Description of the REMIND model (Version 1.5)

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Contents

1 Overview

This document describes the Integrated Assessment Model, REMIND (version 1.5), which stands for "Regional Model of Investments and Development." The model was introduced by Leimbach et al. (2010a). More information—including a documentation of the system of equations—is available on the REMIND website.[1]

REMIND is a **global energy-economy-climate model spanning the years 2005–2100**. Its general structure is illustrated in Figure 1. The macro-economic core of REMIND is a Ramsey-type optimal growth model in which inter-temporal **global welfare is maximized**. The model computes a unique Pareto-optimal solution that corresponds to the market equilibrium in the absence of non-internalized externalities. The world is divided into **11 regions**: five individual countries (China, India, Japan, United States of America, and Russia) and six aggregated regions formed by the remaining countries (European Union, Latin America, sub-Saharan Africa without South Africa, Middle East / North Africa / Central Asia, other Asia, Rest of the World). **Trade** is represented explicitly by final goods, primary energy carriers, and in the case of climate policy, emissions allowances. **Macro-economic production** factors are capital, labor, and final energy. Economic **output** is used for investments in the macro-economic capital stock as well as consumption, trade, and energy system expenditures.

The macro-economic core and the energy system module are **hard-linked** via the final energy demand and costs incurred by the energy system. Economic activity results in demand for final energy such as transport energy, electricity, and non-electric energy for stationary end uses. Final energy demand is determined by a production function with constant elasticity of substitution (nested **CES production function**). The energy system module accounts for endowments of exhaustible primary **energy resources** as well as renewable energy potentials. More than 50 **technologies** are available for the conversion of primary energy into secondary energy carriers as well as for the distribution of secondary energy carriers into final energy.

The model accounts for CO_2 emissions from fossil fuel combustion and land use as well as emissions from other greenhouse gases (GHGs). The latter are determined via marginal abatement costs curves or by assuming exogenous scenarios. For numerical reasons, a reduced-form climate module is used to translate emissions into changes in atmospheric GHG concentrations, radiative forcing, and global mean temperature. For a more detailed

[1] See http://www.pik-potsdam.de/research/sustainable-solutions/models/remind for further resources and information on REMIND. The model is programmed in GAMS.

evaluation, the model can be coupled with the more complex ACC2 (Tanaka and Kriegler 2007) or MAGICC 6 (Meinshausen et al. 2011) climate models.

