Description of the ReMIND-R model

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1 Overview

REMIND-R is a global energy-economy-climate model. This model description is based on the introduction of the REMIND-R model in Leimbach et al. (2009), as well as the technical description in Bauer et al. (2008) and Bauer et al. (2010). More information is also available from the ReMIND-website[1].

Figure 1 provides an overview of the general structure of ReMIND-R. The macro-economic core of ReMIND-R is a Ramsey-type optimal growth model in which intertemporal global welfare is optimized subject to equilibrium constraints. It considers 11 world regions and explicitly represents trade in final goods, primary energy carriers, and, in the case of climate policy, emission allowances. It is formulated such that it yields a distinguished Pareto-optimal solution which corresponds to the market equilibrium in the absence of non-internalized externalities. For macro-economic production, capital, labor and energy are considered as input factors. The macro-economic output is available for investment into the macro-economic capital stock, consumption, trade, and costs incurred from the energy system.

The macro-economic core is hard-linked to the energy system module. Economic activity results in demand for final energy such as transport energy, electricity, and non-electric energy for the stationary end-uses. The demand for final energy is determined via nested constant elasticity of substitution (CES) production function (cf. Section 2.1). The energy system module considers endowments of exhaustible primary energy resources as well as renewable energy potentials. A substantial number (~50) of technologies are available for the conversion of primary energies to secondary energy carriers. Moreover, capacities for transport and distribution of secondary energy carriers for final end use are represented. The costs for the energy system, including

[1] At http://www.pik-potsdam.de/research/research-domains/sustainable-solutions/remind-code-1 the technical description of REMIND-R is available. REMIND-R is programmed in GAMS. The code is available from the authors on request.

investments into capacities, operation and maintenance costs as well as extraction and fuel costs appear in the macroeconomic budget function, thus reducing the amount of economic output available for consumption.

The model system also includes a climate module. In addition to CO_2 emissions from the combustion of fossil fuels, other greenhouse gas emissions are determined via marginal abatement costs curves or by assuming exogenous scenarios. A rather simple reduced form climate model is used in the current version of ReMIND-R (cf. Section 4). The integration of the more complex climate module ACC2 (Tanaka and Kriegler, 2007) is under way, but its deployment is subject to computational constraints.

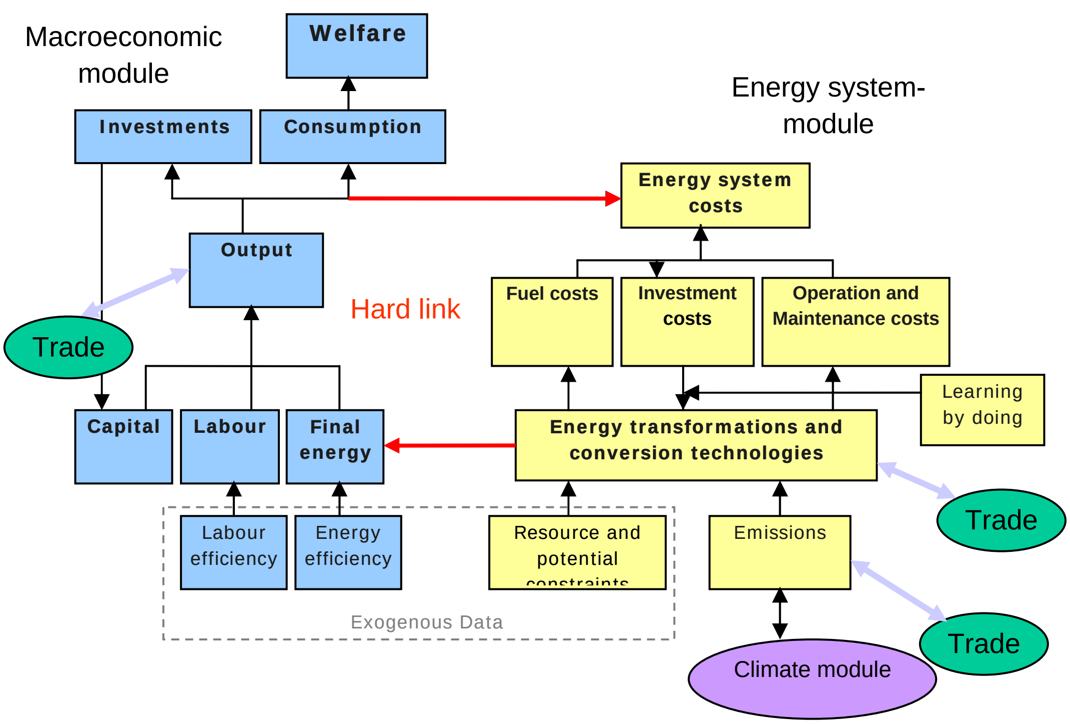

Figure 1: Overall structure of the ReMIND-R model

In particular in terms of its macro-economic formulation, REMIND-R resembles well-known energy-economy-climate models like RICE (Nordhaus and Yang, 1996) and MERGE (Manne et al., 1995; Kypreos and Bahn, 2003). REMIND-R is distinguished from these models by a high technological resolution of the energy system and intertemporal trade relations between regions. This results in a high degree of where-flexibility (abatement can be performed where it is cheapest) and what-flexibility (optimal allocation of abatement among end-use sectors) for the mitigation effort

Description of the ReMIND-R model

Table 1 provides an overview of the key features of the model. The individual modules along with relevant parameters and assumptions are described in more detail in the following sections.

key distinguishing feature	**ReMIND-R**
Macro-economic core and solution concept	Intertemporal optimization: Ramsey-type growth model, Negishi approach for regional aggregation
Expectations/Foresight	Default: perfect foresight.
Substitution possibilities within the macro-economy / sectoral coverage	Nested CES function for production of generic final good from basic factors capital, labor, and different end-use energy types
Link between energy system and macro-economy	Economic activity determines demand; energy system costs (investments, fuel costs, operation and maintenance) are included in macro-economic budget constraint. Hard link, i.e. energy system and macro-economy are optimized jointly.
Production function in the energy system / substitution possibilities	Linear substitution between competing technologies for secondary energy production. Supply curves for exhaustibles (cumulative extraction cost curves) as well as renewables (grades with different capacity factors) introduce convexities.
Land use	MAC curves for deforestation
International macro-economic linkages / Trade	Single market for all commodities (fossil fuels, final good, permits)
Implementation of climate policy targets	Pareto-optimal achievement of concentration, forcing or temperature climate policy targets under full when-flexibility. Allocation rules for distribution of emission permits among regions. Other options: Emission caps & budgets, taxes equivalent.
Technological Change / Learning	Learning by doing (LbD) for wind and solar. A global learning curve is assumed. LbD spillovers are internalized. Labor productivity and energy efficiency improvements are prescribed exogenously.
Representation of end-use sectors	Three energy end-use sectors: Electricity production, stationary non-electric, transport
Cooperation vs. non-cooperation	Pareto: full cooperation
Discounting	Constant rate of pure time preference (3%)
Investment dynamics	Capital motion equations, vintages for energy supply technologies, adjustment costs for acceleration of capacity expansion in the energy system

Table 1: Overview of key characteristics of the ReMIND-R model.

