclear energy is not at all very costly (see Figure 4.46). The option value of nuclear energy is quite low; the incremental mitigation costs are in the order of 0.2% globally. The nuclear option is slightly more important for Russia that faces highest additional costs compared to policy scenario A, while India and ROW are not at all confronted with additional mitigation costs.

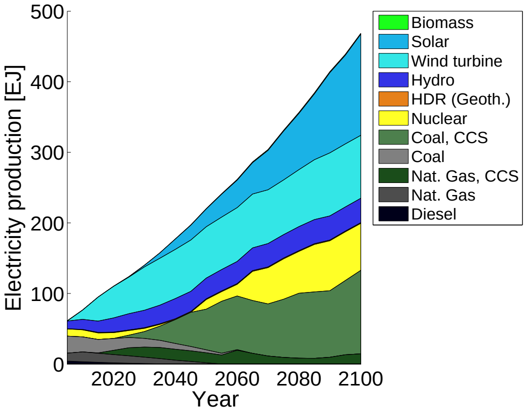


Figure 4.45: Global power generation in the fixed nuclear scenario

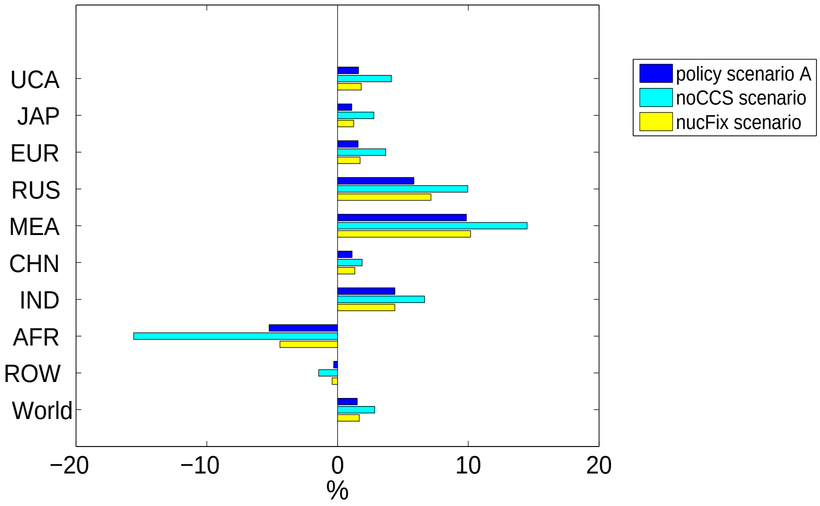


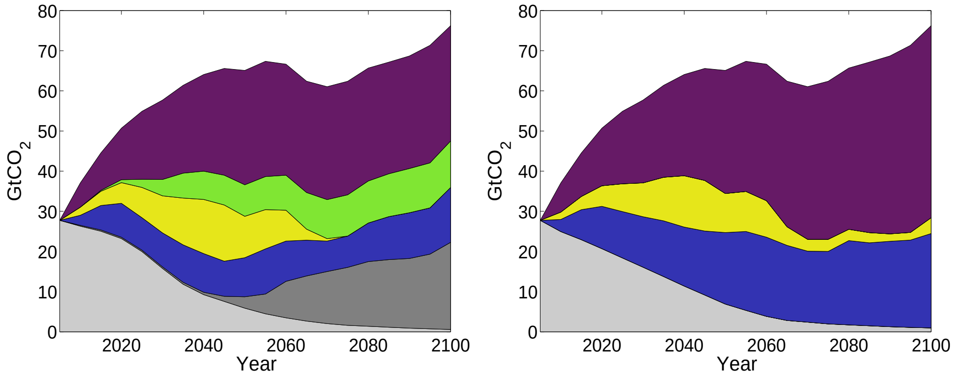
Figure 4.46: Average mitigation costs

4.5.3 Filling the mitigation gap

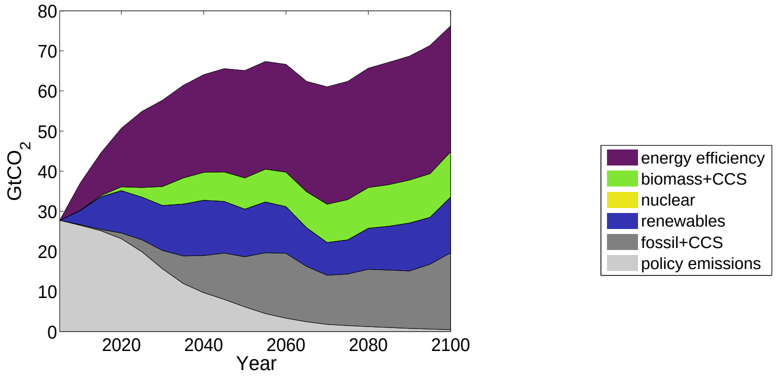
In this section, we will further qualify the contribution of single mitigation options in filling the mitigation gap. The mitigation gap is defined by the amount of baseline emission that has to be reduced in a policy scenario. It can graphically be represented as the area between the emission trajectory of the reference scenario and that of the policy scenario. The entire mitigation gap is filled by so-called mitigation wedges, which represent the contribution of single mitigation options to the reduction of emissions.

Figure 4.47 shows the respective mitigation wedges for the C&C scenario, the No-CCS scenario and the fixed nuclear scenario on a global level. The mitigation option labeled as energy efficiency is a composite that includes the first three options identified in section 4.3 (i.e. lowering energy consumption, modernising the structure of secondary energy, reducing fuels and gases). In the C&C scenario, the cumulated contribution of energy efficiency improvements amounts to approximately 44%, that of renewables and biomass including CCS to 31%. Fossil energy technologies including CCS and nuclear energy fill the remaining mitigation gap by 15% and less than 10%. While the contribution of renewables is equally allocated over time, the contribution of nuclear energy is concentrated on the mid term and that of CCS based fossil energy on the long term.

Within the No-CCS scenario, the cumulated contribution of nuclear energy does not increase much. The share of energy efficiency improvements and renewables increases to more than 57% and 30%, respectively. Within the fixed nuclear scenario, the share of nuclear energy is taken over partly by renewables but mostly by fossil energies with CCS.



(a) Policy scenario A (b) No-CCS scenario



(c) Fixed nuclear scenario

Figure 4.47: Mitigation wedges

Chapter 5

Conclusions