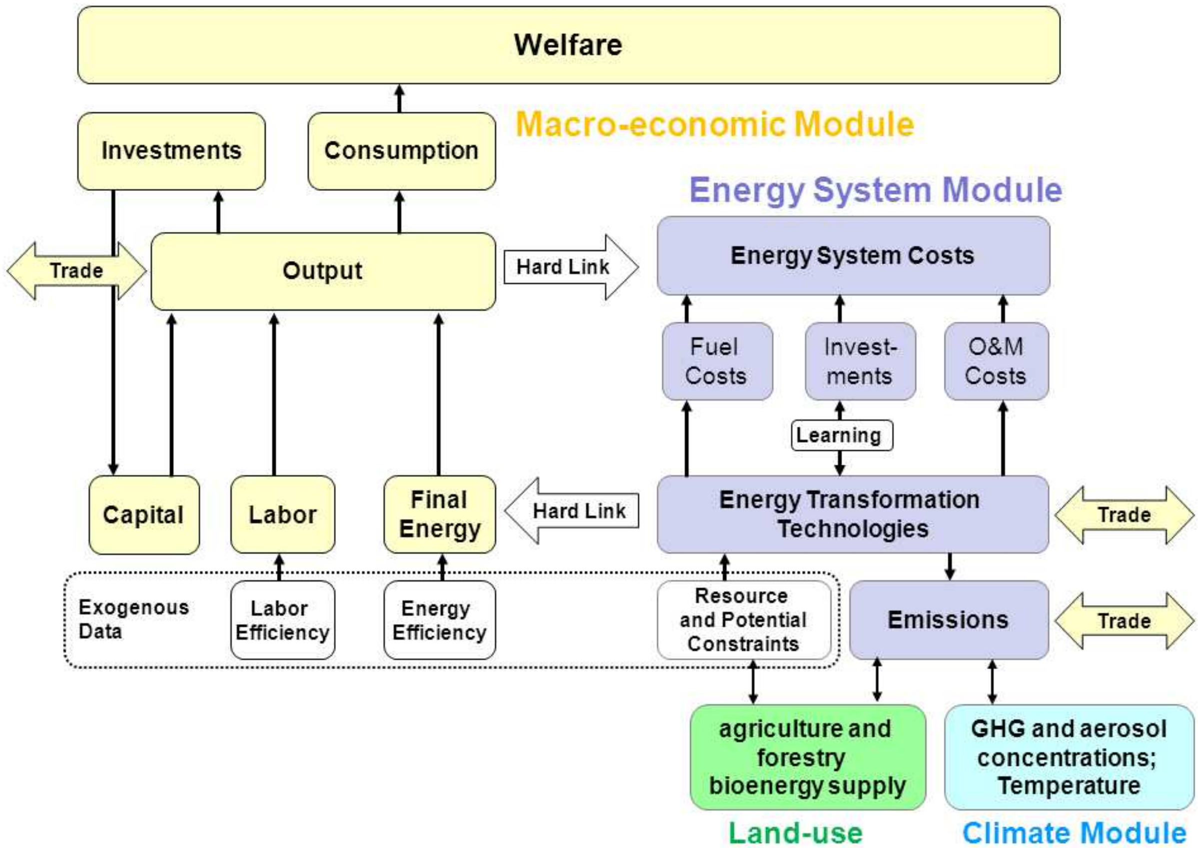

Figure 1. General structure of the REMIND model.

In terms of its macro-economic formulation, REMIND resembles well-known energy-economy-climate models such as **RICE** (Nordhaus and Yang 1996) and **MERGE** (Manne et al. 1995). However, REMIND features a higher level of detail in the representation of energy-system technologies, trade, and global capital markets.

Table 1 provides an overview of REMIND's key features. Individual modules, along with the relevant parameters and assumptions, are described in Sections 2–4. The strength and limits of the model are listed in Section 5, while the model applications are sketched in Section 6.

Table 1. Key features of the REMIND model.

Key feature	REMIND
Macro-economic core and solution concept	Inter-temporal optimization of global welfare: Ramsey-type growth model, Negishi approach to regional welfare aggregation.
Discounting	Endogenous interest rate in the international capital market reflects the pure time preference rate (default 3%). Marginal utility of consumption diminishes with increasing per-capita consumption.
Expectations/Foresight	Default: perfect foresight.
Cooperation	Pareto-optimal solution: full cooperation.
Economic coverage / Substitution within the macro-economy	Closed-economy growth model with a detailed energy sector. Nested CES production function: a generic final good is produced from capital, labor, and different final energy types.
International macro-economic linkages / Trade	Single market for all commodities (fossil fuels, final good, permits).
Investment dynamics	Capital motion equations, vintages for energy supply technologies, adjustment costs for acceleration of capacity expansion.
Link between energy system and macro-economy	Hard-linked hybrid model. Economic activity determines final energy demand. Energy system costs (investments, fuel costs, operation, and maintenance) are included in the macro-economic budget.
Representation of end-use sectors	Three energy end-use sectors: electricity production, stationary non-electric, transport.
Production function in the energy system / Substitution possibilities	Linear substitution between competing technologies for secondary energy production. Supply curves for exhaustible resources (cumulative extraction cost curves) as well as renewable potentials (grades with different capacity factors) introduce convexities.
Technological Change / Learning	Endogenous technological change through learning-by-doing for wind and solar power as well as electric and fuel cell vehicle technologies (global learning curve, internalized spillovers). Labor productivity and energy efficiency improvements are calibrated.
Implementation of climate policy targets	Pareto-optimal achievement of policy targets on GHG concentration, radiative forcing, or temperature levels under full when-flexibility. Allocation rules for distribution of emissions permits among regions. Other options: emissions caps and budgets, taxes equivalent.
Land-use	Marginal abatement cost curves for avoided deforestation, non-CO_2 emission from agriculture, and bioenergy supply curves based on results from the MAgPIE model

2 Macro-economic module

REMIND is a multi-regional hybrid model that couples an economic growth model with a detailed energy system model and a simple climate model (see Leimbach et al. 2010a). The hard link between the energy system and the macroeconomic system follows the method outlined by Bauer et al. (2008). By assuming perfect foresight and aiming at welfare maximization, REMIND simulates the dynamics of the world economy between the years 2005–2150. The spacing of time-steps is flexible: in the default case, there are five-year time steps until 2050 and 10-year time steps until 2100. The period from 2100–2150 is also calculated to avoid distortions due to end effects. Typically, we only use the time span from 2005–2100 for model applications.

The world is divided into 11 regions (Figure 2). There are **5 countries** (**CHN** – China; **IND** – India; **JPN** – Japan; **USA** – United States of America; and **RUS** – Russia) and **6 aggregated regions** (**AFR** – Sub-Saharan Africa excluding Republic of South Africa; **EUR** – Members of the European Union; **LAM** – Latin America; **MEA** – including countries from the Middle East, North Africa, and central Asia; **OAS** – other Asian countries mainly located in South East Asia; and **ROW** – the rest of the world including Australia, Canada, New Zealand, Norway, and the Republic of South Africa).