2 The Macro-Economic Kernel and Solution Concept

REMIND-R as introduced by Leimbach et al. (2009) is a multi-regional hybrid model which couples an economic growth model with a detailed energy system model and a simple climate model. The hard-link between the energy system and the macroeconomic system follows the method by Bauer et al. (2008). Assuming perfect foresight and aiming at welfare maximization, REMIND-R simulates the world-economic dynamics over the time horizon 2005 to 2150 with a time step of five years. In order to avoid distortions due to end-effects, our analysis focuses on the results for the time span 2005-2100.

In its present version, ReMIND-R distinguishes 11 world regions (Figure 2):

- USA - USA
- EUR - EU27
- JAP - Japan
- CHN - China
- IND - India
- RUS - Russia
- AFR - Sub-Saharan Africa (excl. Republic of South Africa)
- MEA - Middle East, North Africa, central Asian countries
- OAS - Other Asia (mostly South East Asia)
- LAM - Latin America
- ROW - Rest of the World (Canada, Australia, New Zealand, Republic of South Africa, Rest of Europe).

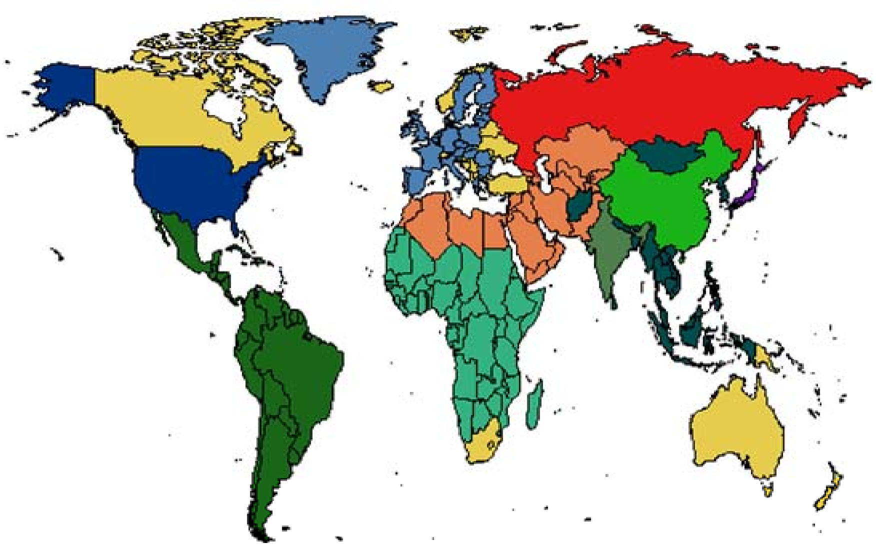

Figure 2: ReMIND-R region definitions.

2.1 Objective function and production structure

Each region is modeled as a representative household with a utility function that depends upon per capita consumption:

$$U_r = \sum_t e^{-\rho t} L_{rt} \log\left(\frac{C_{rt}}{L_{rt}}\right),$$

where L_t and C_t are population and consumption and time t, respectively. Utility calculation is subject to discounting. We assume a pure rate of time preference ρ of 3 %. The logarithmic functional relation between per-capita consumption and utility implies an elasticity of marginal consumption of 1. Thus, in line with the Keynes-Ramsey-Rule, ReMIND-R yields an endogenous interest rate in real terms of 5-6% for an economic growth rate of 2-3%. This is well in line with interest rates typically observed on capital markets.

It is the objective of REMIND-R to maximize a global welfare function that results as a weighted sum of the regional utility functions:

$$W = \sum_r n_r U_r \,.$$

The weights n_r (also called Negishi weights) are chosen such that the sum of the discounted value of exports equals that of the imports over the time horizon considered. Numerically, this clearing of each region’s intertemporal trade balance is achieved via an iterative algorithm. It ensures that the Pareto-optimal solution of the model corresponds to the market equilibrium in absence of non-internalized externalities (cf. Section 2.2).

Marco-economic output, i.e. gross domestic product (GDP), of each region is determined by a "constant elasticity of substitution" (CES) function of the production factors labor, capital and end use energy. The end use energy of the upper production level is calculated as a production function which comprises transportation energy and stationary used energy. Both are connected by a substitution elasticity of 0.3. These two energy types are in turn determined by means of nested CES functions of more specific final energy types (see Figure 3). Substitution elasticities between 2.5 and 3 hold for the lower levels of the CES nest. An efficiency parameter is assigned to each production factor in the various macroeconomic CES functions. Changes in the efficiency of the individual production factors for each region are given by exogenous scenarios.

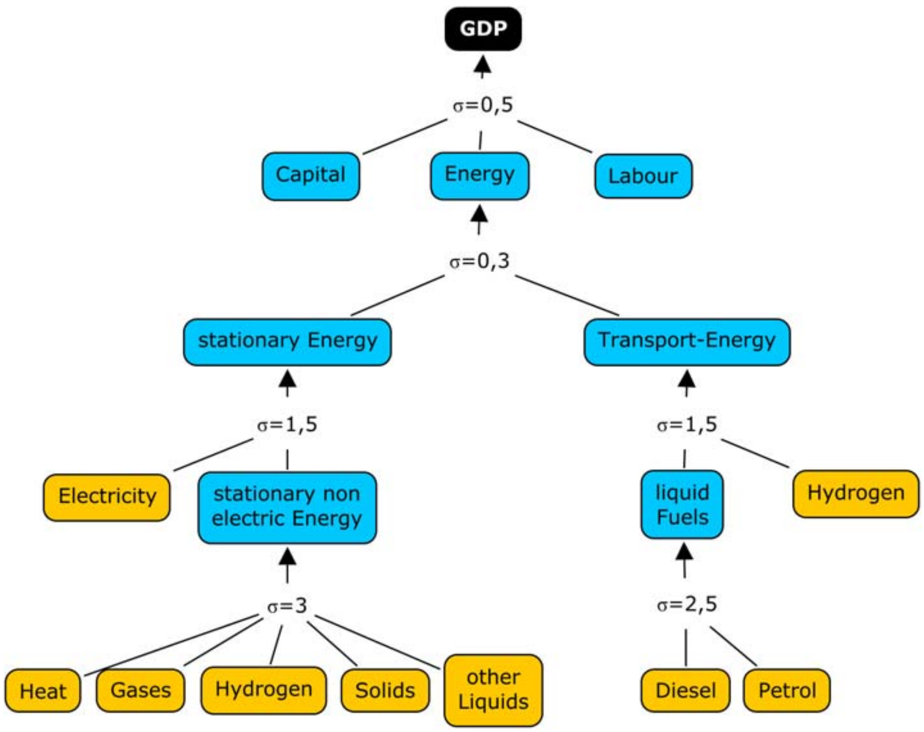

Figure 3: CES production structure in the macroeconomic module.