The present report analyses implications of suggestions for the design of post-2012 climate policy regimes on the basis of model simulations. The model REMIND-R serves here as an analysis tool. Macro-economic distribution and/or income effects as well as technological developments in the energy sector can be considered by means of REMIND-R. The focus of the analysis, the determination of regional mitigation costs, also considers the feedbacks between investment and trade decisions of the regions that are linked by different global markets for emission permits, goods and resources. Climate policy regimes based on the following permit allocation schemes were investigated in this report:

- Contraction & convergence
- Intensity target
- Multi-stage approach

These regimes represent alternative designs of an international cap & trade system that is geared to meet the 2°C climate target. Based on the distribution of mitigation costs, the following conclusions can be drawn:

- Ambitious climate targets that meet the 2°C climate target with high likelihood can be reached with costs amounting to approx. 1.5% of the global gross product; this roughly confirms cost estimates of low stabilisation scenarios from earlier studies based on global models (Edenhofer et al., 2006).
- The regional burden of emission reductions considerably varies with the particular designs of a post-2012 climate policy regime; however, the variance of mitigation costs between the regions is higher than between the policy regimes.
- Regions with high shares in trade of fossil resources in the reference case (MEA and Russia) bear highest cost.

- Cap & trade systems based on a GDP-intensity target are more favourable for industrialised countries (except for Russia), the contraction & convergence approach and/or the multi-stage approach are more favourable for developing countries.
- The global average mitigation costs are nearly the same for different allocations of emission permits.
- Africa can considerably benefit from an integration into a global emissions trading system.
- Doing without the nuclear energy option is not costly, but forgoing the CCS option will increase the global mitigation costs by more than one percentage point.

The present study analyses ambitious climate protection scenarios that require drastic reduction policies (emission reductions of 60%-80% globally until 2050). Immediate and multilateral action is needed in such scenarios. Given the rather small variance of mitigation costs in major regions like UCA, Europe, MEA and China, a policy regime should be chosen that provides high incentives to join an international agreement for the remaining regions. From this perspective either the C&C scenario is preferable (Russia) or the multi-stage approach (Africa and India).