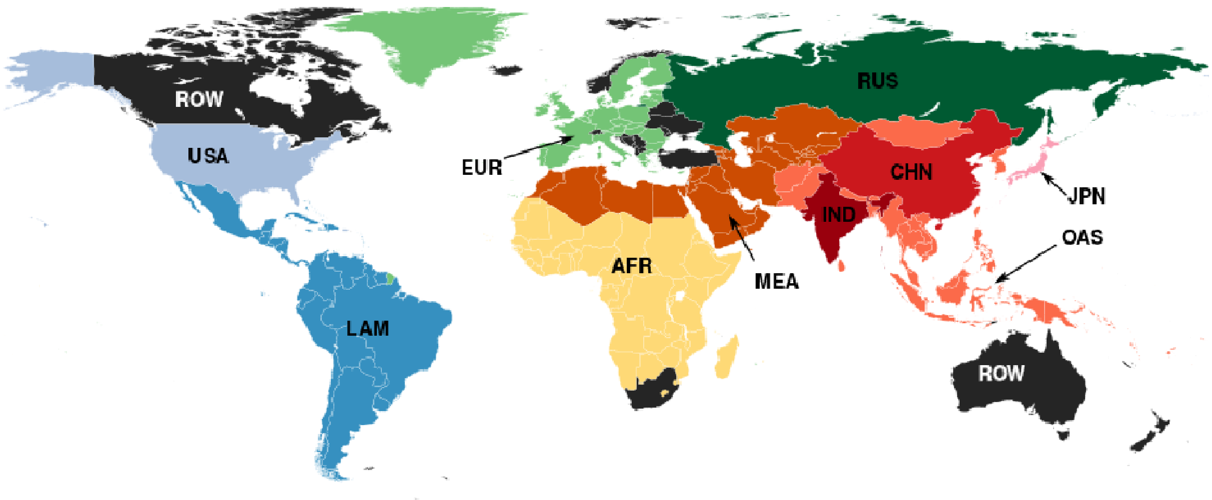

Figure 2. Regional definitions used in the REMIND model.

2.1 Objective function and production structure

Each region *r* is modeled as a representative household with a utility function U_r that depends upon per-capita consumption

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

where C_{rt} is the consumption of region *r* at time *t*, and P_{rt} is the population in region *r* at time *t*. The calculation of utility is subject to discounting; 3% is assumed for the pure rate of time preference ρ. The logarithmic relationship between per-capita consumption and regional utility implies an elasticity of marginal consumption of 1. Thus, in line with the Keynes-Ramsey rule, REMIND yields an endogenous interest rate in real terms of 5–6% for an economic growth rate of 2–3%. This is in line with the interest rates typically observed on capital markets.

REMIND's objective is to maximize global welfare. **Global welfare**, *W*, is calculated as the weighted sum of the regional utility functions:

$$W = \sum_r n_r U_r$$

The Negishi weights, n_r, are chosen such that for each region, the sum of the discounted value of exports equals that of imports over the time horizon (see Section 2.2). An iterative algorithm is used to achieve a clearing of regional inter-temporal trade balances. It ensures that the Pareto-optimal solution of the model corresponds with the market equilibrium in the absence of non-internalized externalities. The algorithm is an inter-temporal extension of the original Negishi approach (Negishi 1972; see also Manne and Rutherford (1994) for a discussion of the extension). Other models such as MERGE (Manne et al. 1995) and RICE (Nordhaus and Yang 1996) use this algorithm in a similar way.

A region's **gross domestic product (GDP)** is determined by a nested production function with constant elasticity of substitution (CES; Figure 3). Inputs at the upper level of the production function include labor, capital, and final energy. Labor is provided by the population at working age. Final energy input to the upper production level forms a CES nest, which comprises energy for transportation and stationary energy coupled with a substitution elasticity of 0.3. These two energy types are, in turn, determined by the nested CES functions of more specific final energy carriers. Substitution elasticities between 1.5 and 3 are assumed 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 efficiencies of the individual production factors for each region are provided by exogenous scenarios (see Section 3.3.2).

The macro-economic budget constraint for each region is given as:

$$Y_{rt} - X^G_{rt} + M^G_{rt} \geq C_{rt} + I_{rt} + E_{rt}$$

This states that in each region and for every time step, the sum of GDP, Y_{rt}, and imports of composite goods, M^G_{rt}, can be spent on consumption, C_{rt}, investments into the macroeconomic capital stock, I_{rt} (depreciation rate of 5%), energy system expenditures, E_{rt}, and the export of composite goods, M^G_{rt}. Energy system expenditures, E_{rt}, consist of investment costs, fuel costs, and operation and maintenance costs.