In each region, produced GDP $Y(t)$ is used for consumption $C(t)$, investments into the macroeconomic capital stock $I(t)$, energy system expenditures and for the export of composite goods X_G. Energy system expenditure consist of fuel costs $G_F(t)$, investment costs $G_I(t)$ and operation & maintenance costs $G_O(t)$. Imports of the composite good M_G increase the available GDP:

$$Y(t) - X_G(t) + M_G(t) \geq C(t) + I(t) + G_F(t) + G_I(t) + G_O(t)$$

This balance of GDP distribution forms the budget constraint each region is subjected to. Macroeconomic investments enter a conventional capital stock equation with an assumed depreciation rate of 5 %.

2.2 Trade

In following the classical Heckscher-Ohlin and Ricardian models (Flam and Flanders, 1991), trade between regions is induced by differences in factor endowments and technologies. In ReMIND-R, this is supplemented by the possibility of intertemporal trade. However, there is no bilateral trade, but exports in and imports from a common pool. Trade is modeled in the following goods:

- Coal
- Gas
- Oil
- Uranium
- Composite good (aggregated output of the macro-economic system)
- Permits (emission rights), in the case of climate policy

Intertemporal trade and the capital mobility implied by trade in the composite good cause factor price equalization and provide the basis for an intertemporal and interregional equilibrium.

In REMIND-R, the balance between exports and imports for each kind of goods in each period is guaranteed by adequate trade balance equations. However, the question whether a 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 intertemporal budget constraint each region is subject to means that each composite goods 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 in a similar way. In the default setting, the presence of a global carbon market is assumed: Initial allocation of emission rights are determined by a burden sharing rule, and permits can be traded freely among world regions. A permit constraint equation ensures that each unit of CO_2 emitted by combusting fossil fuels is 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 specialization and, related to the cooperative setting implied by the solution concept, to rather optimistic results. For climate policy assessments this is less critical as it applies to both baseline and policy scenarios.

2.3 Climate policy analysis

The ReMIND model is usually run in two modes.

- A “business as usual” mode in which the global welfare function is optimized without constraints. This resembles a situation where the occurrence of climate change would have no effect on the economy and the decisions of the representative households in the regions.
- A “climate policy” mode where an additional climate policy constraint is imposed on the welfare optimization. The constraint can take the form of a limit on

temperature, forcing (from Kyoto gases or all radiative substances), CO2 concentration, cumulative carbon budget, or CO2 emissions over time. The mitigation costs of reaching the policy goal to meet the climate constraint is calculated as percentage reduction of net present value consumption or GDP w.r.t. to the business as usual case.

The impact of a pre-specified carbon tax can also be studied in ReMIND, although it is less straightforward. This requires the implementation of the tax as a penalty on emissions. This tax as part of each region's budget constraint is counterbalanced by an fixed amount of tax revenues. The model is solved iteratively with adjusted tax revenues until these match the tax payments.

3 The energy system

The energy system module (ESM) of ReMIND-R comprises a detailed description of energy carriers and conversion technologies. The ESM is embedded into the macroeconomic growth model: the techno-economic characteristics and the system of balance equations that set up the energy system are constraints to the welfare maximization problem of the macroeconomic module.

The energy system can be considered as an economic sector with a heterogenous capital stock that demands primary energy carriers and supplies secondary energy carriers. The structure of the capital stock determines the energy related demand-supply structure. The macro-economy demands final energy as an input factor for the production of economic output. In return, the energy sector requires financial resources from the capital market that are allocated among a portfolio of alternative energy conversion technologies. The techno-economic characteristics of the technologies and endogenously evolving prices of energy and CO_2 emissions determine the size and structure of the energy sector capital stock. Hence, the energy sector develops according to an equilibrium relationship to the remaining economy with which it is interrelated through capital and energy markets.

3.1 Primary energy resources

The primary energy carriers available in the ESM include both exhaustible and renewable resources:

- Coal
- Oil

- Gas
- Uranium
- Hydro
- Wind
- Solar
- Geothermal
- Biomass

The exhaustible resources (coal, oil, gas and uranium) are characterized by extraction costs that increase over time as cheaply accessible deposits become exhausted. In ReMIND-R, this is represented via region-specific extraction cost curves which prescribe increasing costs of energy production with increasing cumulative extraction. These resources are assumed to be fully tradable across regions. This implies that the extraction occurs in an globally optimal sequence, with cheapest deposits exploited first.

By contrast, renewable energy sources do not deplete over time. They are represented via region-specific potentials. For each renewable energy type, the potentials are classified into different grades, each of which is characterized by a specific capacity factor. Superior grades feature high capacity factors and will produce more energy for a given installed capacity, while inferior grades will have lower yields. As a result of the optimization, this grade structure leads to a gradual expansion of renewable energy deployment over time.

The potentials for solar PV and CSP are based on DLR (2009). To account for the competition of PV and CSP for certain sites, an additional constraint for the combined deployment of PV and CSP was introduced (Pietzcker et al., 2009). The total solar potential is as high as 10 000 EJ/yr, with almost half of it located in Africa.

Global potentials for onshore wind are assumed to be 120 EJ/yr. This value is twice the potential estimated by WBGU (2003), and about half that given by De Vries et al. (2006). Regional disaggregation is based on Hoogwijk (2004). An additional resource potential of 40 EJ was assumed for offshore wind. Since offshore wind is not represented explicitly in the present version of ReMIND-R, the offshore wind potential was added to the potential for conventional wind energy, albeit at an investment cost penalty of 50%.

Global potentials of hydro-power are based on WBGU (2003) and disaggregated into regional potentials based on Hoogwijk (2004).

3.2 Secondary energy carriers and energy conversion matrices

Secondary energy carriers considered in ReMIND-R include:

- Electricity

- Heat
- Hydrogen
- Other liquids
- Solid fuels
- Gases
- Transport fuel petrol
- Transport fuel diesel

In the present version of ReMIND-R, electricity is only demanded for stationary use. An implementation of electrification of the transport sector is under way.

The most notable part of the energy system is the conversion of primary energy into secondary energy carriers via specific energy conversion technologies. In total, some 50 different energy conversion technologies are represented in ReMIND-R. The energy conversion matrix in Table 2 provides an overview of the primary energy types, secondary energy types and relevant conversion technologies between them.

		PRIMARY ENERGY CARRIERS						
		Exhaustible				**Renewable**		
		Coal	**Oil**	**Gas**	**Ura-nium**	**Solar, Wind, Hydro**	**Geo-thermal**	**Bio-mass**
SECONDARY ENERGY CARRIERS	**Electricity**	PC, IGCC	DOT	NGCC	LWR, *Gen IV Fast Reactors*	SPV, WT, Hydro, *CSP*	HDR	BIGCC
	H2	C2H2		SMR				B2H2
	Gases	C2G		GasTR				B2G
	Heat	CoalHP, CoalCHP		GasHP, GasCHP			GeoHP	BioHP, BioCHP
	Liquid fuels	C2L	Refin.					B2L Bioethanol
	Other Liquids		Refin.					
	Solids	CoalTR						BioTR

Abbreviations: PC = conventional coal power plant, IGCC = integrated coal gasification combined cycle, CoalCHP = coal combined hat power, C2H2 = coal to H2, C2G = coal to gas, CoalHP = coal heating plant, C2L = coal to liquids, CoalTR = coal transformation, DOT = diesel oil turbine, Refin. = Refinery, GT = gas turbine, NGCC = natural gas combined cycle, GasCHP = Gas combined heat power, SMR = steam methane reforming, GasTR = gas transformation, GasHP= gas heating plant, LWR = light water reactor, SPV = solar photo voltaic, WT = wind turbine, Hydro = hydro power, HDR = hot-dry-rock, GeoHP = heating pump, BioCHP = biomass combined heat and power, BIGCC = Biomass IGCC, B2H2 = biomass to H2, B2G = biogas, BioHP = biomass heating plant, B2L = biomass to liquids, BioEthanol = biomass to ethanol, BioTR = biomass transformation

Table 2: The energy conversion matrix - overview on primary and secondary energy carriers and the available conversion technologies. Yellow colors indicate that technologies can be combined with CCS.