All comparative statements are only valid for the concrete forms of policy regimes investigated here. Moreover, all results are only valid within the framework of the assumptions made. Such assumptions are necessary to reduce the model complexity and to restrict the number of scenarios to be analysed.

Important assumptions and/or simplifications are:

- Fossil resources are assumed to be abundant and extractable at moderate costs (the assumption of high-cost fossil resources would tend to lower the mitigation costs as well as the share of fossil energy technologies that will in the long term be operated with CO_2 capturing technology),
- Flexibility of investments in the energy sector (investment restrictions would tend to raise mitigation costs),
- no trade of secondary energy sources (if this trade is permitted, the use of fossil energy technologies will decrease in favour of renewable energy technologies; the mitigation costs would decrease),
- no ”fast breeder” technology,
- Perfect market (a restriction of this assumption could lead to an intensified use of domestic resources, and the mitigation costs could tend to rise),

- Perfect foresight of all representative actors (applies to e.g. the knowledge about the dynamics in the distribution of emission rights; a restriction of this assumption could tend to raise the mitigation costs)
- exogenous non-CO_2 and land use emission scenarios; thereby additional mitigation potential as well as mitigation costs are neglected.

Within this report, a highly advanced analysis of the costs of climate stabilisation based on a state-of-the-art energy-economy-climate model is presented. This analysis is unique due to the degree of consistency. Mitigation costs estimates are based on technological opportunities and constraints in the development of new energy technologies. But most essential, technological change in the energy sector is embedded in a macro-economic environment that by means of investments and trade decisions governs regional developments. All together, this provides a new standard of climate policy decision support.

Chapter 6

Summary

Based on the EU's 2°C climate target, it was the mission of the research project to identify the costs of climate stabilisation. Regional mitigation options and their costs should be analysed under different designs of a post-2012 cap & trade climate policy regime. An advanced multi-region energy-economy-climate model was developed and used for the requested policy analysis. In a first step of model application, we run a baseline scenario and investigated in each region the simulated macro-economic development, trade, technological development, energy production and related CO_2 emissions. In a second step, we analysed the same development parameters for a set of policy scenarios which differ from each other by the permit allocation schemes which follow either the contraction & convergence approach, an intensity target or the multi-stage approach.

A detailed comparison of the three policy regimes focusing on the regional mitigation costs and the mitigation strategies in the energy sector is given in this report. This is supplemented by investigating the contribution of different technological options (e.g. carbon capturing and sequestration) for climate change mitigation. From simulation experiments with REMIND-R, it turns out that the variance of mitigation costs is higher across regions than across policy regimes and that quite different strategies of restructuring the energy system are pursuit by the regions. The 2°C climate target can most likely be reached with average mitigation costs of approx. 1.5% of the global GDP. Doing without the nuclear energy option is not costly, but forgoing the carbon capturing and sequestration option will increase the global mitigation costs by more than one percentage point.

Bibliography

[1] Edenhofer, O., Bauer, N., Kriegler, E. (2005), The impact of technological change on climate protection and welfare: Insights from the model MIND. Ecological Economics 54, 277-292.

[2] Edenhofer, O., Lessmann, K., Kemfert, C., Grubb, M., Köhler, J. (2006), Induced Technological Change: Exploring its Implications for the Economics of Athmospheric Stabilization: Synthesis Report from Innovation Modeling Comparison Project. The Energy Journal, Special Issue 2006, 57-107.

[3] den Elzen, M., Lucas, P.L. (2005), The FAIR model: A tool to analyse environmental and costs implication of regimes of future commitments. Environmental Modeling and Assessment 10, 115-134.

[4] den Elzen, M., Lucas, P., van Vuuren, D. (2005), Abatement costs of post-Kyoto climate regimes. Energy Policy 33, 2138-2151.

[5] Gerlagh, R., van der Zwaan, B. (2003), Gross world product and consumption in a global warming model with endogenous technological change. Resource and Energy Economics 25, 35-57.

[6] Goulder, L., Mathai, K. (2002), Optimal CO2 Abatement in the Presence of Induced Technological Change. Journal of Environmental Economics and Management 39, 1-38.