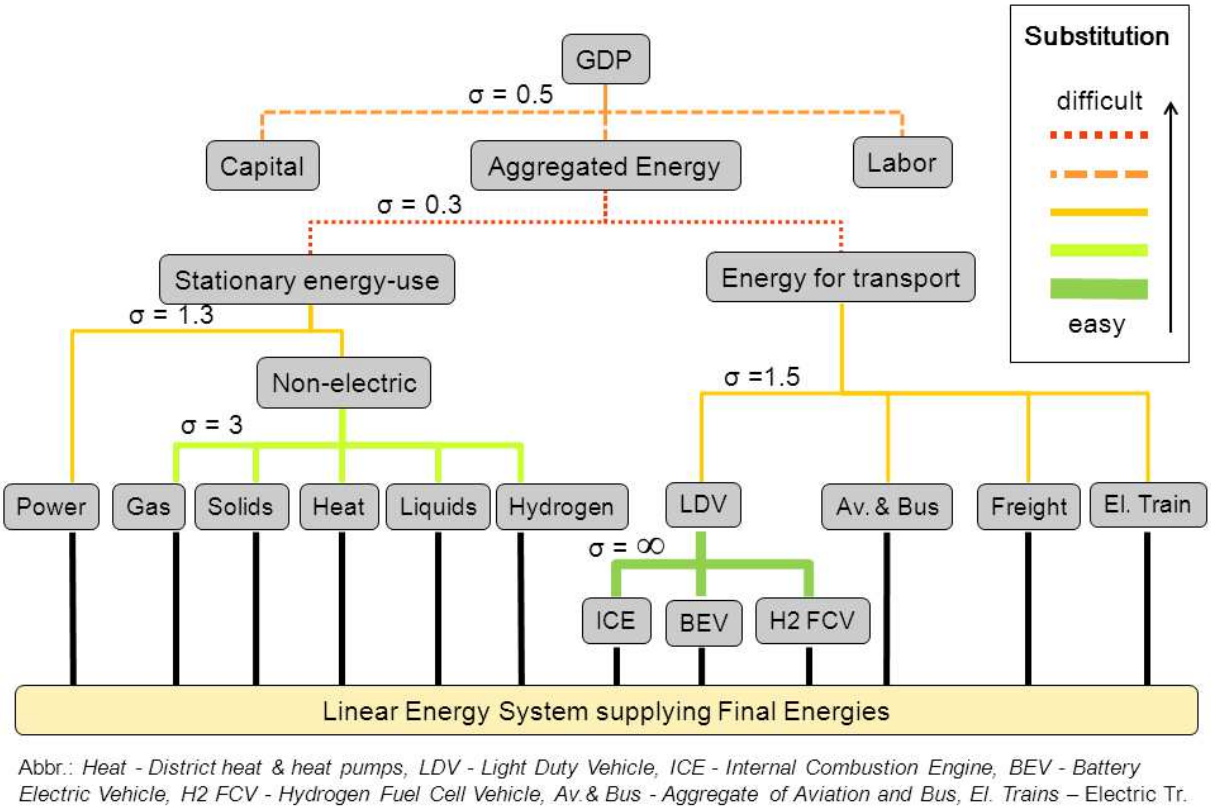

Figure 3. Production structure of REMIND. The conversion of primary energy (lowest level) to final energy carriers is described by linear production functions. The aggregation of final energy carriers for end-use is described via nested CES structures.

2.2 Trade

REMIND considers the trade of **coal, gas, oil, biomass, uranium, the composite good** (aggregated output of the macro-economic system), **and emissions permits** (in the case of climate policy).

For each good, *i*, a global trade balance equation ensures that markets are cleared:

$$\sum_r X_{rt}^i = \sum_r M_{rt}^i \quad , \qquad \forall\, t, i$$

There is no bilateral trade since regional trade is modeled via a **common pool**. While each region is an open system—meaning that it can import more than it exports—the global system is closed. The combination of regional budget constraints and international trade balances ensures that the sum of regional consumption, investments, and energy-system expenditures cannot be greater than the global total output in each period.

According to the classical Heckscher-Ohlin and Ricardian models (Heckscher et al. 1991), trade between regions is induced by differences in factor endowments and technologies. In REMIND this is supplemented by the possibility of inter-temporal trade. This means that for each region, the value of exports must balance the value of imports within the time horizon of the model. This is ensured by the inter-temporal budget constraint

$$\sum_t \sum_i \pi_r^i \left(X_{rt}^i - M_{rt}^i \right) = 0 \qquad \forall\, r$$

where π_r^i is the present value price of good *I*. Therefore, discounting is implicit. Alternatively, this can be interpreted as capital trade or borrowing and lending. Inter-temporal trade and the capital mobility implied by trade in the composite good, cause factor prices to equalize, thus providing the basis for an inter-temporal and interregional equilibrium.