Coal and biomass are highly flexible primary energy carriers since all types of secondary energy can be produced from them. Crude oil and natural gas are mainly used to produce liquids and gases. Renewable energy carriers other than biomass are well suited for the production of electricity, but they are less suited to produce other secondary energy carriers. Renewable energy sources including biomass are assumed to be non-tradable.

In the default setting, all secondary energy carriers are assumed to be non-tradable across regions, while statistical data indicates that liquid fuels are traded globally. However, the scale of trade in refined fuels is relatively small compared to trade in crude oil. Since the ReMIND-R model considers crude oil to be tradable the bias is limited. Secondary energy carriers are converted into final energy carriers by considering mark-ups for transmission and distribution. Final energy is demanded by the macro-economic sector and rewarded with equilibrium prices. Note that in the present ReMIND-R version, the end use sectors household and industry are aggregated to the stationary sector. Hence, we distinguish the stationary and the transport sector as final energy demanding sectors.

All technologies are represented in the model as capacity stocks. Since there are no constraints on the rate of change in investments, the possibility of investing in different capital stocks provides high flexibility of the technological evolution. Nevertheless, every additional energy production (either based on existing or new technologies) needs investments in capacities in advance. Moreover, the model does not allow for idle capacities. The lifetime of capacities differs between various types of technologies. Depreciation rates are quite low in the first two decades, and increase afterwards.

Each region is initialized with a vintage capital stock calibrated to meet the input-output relations given by IEA energy statistics (IEA 2007a,b). The technical transformation coefficients for new vintages are the same for all regions and 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.

Ambitious mitigation targets typically result in substantial expansion of renewables, mostly solar and wind. Techno-economic parameters for electricity generation from renewable energy sources are given in Table 3. Wind, solar PV and CSP feature learning by doing, i.e. specific investment costs decrease by 12, 20, 9%, respectively, for each doubling of capacity.

	Lifetime [Years]	Investment costs [$US/kW]	Floor costs [$US/kW]	Learning Rate [%]	Cumulative capacity 2005 [GW]	O&M costs [$US/GJ]
Hydro	95	3000	-	-	-	4.23
Geo HDR	35	3000	-	-	-	4.2
Wind	40	1200	883	12	60	0.89
SPV	40	4900	650	20	5	2.33
CSP	40	9000	2000	9	0.4	

Table 3: Techno-economic characteristics of technologies based on non-biomass renewable energy sources. For details see Neij (2003), Nitsch et al. (2004), IEA (2007a), Junginger et al. (2008), Lemming et al. (2008).

	Units	Daily variation	Weekly variation	Seasonal variation
Technology		Redox-Flow-batteries	H2 electrolysis + combined cycle gas turbine	Capacity penalty to secure supply
Efficiency	[%]	80	40	
Storage capacity	[Hours]	12	160	
Investment costs	[$US/kW]	4000	6000	
Floor costs	[$US/kW]	1000	3000	
Learning rate	[%]	10	10	
Cumulative capacity in 2005	[TW]	0.7	0.7	
Life time	[Years]	15	15	
Cheaper technologies but not included due to limited potential		Pump-storage hydro & compressed air storage	Pump-storage hydro & compressed air storage	

Table 4: Techno-economic parameters of storage technologies; based on Chen et al. (2009) and expert interviews.

The fluctuating renewable electricity sources wind and solar PV require storage to guarantee stable supply of electricity; see Pietzcker et al. (2009). Since the techno-economic parameters applied for CSP include the costs for thermal storage to continue electricity production at night-time, CSP is assumed not to require any further storage for balancing fluctuations.

The approach implemented into the ReMIND model distinguishes between variations on the daily, weekly and seasonal time scale. The general idea of storage is that increasing market shares of fluctuating energy sources increase the need for storage because balancing the fluctuations becomes ever more important to guarantee stable electricity supply. The superposition of variations on the three time scales is completely represented. Daily and weekly variations are compensated by explicit installation of storage plants; the techno-economic parameters are provided in Table 4. Seasonal variations demand a penalty on the capacity factors; i.e. a certain fraction of the capacity remains unused due to over-supply. By 2050, the storage requirement results in a markup in investment cost of typically about 20% for wind and 30% for solar PV.

Techno-economic parameters for technologies based on exhaustible resources and biomass are listed in Table 5. A relevant mitigation option for the power sector, albeit typically somewhat less dominant than renewables, is the expansion of nuclear energy. Investment costs for nuclear power plants are set to 3000 $US/kW. In the present version, only thermal nuclear reactors are considered. The use of nuclear is largely constrained by limited competitiveness vis-à-vis renewable electricity sources as well as limited resource potentials for uranium. No external effects such as the risk of nuclear accidents or risks arising from nuclear waste are considered.

Emissions from fossil fuel combustion can be curbed by deploying carbon capture and storage (CCS). In ReMIND-R CCS technologies exist both for generating electricity as well as for the production of liquid fuels, gases and hydrogen from coal. Moreover, biomass can be combined with CCS to generate net negative emissions. Such bioenergy CCS (BECCS) technologies are available for electricity generation (biomass integrated gasification combined cycle power plant), biofuels (biomass liquefaction), hydrogen, and syngas production. The sequestration of captured CO_2 is represented explicitly in ReMIND-R with costs for transportation and storage based on Bauer (2005). While the overall global CO_2 storage potential is estimated to be as high as 1000 GtC, the regional potentials for the EU (50 GtC), Japan (20 GtC) and India (50GtC) constrain the deployment of CCS technologies significantly in these regions.

		Life-time	Investment costs		O&M costs		Conversion efficiency		Capture Rate
		[Years]	[$US/kW]		[$US/GJ]		[%]		[%]
			No CCS	With CCS	No CCS	With CCS	No CCS	With CCS	With CCS
Coal	PC	55	1400	2400	2.57	5.04	45	36	90
	Oxyfuel	55		2150		4.32		37	99
	IGCC	45	1650	2050	3.09	4.20	43	38	90
	C2H2*	45	1264	1430	1.65	1.87	59	57	90
	C2L*	45	1000	1040	1.99	2.27	40	40	70
	C2G	45	900		0.95		60		
Gas	NGCC	40	650	1100	0.95	1.62	56	48	90
	SMR	40	498	552	0.58	0.67	73	70	90
Biomass	BIGCC *	40	1860	2560	3.95	5.66	42	31	90
	BioCHP	40	1700		5.06		43.3		
	B2H2*	40	1400	1700	5.27	6.32	61	55	90
	B2L*	40	2500	3000	3.48	4.51	40	41	50
	B2G	40	1000		1.56		55		
Nuclear	TNR	40	3000		5.04		33~		

Table 5: Techno-economic characteristics of technologies based on exhaustible energy sources and biomass (cf. Iwasaki (2003), Hamelinck (2004), Bauer (2005), MIT (2007), Ragettli, (2007), Rubin et al. (2007), Schulz (2007), Uddin and Barreto (2007), Takeshita and Ymaij (2008), Guel et al. (2007), Brown et al. (2009), Chen and Rubin (2009), Klimantos et al. (2009)).