[7] Grubb, M., Köhler, J., Anderson, D. (2002), Induced Technological Change in Energy and Environmental Modeling. Annual Review of Energy and the Environment 27, 271-308.

[8] Grübler, A., Nakicenovic, N., Victor, D. (1999), Modeling Technological Change: Implications for Global Environment. Annual Review of Energy and the Environment 24, 545-569.

[9] Hare, B., Meinshausen, M. (2004), How much warming are we committed to and how much can be avoided?, PIK-Report No. 94, Potsdam.

[10] Höhne, N., Galleguillos, C., Blok, K., Harnisch, J., Phylipsen, D. (2003), Evolution of commitments under the UNFCCC: Involving newly industrial economies and developing countries, Research Report, UBA-FB 000412, Umweltbundesamt.

[11] IPCC (2000), Special Report on Emissions Scenarios, Special Report of WG III, Intergovernmental Panle on Climate Change.

[12] IPCC (2001), Third Assessment Report, Climate Change 2001. Cambridge University Press, UK, $http://www.grida.no/climate/ipcc\_tar/$.

[13] Jacoby, H.D., Ellerman, A.D., Prinn, R.G., Reiner, D.M., Yang, Z. (1997), QELRO impacts: domestic markets, trade and distribution of burdens, and climate change. Energy Journal 18, 345-387.

[14] Kriegler, E., Bruckner, T. (2004), Sensitivity of emissions corridors for the 21st century. Climatic Change 66, 345-387.

[15] Kypreos, S., Bahn, O. (2003), A MERGE model with endogenous technological progress. Environmental Modelling and Assessment 19, 333-358.

[16] Leimbach, M., Baumstark, L. (2008), The impact of capital trade and technological spillovers on climate policies: Model analysis with REMIND-S, submitted to Environmental and Resource Economics.

[17] Leimbach, M., Toth, F. (2003), Economic development and emission control over the long term: The ICLIPS aggregated economic model. Climatic Change, 56, 139-165.

[18] Löschel, A. (2002), Technnological Change in Economic Models of Environmental Policy: A survey. Ecological Economics 43, 105-126.

[19] Manne, A. S., Rutherford, T. (1994), International trade, capital flows and sectoral analysis: formulation and solution of intertemporal equilibrium models. In: Cooper, W. W. and Whinston, A. B. (eds.), New directions in computational economics, Kluwer Academic Publishers, Dordrecht, The Netherlands, 191-205.

[20] Manne, A.S., M. Mendelsohn, R. Richels (1995), MERGE - A Model for Evaluating Regional and Global Effects of GHG Reduction Policies. Energy Policy 23, 17-34.

[21] Manne, A. S., Richels, R. (1997), On stabilizing CO2 concentrations - cost-effective emission reduction strategies. Environmental Modeling and Assessment 2, 251-265.

[22] Manne, A. S., Barreto, L. (2004), Learning-by-doing and Carbon Dioxide Abatement. Energy Economics 26, 6211-633.

[23] Nakicenovic, N., Riahi, K. (2003), Model runs with MESSAGE in the context of the further development of the Kyoto Protocol. Externe Expertise für das WBGU Sondergutachten ”Welt im Wandel: Über Kyoto hinausdenken. Klimaschutzstrategien für das 21. Jahrhundert”, Berlin 2003. http://www.wbgu.de/wbgu-sn2003-ex03.pdf.

[24] Nordhaus, W.D., Z. Yang (1996), A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies. American Economic Review 86, 741-765.

[25] Petschel-Held, G, Schellnhuber, H.J., Bruckner, T., Toth, F.L., Hasselmann, K. (1999), The tolerable windows approach: theoretical and methodological foundations. Climatic Change 41, 303-331.

[26] Penn World Tables (2007), Version 6.2, http://pwt.econ.upenn.edu/php-site/pwt-index.php

[27] Rose, A., Stevens, B., Edmonds, J, Wise, M. (1998), International equity and differentiation in global warming. Environmental and Resource Economics 12, 25-51.

[28] World Development Indicators (2005), World Bank, Washington, DC.

[29] Weyant, J. P. (2004), Introduction and overview. Energy Economics, 26, 501 - 515.