Trade balances imply that the regional current accounts (and their counterparts—capital accounts) have a sum of zero at each point in time. In other words, regions with a current account deficit are balanced by regions with a current account surplus. Debts and assets that accrue through trade are balanced inter-temporally by the above budget constraint. This means that an export surplus qualifies the exporting region for an import surplus (of the same present value) in the future, thus also implying a loss of consumption for the current period. The trading of emissions permits is modeled in a similar way: In the presence of a global carbon market, the initial allocation of emissions rights is determined by a burden-sharing rule wherein permits can be traded freely among world regions. A permit-constraint equation ensures that an emissions certificate covers each unit of GHG emissions.

The trading of resources is subject to **trade costs**. In terms of consumable generic goods, the representative households in REMIND are indifferent to domestic and foreign goods as well as foreign goods from different origins. This can potentially lead to a strong specialization pattern.

3 The energy system module

REMIND's energy system module (ESM) is comprised of a detailed description of energy carriers and conversion technologies. Techno-economic characteristics and the energy balance equations constrain the welfare maximization problem of the macroeconomic module.

The energy system can be regarded as an economic sector with a heterogeneous capital stock that demands primary energy carriers and supplies final energy. The structure of the capital stock determines the energy-related demand-supply structure. In other words, the macro-economy demands final energy as an input factor and in return, the energy sector consumes part of the economic output to cover ESM investments as well as the costs of extracting resources, and operation and maintenance of installations. Energy system expenditures are allocated among a portfolio of alternative energy conversion technologies. The techno-economic characteristics of technologies and the endogenously evolving prices of energy and CO_2 emissions determine the size and structure of the energy sector's capital stock.

3.1 Primary energy resources

The primary energy carriers in REMIND include both exhaustible and renewable resources. Exhaustible resources comprise uranium as well as three fossil resources, namely coal, oil, and gas. Renewable resources include hydro, wind, solar, geothermal, and biomass. Coal, oil, gas, uranium, and biomass can be traded across regions, but the trading of resources is subject to regional and resource-specific trade costs.

3.1.1 Exhaustible resources

Exhaustible resources such as coal, oil, gas, and uranium are characterized by extraction cost curves. Fossil resources (e.g., oil, coal, and gas) are further defined by decline rates and adjustment costs. Extraction costs increase over time as low-cost deposits become exhausted (Herfindahl 1967; Rogner 1997; Aguilera et al. 2009; BGR 2010; Rogner et al. 2012). In REMIND, this is represented by region-specific extraction cost curves that relate production cost increases to cumulative extraction (IHS CERA 2012; Rogner et al. 2012).

Piecewise constant functions are employed for **fossil resource extraction curves**, while uranium extraction costs follow a third-order polynomial parameterization. Additionally, as a scenario choice, oil and gas extraction cost curves can be made time dependent. This means that resources and costs may increase or decrease over time depending on expected future conditions such as technological and geopolitical changes. The amount of available uranium is limited to 23 Mt. This resource potential includes reserves, conventional resources, and a conservative estimate of unconventional resources (NEA 2009).

Decline rates are modeled for the extraction of coal, oil, and gas. In the case of oil and gas, these are dynamic extraction constraints based on data published by the International Energy Agency (IEA 2008, 2009). An additional dynamic constraint limits the extraction growth of coal, oil, and gas to 10% per year. **Adjustment costs** are used to represent short-term price markups resulting from rapid expansion of resource production rapidly expand (Dahl and Duggan 1998; Krichene 2002; Askari and Krichene 2010).

Trade costs are region- and resource-specific. Oil trade costs range between 0.22 USD/GJ in AFR and 0.63 USD/GJ in EUR. Gas trade costs are lowest in EUR and JPN with a value of 1.52 USD/GJ and reach a maximum in CHN with a value of 2.16 USD/GJ. Coal trade costs range between 0.54 USD/GJ in JPN and 0.95 USD/GJ in IND.

3.1.2 Biomass

Bioenergy supply from the land-use sector is represented by an emulation of the land-use model MAgPIE (Model of Agricultural Production and its Impact on the Environment), see Lotze-Campen et al. (2008, 2010); Popp et al. (2010). The emulator focuses on bioenergy supply costs and total agricultural emissions. REMIND models three types of bioenergy feedstocks:

(a) Small amounts of **first-generation biomass** produced from sugar, starch, and oilseeds;
(b) **Ligno-cellulosic residues** from agriculture and forest; and
(c) **Second-generation** purpose-grown **biomass** from specialized ligno-cellulosic grassy and woody bioenergy crops, such as miscanthus, poplar, and eucalyptus.