*Abbreviations analogous to Table 1. Technologies marked with * represent joint production processes. For these processes, investment cost and efficiency penalties for capturing can be rather small. ~ a thermal efficiency of 33% is assumed for thermal nuclear reactors.*

		SECONDARY ENERGY CARRIERS						
		Electricity	**H2**	**Gases**	**Heat**	**Liquid Fuels**	**Other liquids**	**Solids**
SECONDARY ENERGY CARRIERS	**Electricity**	-						
	H2	Electrolysis	-					
	Gases			-				
	Heat				-			
	Liquid fuels					-		
	Other Liquids						-	
	Solids							-

Table 6: Matrix for energy conversion from secondary to secondary energy carrier.

The only technology represented in ReMIND-R for conversion from secondary energy to secondary energy is the production of hydrogen from electricity via electrolysis (Table 6).

3.3 From secondary energy to final energy

The distribution of energy carriers to end use sectors forms the interface between the macro-economic module and the energy system module. ReMIND-R distinguishes between the stationary end-use sector (aggregating industry and residential/buildings) and end use in the transport sector. Secondary energy carriers available for supply in the stationary sector are electricity, heat, solids, gases, liquids, and hydrogen. The transport sector consumes diesel, petrol, and hydrogen. An implementation of electricity use in the transport sector is under way. Transport and distribution of secondary energy carriers is represented via capacities that require investments and incur costs for operation and maintenance.

In the present version of ReMIND-R, no energy services (such as transportation service in passenger km) are represented.

		END-USE SECTORS	
		Stationary	**Transport**
SECONDARY ENERGY CARRIERS	**Electricity**	Transport and distribution	
	H2	Transport and distribution	Transport and distribution
	Gases	Transport and distribution	
	Heat	Transport and distribution	
	Diesel		Transport and distribution
	Petrol		Transport and distribution
	Other Liquids	Transport and distribution	
	Solids	Transport and distribution	

Table 7: Matrix representing distribution of secondary energy to end-use sectors.

4 Climate module

The present version of REMIND-R includes a rather simple reduced-form climate model similar to the DICE model. The model includes an impulse-response function with three time scales for the carbon-cycle, and an energy balance temperature model with a fast mixed layer and a slow deep ocean temperature box. The carbon cycle – temperature model is amended by equations describing the concentration and radiative forcing resulting from CH4 and N2O as well as sulphate aerosols and black carbon (Tanaka and Kriegler, 2007; Lüken et al., 2010). The emission of sulphates is directly linked to the combustion of fossil fuels in the energy sector. CO_2 emissions from land-use changes as well as emissions of CH4 and N2O are calculated based on marginal abatement costs curves (Lucas et al., 2006). The climate module determines the atmospheric CO_2 concentration and considers the impact of greenhouse gas emissions and sulphate aerosols on the level of global mean temperature. The climate sensitivity - as the most important parameter of the climate module – is set to 3.0°C. The integration of the more complex climate module ACC2 (Tanaka and Kriegler, 2007) is under way, but its deployment is subject to computational constraints.

	REMIND
CO_2 fuel combustion	By source
other CO_2 industry	Exog.
CO_2 LUC	MAC
CH_4	MAC
N_2O	MAC
CFCs	Exog.
PFCs	Exog.
SF_6	Exog.
Montreal gases	Exog.
CO	Exog.
NO_x	Exog.
VOC	Exog.
SO_2	Coupled to CO_2
Fossil fuel burning BC	Exog. / Coupled to CO_2 depending on climate module
Fossil fuel burning OC	
Biomass burning BC	Exog.
Biomass burning OC	Exog.
Nitrate	Exog.
Mineral dust	Exog.
Albedo	Exog.

Table 8: Overview of the treatment of radiative forcing components in the climate module.

5 Key strengths and caveats

Since ReMIND-R is a hard-linked coupled multi-regional energy-economy model it can fully capture the interactions between economic development, trade, and climate mitigation policy. The full macro-economic integration is particularly valuable for the assessment of the regional distribution of mitigation costs.

The central strength of ReMIND-R is its ability to calculate first-best mitigation strategies that provide benchmark development pathways against which mitigation scenarios under sub-optimal settings can be compared. In particular, in its default setting ReMIND-R features

- full *where-flexibility* due to interregional trade of goods and emission permits;
- full *when-flexibility* due to the intertemporal optimization and the endogenous choice of a welfare-optimizing emission reduction trajectory;
- *what-flexibility* within the energy system due to a fully integrated perspective on primary energy endowments and end-use demand. An improved representation of non-CO_2 greenhouse gases is under development.

The fully integrated, hard-linked formulation of ReMIND-R along with the intertemporal optimization make the model numerically very heavy. This computational complexity puts a hard limit to the amount of detail that can be represented in the model. In particular, the following caveats exist:

- The spatial resolution of the model is limited to 11 world regions. Many relevant sub-scale processes, particularly in terms of infrastructure for power grids, transportation, pipelines etc. are not resolved explicitly.
- Electricity from renewables such as wind and solar is characterized by strong fluctuations of supply. The challenge of integrating these intermittent power sources into the grid is represented rather crudely (cf. Section 3.2).
- The demand for final energy is represented via the macro-economic production function. This approach lacks detail on the level of energy consuming activities. Demand side efficiency is therefore exogenously prescribed (via efficiency parameters that change over time) or parameterized as substitution within the production system. This approach can only to a limited extent capture the real-world efficiency potentials (e.g. McKinsey, 2007).
- Technological change in the macro-economic module is exogenously driven. Consequently, climate policy relevant feedbacks from knowledge accumulation and technological spillovers are missing.
- In particular for ambitious climate policy scenarios, the availability of substantial amounts of bioenergy is critical. Such massive up-scaling of bioenergy production may have strong implication for conservation and food security. An effort is underway to soft-couple ReMIND to the land-use model MAgPIE (Lotze-Campen et al., 2008), in order to explore constraints and side-effects to bioenergy production.

6 Model Applications

6.1 Analysis of decarbonization pathways in an integrated framework

Numerous interactions exist between climate policy, the energy system, and global macro-economic development. A central strength of ReMIND is the analysis of these interactions in an integrated framework. Figure 4 displays exemplary primary energy and electricity mixes as simulated by ReMIND-R. Leimbach et al. (2009) used ReMIND-R to assess the interrelations of climate policy and trade. In the context of the RECIPE project, a detailed analysis of the interplay of decarbonization strategies in different sectors was performed (Luderer et al., 2009). Moreover, the change of investment patterns required for a low-carbon transition was analyzed in this study (Figure 5).