The supply of purpose-grown biomass is provided by regional supply cost curves that are calculated using the price responses of MAgPIE to different bioenergy demand scenarios (Klein et al., in prep.). The supply curves capture the path-dependency of bioenergy production costs resulting from past land conversions and induced technological changes in the land-use sector, as represented in MAgPIE. Ligno-cellulosic agricultural and forest residues are based on low-cost bioenergy supply options. Their potential is assumed to increase from 20 EJ/yr in 2005 to 70 EJ/yr in 2100 (Chum et al. 2011, based on Haberl et al. 2010).

In REMIND, bioenergy is mainly produced in the form of second-generation purpose-grown biomass and from ligno-cellulosic agricultural and forestry residues. There are two rational motives. First, the use of traditional biomass (supplied by residues) is assumed to be phased out by 2050, because modern and less harmful fuels are increasingly used as incomes rise (Sims et al. 2010). Secondly, we assume that first generation fuels are phased-out as well, to take into account concerns about land-use impacts, co-emissions, and competition with food production from first-generation biofuels (Searchinger et al. 2008; Fargione et al. 2008).

Given the concerns about the sustainability of large-scale bioenergy deployment, REMIND assumes a default upper limit of 300 EJ for second-generation biomass-use. This constraint is consistent with the upper end of potential 2050 deployment levels identified in the Intergovernmental Panel on Climate Change's *Special Report on Renewable Energy Sources and Climate Change Mitigation* (Chum et al. 2011). Based on the current public debate, we consider this constraint to be a reflection of the potential institutional limitations on the widespread-use of bioenergy. However, the MAgPIE model does not reflect this limitation on bioenergy supply.

3.1.3 Non-biomass renewable resources

The resource potentials for non-biomass renewables (**hydro, solar, wind, and geothermal**) are modeled using region-specific potentials. For each renewable energy type, the potentials are classified into different grades, which are specified by capacity factors. Superior grades have higher capacity factors, which correspond to more full-load hours per year. This implies that more energy is produced for a given installed capacity. Therefore, the grade structure leads to a gradual expansion of renewable energy deployment over time as a result of optimization.

REMIND's renewable energy potentials often appear higher than the potentials used in other models. However, these models typically limit potentials to specific locations that are currently competitive or close to becoming competitive. REMIND's grade structure allows for the inclusion of sites that are less attractive, but may become competitive in the long-term as the costs of other power-generation technologies increase. This choice is dependent on the model. The regionally aggregated potentials for solar PV and CSP used in REMIND draw from Trieb et al. (2009), Tzscheutschler (2005), and communication with German Aerospace Center DLR. In total, the solar potentials amount to 2,200 EJ/year for PV and 1.700EJ/year for CSP. Half of this amount is allocated to sites with less than 1500 full-load hours for PV and 5000 full-load hours for CSP with thermal storage. The total potential, however, is less than half of that given in Trieb et al. (2009) and less than a fifth of that in Tzscheutschler (2005). To account for the competition between PV and CSP for the same sites with good irradiation, REMIND introduced an additional constraint for the combined deployment of PV and CSP (Pietzcker et al. 2009).

The regionally aggregated wind potentials were developed based on a number of studies (see Hoogwijk 2004; Hoogwijk and Graus 2008; Brückl 2005; and EEA 2009). The technical potentials for combined on- and off-shore wind power amount to 370EJ/year (half of this amount is at sites with less than 1400 full-load hours). The total value is twice as large as the potential estimated by WBGU (2003), but is less than one fifth of the potential in Lu et al. (2009).

The global potentials of hydropower amount to 50 EJ/year. These estimates are based on the technological potentials provided in WBGU (2003). The regional disaggregation is based on information from a background paper produced for this report (Horlacher 2003).

3.2 Technologies for the conversion of primary energy into secondary energy

The core part of the energy system is the conversion of primary energy into secondary energy carriers via specific energy conversion technologies. Around fifty different energy conversion technologies are represented in REMIND. The energy conversion matrix in Table 2 provides an overview of their primary energy types, secondary energy types, and relevant conversion technologies.

The secondary energy carriers included in REMIND are:

- **Electricity** – used for stationary sector and light duty vehicles.
- **District heat and local renewable heat** – used for the stationary sector.
- **Hydrogen** – used for stationary sector and light duty vehicles.
- **Liquids** – used for the stationary sector and transport sector.
- **Solid fuels** – used for the stationary sector.
- **Gases** – used for the stationary sector.

Coal and biomass are very flexible primary energy carriers because they can be used as feedstocks for all types of secondary energy. Crude oil and natural gas are mainly used for the production of liquids, gases, and electricity. Renewable energy carriers other than biomass are well suited for the production of electricity. However, they are less well suited to produce other secondary energy carriers. Renewable energy sources other than biomass are not traded, while other unprocessed primary energy carriers can be. All secondary energy carriers are assumed to be non-tradable across regions. According to energy statistics, trade in refined liquid fuels does take place, but to a smaller extent than crude oil. Since REMIND considers crude oil trade, the omission only has a small effect on the model results.

REMIND considers separate capital stocks for the transportation and distribution of secondary energy carriers to end-use sectors. The balance of demand from the macro-economy and supply from the energy system delivers equilibrium prices at the final energy level. Note that the buildings and industry end-use sectors are aggregated to one stationary sector.

All technologies are represented in the model as capacity stocks with full vintage tracking. Since there are no hard constraints on the rate of change in investments, the possibility of investing in different capital stocks provides high flexibility for technological evolution. However, the model includes cost mark-ups for the fast up-scaling of investments into individual technologies; therefore, a more realistic phasing in and of technologies is achieved. The model allows for early retirement (4 %/year) and the lifetimes of capacities differ between various types of technologies. Furthermore, depreciation rates are relatively low in the first half of the lifetime and increase thereafter.

Each region is initialized with a vintage capital stock and conversion efficiencies are calibrated to reflect the input-output relations provided by IEA energy statistics (IEA 2007a; b). The conversion efficiencies for new vintages converge across the regions from the 2005 values to a global constant value in 2050. Furthermore, for some fossil power plants, transformation efficiencies improve exogenously over time. Finally, by-production coefficients of combined power-heat technologies (CHP) are adjusted by region to meet the empirical conditions of the base year.

Table 2. Energy conversion matrix. Overview of primary and secondary energy carriers and available conversion technologies (in yellow if combination with CCS possible).

		PRIMARY ENERGY CARRIERS						
		Exhaustible resources				Renewable resources		
		Coal	**Oil**	**Gas**	**Urani-um**	**Solar, wind, hydro**	**Geo-thermal**	**Biomass**
SECONDARY ENERGY CARRIERS	**Electricity**	PC, IGCC	DOT	NGT, NGCC	LWR	SPV,WT, CSP, Hydro	HDR	BIGCC
	Hydrogen	C2H2		SMR				B2H2
	Gases	C2G		GasTR				B2G
	Heat	CoalHP, CoalCHP		GasHP, GasCHP			GeoHP	BioHP, BioCHP
	Liquid fuels	C2L	Refin.					B2L Bioethanol
	Solids	CoalTR						BioTR

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

3.2.1 Techno-economic parameterization of variable renewable sources

Ambitious mitigation targets typically result in the substantial expansion of renewables, mostly by solar and wind. Table 3 provides the techno-economic parameters for electricity generation from renewable energy sources. Wind, solar PV, and CSP improve via learning-by-doing; therefore, the specific investment costs decrease by 12, 20, and 9%, respectively, for each doubling of cumulated capacity. Learning rates are reduced as capacities increase so that the investment costs asymptotically approach the floor costs.

Table 3. Techno-economic characteristics of technologies based on non-biomass renewable energy sources (see Neij et al. 2003; Nitsch et al. 2004; IEA 2007b; Junginger et al. 2008; Pietzcker et al. 2009).

	Lifetime	Overnight Investment costs	Floor costs	Learning Rate	Cumulative capacity 2005	O&M costs
	Years	**$US/kW**	**$US/kW**	**%**	**GW**	**% of Inv.Costs**
Hydro	95	2300	-	-	-	**2**
Geo HDR	35	3000	-	-	-	**4**
Wind	40	1400	900	12	60	**2**
SPV	40	5300	600	20	5	**2**
CSP	40	9500	1900	9	0.4	3

Variable renewable electricity (VRE) sources such as wind and solar PV require storage to guarantee a stable supply of electricity (see Pietzcker et al. 2009). Since the techno-economic parameters applied to CSP include the cost of thermal storage to continue electricity production at nighttime, CSP is assumed to require only limited additional storage for balancing fluctuations.