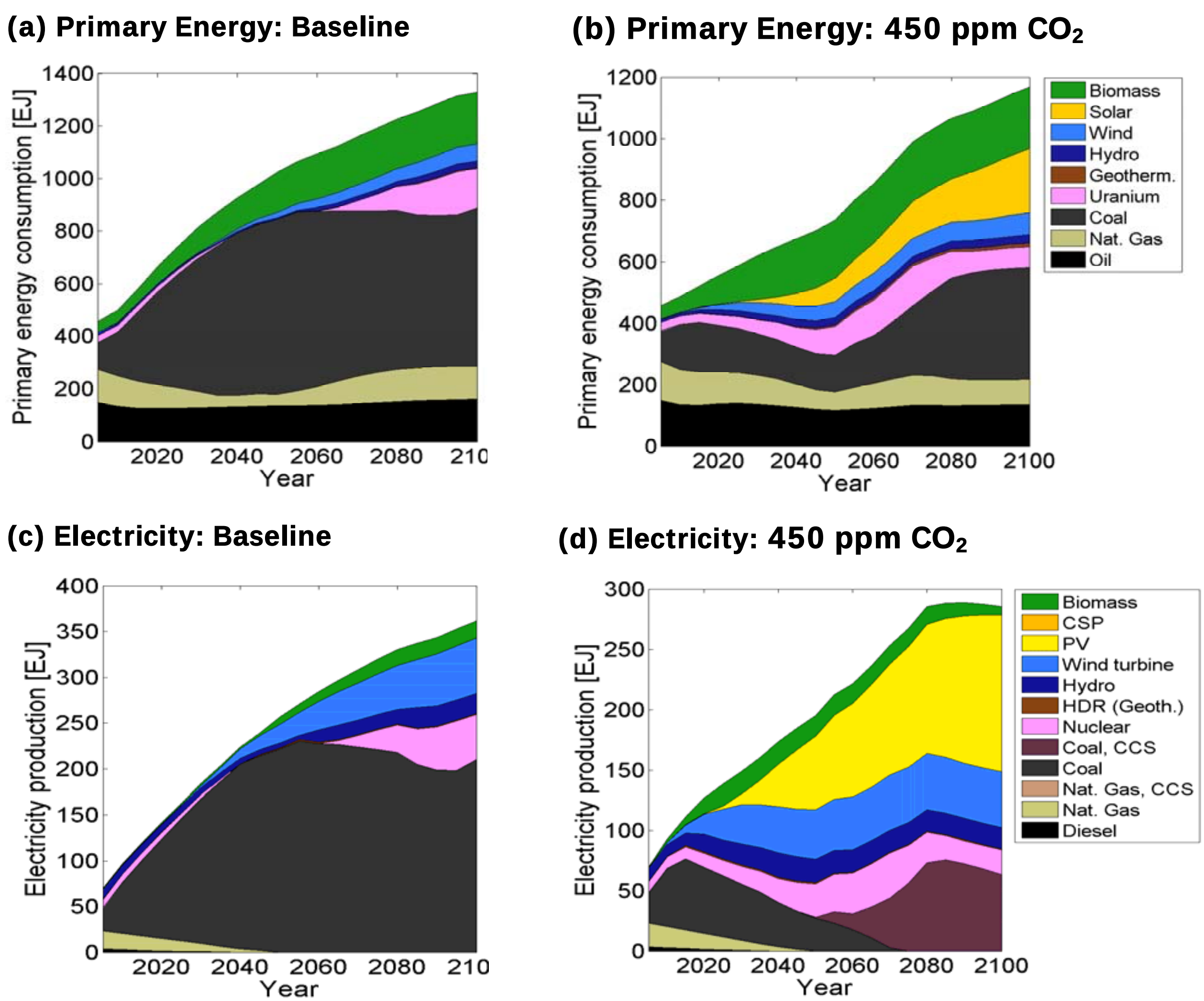

Figure 4: Sample primary energy and electricity mixes for baseline and policy (450 ppm CO_2 only stabilization target.

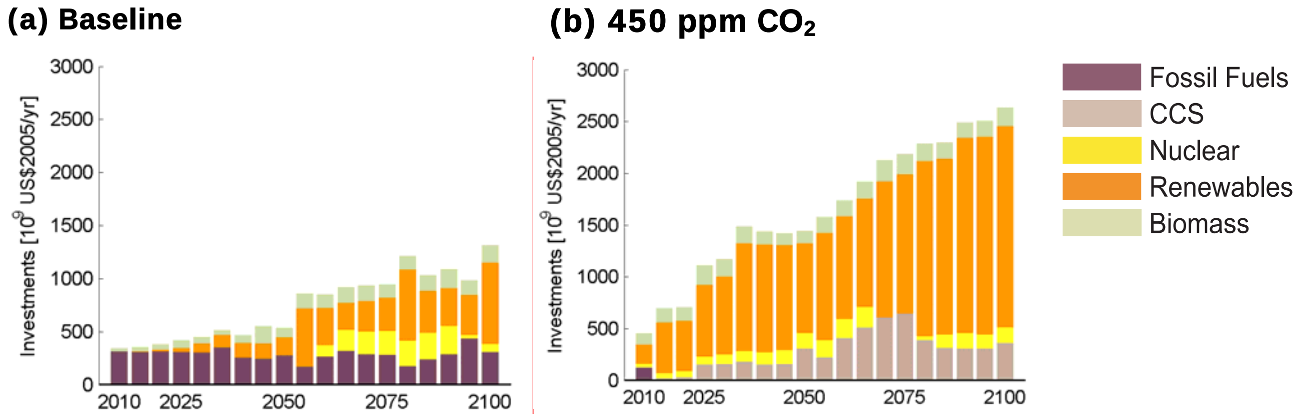

Figure 5: Energy system investment for baseline (a) and 450 ppm CO_2 only stabilization scenario.

6.2 Regional distribution of mitigation costs

While a large body of literature addresses the global costs of climate change mitigation, the regional distribution of costs remains largely unexplored. Since ReMIND-R is a fully coupled energy-economy model with explicit representation of relevant technologies, resource endowments and trade, it is excellently suited for such an analysis.

First analyses of regional mitigation costs for different climate policy regimes were presented by Leimbach et al. (2008). A detailed analysis performed in the context of RECIPE (Luderer et al., 2009) shows that regional mitigation costs can depart substantially from the global mean. The cost distribution can be decomposed into (1) differences in domestic abatement costs, (2) effects related to shifts in trade volumes and prices of fossil energy carriers, and (3) financial transfers in the context of a global carbon market. The first component relates to structural differences in abatement costs and the potential for low-carbon technologies, for instance renewable potentials. The second component is particularly important for the large exporters of fossil fuels, like Russia and the Middle East. The third component depends not only critically on the international burden sharing and institutional framework, but also on the price of carbon, which in turn depends on the stabilization target and low-carbon technology innovations. Based on an analysis with ReMIND, Lueken et al. (2009) showed that the portfolio of technologies strongly influences the regional distribution of mitigation costs. A notable conclusion is that under a restricted technology portfolio the initial allocation of emission permits among nations has a greater influence on mitigation costs than under full availability of all relevant low-carbon options.

6.3 Exploration of very low stabilization targets

The international community is committed to limit global warming to no more than 2°C. Achieving this target with a high probability requires stabilizing greenhouse gases at less than 450 ppm CO_2eq. As part of the ADAM model intercomparison exercise, the cost and feasibility of an emission reduction trajectory that aims at 450 ppm CO_2eq by 2100 and 400 ppm CO_2eq by 2150 was explored. ReMIND, along with four other participating models, found such ambitious mitigation pathways to be feasible, albeit contingent upon the large-scale availability of technologies to generate negative emissions.

The results suggest that stabilization in line with the 2°C target is feasible in terms of technologies and moderate in costs. While a broad range of technologies are required for climate change mitigation, very low stabilization relies particularly heavily on the availability of Carbon Capture and Storage (CCS) in combination with biomass as options for removing carbon from the atmosphere.

6.4 Analysis of first-best vs. second best mitigation strategies

ReMIND is characterized by a high degree of flexibility and a large number of mitigation options. Assuming limited global cooperation on climate change mitigation or constraining the portfolio of mitigation options allows us to explore explicitly the increases in mitigation costs and changes in decarbonization pathways under imperfect settings.

As part of the ADAM project Knopf et al. (2009) and Leimbach et al. (2010) assessed the cost and achievability of climate mitigation targets under restricted technology portfolios for a 550 and 400 ppm CO_2eq stabilization target (Figure 6). Similarly, in the context of the RECIPE project, technology constraints for a 450 ppm CO_2 only target were assessed (Luderer et al., 2009). A robust conclusion across different stabilization scenarios and models is that restricting the deployment of renewables and CCS results in a substantial increase of mitigation costs, while limiting the expansion of nuclear power has a comparatively small effect. With increasing stringency of the target, biomass and CCS become increasingly important. This is due to the fact that combining bioenergy with CCS can generate negative emissions and therefore is pivotal for low stabilization scenarios.

Further analysis performed in RECIPE addressed the consequences of a delay in the setup of an international climate policy regime (Edenhofer et al., 2009). The study found that postponing climate policy action beyond 2020 will render the 450 ppm CO_2only unattainable. If a climate policy regime in place by 2020, the target can be achieved, albeit at 40% higher costs than in the case of immediate action. The analysis also showed that there is a benefit for world regions to adopt climate policies early. For instance, the EU benefits from taking action immediately while others wait until 2020, compared to a scenario in which all world regions delay action until 2020 (Figure 7).

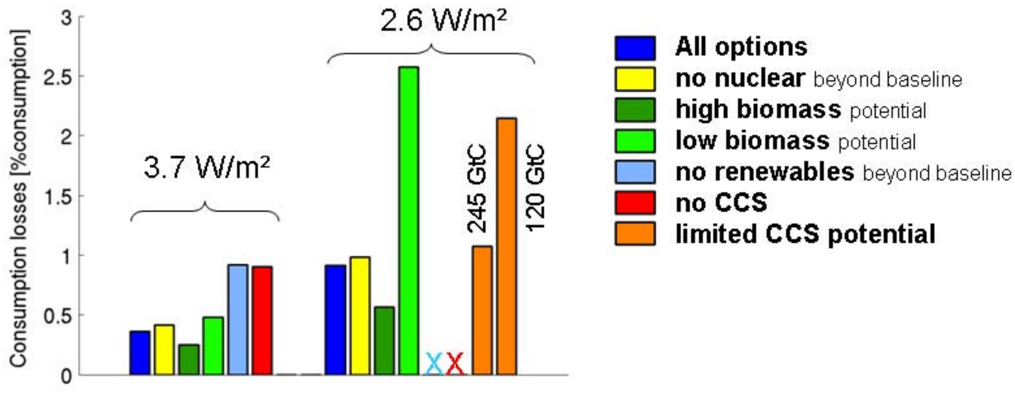

Figure 6: Mitigation costs for different stabilization levels and technology portfolios. Source: ADAM project (Knopf et al., 2009).

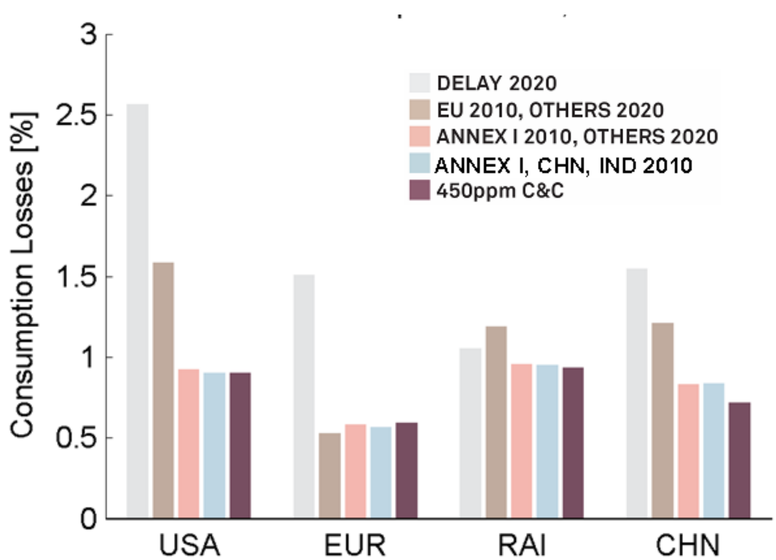

Figure 7: Regional mitigation costs for different climate policy scenarios. Source: RECIPE project (Luderer et al., 2009).

References

Bauer, N., O. Edenhofer, S. Kypreos (2008): Linking Energy System and Macroeconomic Growth Models. Journal of Computational Management Science 5, 95-117.

Bauer, N. (2005): Carbon Capture and Sequestration-An Option to Buy Time? Ph.D. thesis, Faculty of Economic and Social Sciences, University Potsdam, Germany.

Brown D, Gassner M, Fuchino T and Marechal F (2009): Thermo-economic analysis for the optimal conceptual design of biomass gasification energy conversion systems. In Applied Thermal Engineering, Vol. 29, pp. 2137 – 2152.

Chen H, Cong TN, Yang W, Tan C, Li Y and Ding Y (2009): Progress in Electrical Energy Storage Systems: A Critical Review. In Progress in Natural Science, Vol. 19, pp. 291 – 312.

Chen C and Rubin ES (2009): CO_2 Control Technology Effects on IGCC Plant Performance and Cost. In Energy Policy, Vol. 37, pp. 915 – 42.

Flam, H. and M.J. Flanders (eds.) (1991): Heckscher-Ohlin Trade Theory, Cambridge, Massachusetts: MIT Press.

Guel T (2009): An Energy-Economic Scenarios Analysis of Alternative Fuels for Transport. ETH-Thesis No. 17888, Zürich, Switzerland.Hamelinck, C. (2004): Outlook for advanced biofuels. Ph.D. thesis, University of Utrecht, The Netherlands.

Hoogwijk, M.M. (2004): On the Global and Regional Potential of Renewable Energy Sources. Ph.D. thesis, University of Utrecht.

International Energy Agency (IEA), 2007a International Energy Agency (IEA), Energy Balances of OECD Countries, IEA, Paris (2007).

International Energy Agency (IEA), 2007b International Energy Agency (IEA), Energy Balances of Non-OECD Countries, IEA, Paris (2007).

Iwasaki, W. (2003): A consideration of the economic efficiency of hydrogen production from biomass. Int. Jour. of Hydrogen Energy 28, 939-944.

Junginger M, Lako P, Lensink S, Sark W and Weiss M. (2008): Technological learning in the energy sector. Scientific Assessment and Policy Analysis for Climate Change WAB 500102 017. University of Utrecht, ECN. URL: http://www.rivm.nl/bibliotheek/rapporten/500102017.pdf (downloaded July 27, 2009)

Junginger, M., A. Faaji, W. Turkenburg (2005): Global Experience Curves for Wind Farms. Energy Policy 33, 133-150.

Junginger, M., A. Faaij, W. Turkenburg (2004): Cost reduction prospects for off-shore wind farms. Wind Engineering 28 (1), 97_118.

Junginger, M., E. Visser, K. Hjort-Gregersen, J. Koornneef, R. Raven, A. Faaij, W. Turkenburg (2006): Technological Learning in Bioenergy Systems. Energy Policy 34, 4024-41.

Klimantos P, Koukouzas N, Katsiadakis A and Kakaras E (2009): Air-blown biomass gasification combined cycles: System analysis and economic assessment. In Energy, Vol. 34, pp. 708 – 714.

Knopf, B., O. Edenhofer, T. Barker, N. Bauer, L. Baumstark, B. Chateau, P. Criqui, A. Held, M. Isaac, M. Jakob, E. Jochem, A. Kitous, S. Kypreos, M. Leimbach, B. Magné, S. Mima, W. Schade, S. Scrieciu, H. Turton, D. van Vuuren (2009): The economics of low stabilisation: implications for technological change and policy. In: M. Hulme, H. Neufeldt (Eds) Making climate change work for us - ADAM synthesis book, Cambridge University Press (in press)

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

Kypreos, S., O. Bahn (2003): A MERGE model with endogenous technological progress. Environmental Modeling and Assessment 19, 333-358.

Leimbach, M., N. Bauer, L. Baumstark, M. Lüken, O. Edenhofer (2010): Technological Change and International Trade – Insights from REMIND-R, Energy Journal 31, 109-136.

Leimbach, M., N. Bauer, L. Baumstark, O. Edenhofer (2009): Mitigation costs in a globalized world: climate policy analysis with REMIND-R, Environmental Modeling and Assessment, doi:10.1007/s10666-009-9204-8, http://www.springerlink.com/content/p52n0447v876497q/

Leimbach, M. N. Bauer, L. Baumstark, O. Edenhofer (2008): Cost-optimized Climate Stbilization (OPTIKS), Study commissioned by the Federal Environment Agency, http://www.umweltdaten.de/publikationen/fpdf-l/3868.pdf

Lemming J, Morthorst PE, Clausen NE, Jensen PH (2008): Contribution to the Chapter on WindPower in: Energy Technology Perspectives 2008, IEA. Report to the International Energy Agency. Roskilde: Risø National Laboratory, Technical University of Denmark. URL: http://130.226.56.153/rispubl/reports/ris-r-1674.pdf (downloaded July 27, 2009)

Lotze-Campen, H., Müller, C., Bondeau, A., Rost, S., Popp, A., Lucht, W. (2008): Global food demand, productivity growth and the scarcity of land and water resources: a spatially explicit mathematical programming approach. Agricultural Economics 39(3): 325-338. doi: 10.1111/j.1574-0862.2008.00336.x [ISI]

Luderer, G., V. Bosetti, J. Steckel, H. Waisman, N. Bauer, E. De Cian, M. Leimbach, O. Sassi, M. Tavoni (2009): The Economics of Decarbonzation: Results from the RECIPE model intercomparison. RECIPE Background Paper. Available at: http://www.pik-potsdam.de/recipe.

Lüken, M., N. Bauer, B. Knopf, M. Leimbach, G. Luderer, O. Edenhofer (2009), The Role of Technological Flexibility for the Distributive Impacts of Climate Change Mitigation Policy. Paper presented at the International Energy Workshop. June 17-19, 2009, Venice, Italy. Available at: http://www.iccgov.org/iew2009/speakersdocs/Lueken-et-al_TheRoleofTechnological.pdf

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.

McKinsey (2007): A cost curve for greenhouse gas reduction, McKinsey Quarterly.

MIT Massachusetts Institute of Technology (2007): The Future of Coal. An Interdisciplinary MIT Study. URL: http://web.mit.edu/coal/The_Future_of_Coal.pdf (downloaded July 30, 2009)

Rubin ES, Chen C and Rao AB (2007): Cost and Performance of Fossil Fuel Power Plants with CO_2 Capture and Storage. In Energy Policy, Vol. 35, pp. 4444 – 54.

Neij, L (2003): Experience Curves: A Tool for Energy Policy Assessment. Final report. Lund University, Sweden, Environmental and Energy Systems Studies Lund University Gerdagatan 13 SE-223 63 Lund Sweden.

Nitsch J, et al. (2004): Ökologisch optimierter Ausbau der Nutzung erneuerbarer Energien in Deutschland. Tech. rep. Stuttgart, Heidelberg, Wuppertal: BMU, DLR, ifeu, Wuppertal Institut. URL: http://www.wind-energie.de/fileadmin/dokumente/Themen_A-Z/Ziele/Oekologisch_optimierter_Ausbau_Langfassung.pdf (downloaded July 27, 2009)

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

Pietzcker R, Manger S, Bauer N, Luderer G and Bruckner T (2009): The Role of Concentrating Solar Power and Photovoltaics for Climate Protection. Paper presented at the 10th IAEE European Conference, Vienna, Austria. http://www.aaee.at/2009-IAEE/uploads/presentations_iaee09/Pr_516_Pietzcker_Robert.pdf

Ragettli M (2007): Cost Outlook for the Production of Biofuels. Master Thesis, ETH Zürich, February, 2007.

Schulz T (2007): Intermediate Steps towards the 2000-Watt Society in Switzerland: An Energy-Economic Scenario Analysis. ETH Thesis No. 17314, Zürich, Switzerland.

Takeshita, T. and K. Yamaij, (2008): Important roles of Fischer–Tropsch synfuels in the global energy future. *Energy Policy* 36, pp. 2773–2784.

Tanaka K, Kriegler E, Bruckner T, Hooss G, Knorr W, Raddatz T (2007) Aggregated carbon cycle, atmospheric chemistry, and climate model (ACC2) Hamburg : Max Planck Institute for Meteorology. 188 p. Reports on Earth System Science No. 40 http://www.mpimet.mpg.de/wissenschaft/publikationen/erdsystemforschung.html

Uddin S and Barreto L (2007): Biomass-fired cogeneration systems with CO_2 capture and storage. In Renewable Energy, Vol. 32, pp. 1006 – 1019.

WBGU (2003): Welt im Wandel: Energiewende zur Nachhaltigkeit. Springer.