The approach used in REMIND follows the idea that storage demands for each VRE type rise with increasing market share. This is because balancing fluctuations becomes ever more challenging with higher penetration[2]. As a measure of the demand for balancing, the model calculates a time-, region-, and VRE-specific scale-factor, α_{VRE}, in the form of:

$$\alpha_{VRE} = E\, s_{VRE}^{\beta} \,,$$

[2]Current electricity systems already require substantial flexibility due to varying demand. This flexibility allows for the use of low shares of individual VRE (below ~10%) without any adaptations or storage requirements, as seen in many of today's electricity networks. Furthermore, many regions have some limited potential for (cheap) pumped hydro storage, leading to low storage costs at low market shares of VRE.

where E is the total electricity produced, s_{VRE} is the market share of the renewable energy source after storage losses and curtailment, and $\boldsymbol{\beta}$ is a scaling exponent that assumes values between 1.7 and 2.

For modeling reasons, there is a "generalized storage unit", tailor-made for each VRE. This construct consists of a VRE-specific mix of short- and medium-term storage as well as curtailment. Examples are redox-flow batteries for short-term storage, electrolysis and hydrogen storage for medium-term storage, as well as curtailment to balance seasonal fluctuations. A specific combination of these three real-world storage options is determined in order to match the VRE-specific fluctuation pattern. From this combination of actual storage technologies, we calculate aggregated capital costs and efficiency parameters for the "generalized storage unit" of a specific VRE.

To then calculate the total storage costs and losses at each point in time, the calculated "generalized storage unit" of a VRE is scaled with this VRE's scale-factor $\boldsymbol{\alpha}_{VRE}$. The capital costs of the generalized storage units decrease through "learning-by-doing" with a 10% learning rate.

Costs for long-term HVDC transmission are included following a similar logic as storage costs. It is assumed that grid requirements increase with market share; the exponent value is between 1.55 and 1.75. Furthermore, since resource potentials for PV (suitable for decentralized installation) are not as localized as those for wind and CSP, grid costs for PV are assumed to be comparatively smaller.

Both storage and grid requirements are partly regionalized: in regions where high demand coincides with high wind (EUR) or solar (USA, ROW, AFR, IND, MEA) incidence, storage requirements are slightly reduced. If a region is small or has homogeneously distributed VRE potentials (EUR, USA, IND, JPN), grid requirements are lower.

For a market share of 20%, storage requirements and curtailments result in typical markup costs (levelized cost of electricity – LCOE) of 6-12 USD/MWh for wind, 10-25 USD/MWh for PV, and 3-10 USD/MWh for CSP. Typical grid costs are 5-12 USD/MWh for wind, 2-5 USD/MWh for PV, and 8-15 USD/MWh for CSP.

3.2.2 Techno-economic parameterization of other technologies

Table 4 lists the Techno-economic parameters for conversion technologies using exhaustible resources and biomass. A relevant mitigation option for the power sector is the expansion of nuclear energy. Overnight investment costs for nuclear power plants are approximately 3000 USD/kW. Currently, REMIND only considers thermal nuclear reactors. The use of nuclear is largely constrained by its limited competitiveness compared to renewable electricity sources.

Furthermore, resource potentials for uranium are limited to 23 Mt. External effects such as the risk of nuclear accidents or nuclear waste are not accounted for.

There are no hard limits on the expansion of technologies. However, we apply cost mark-ups ("adjustment costs"), which scale with the square of relative changes in capacity additions between time steps.

Table 4. Techno-economic characteristics of technologies based on exhaustible energy sources and biomass (Iwasaki 2003; Hamelinck 2004; Bauer 2005; Ansolabehere et al. 2007; Schulz 2007; Gül et al. 2007; Ragettli 2007; Uddin and Barreto 2007; Rubin et al. 2007; Takeshita and Yamaji 2008; Brown et al. 2009; Chen and Rubin 2009; Klimantos et al. 2009).

		Life-time	Overnight 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	40	1400	2400	2.8	5.1	45-51[#]	36	90
	Oxyfuel	40		2150		4.7		37	99
	IGCC	40	1650	2050	3.4	4.6	43-52[#]	38-48[#]	90
	C2H2*	35	1260	1430	1.9	2.1	59	57	90
	C2L*	35	1450	1520	4.2	5.0	40	40	70
	C2G	35	1200		1.4		60		
	NGT	30	350		1.5		38-43[#]		
Gas	NGCC	35	650	1100	1.0	1.7	56-64[#]	48/59	90
	SMR	35	500	550	0.6	0.7	73	70	90
Biomass	BIGCC*	40	1860	2560	4.2	6.0	42	31	90
	BioCHP	40	1375		5.0		43		
	B2H2*	35	1400	1700	5.7	6.8	61	55	90
	B2L*	35	2500	3000	3.8	4.9	40	41	50
	B2G	40	1000		1.9		55		
Nuclear	TNR	40	3000		5.2		33[§]		

*For abbreviations see Table 1; ** for *joint production processes;* [§] *nuclear reactors with thermal efficiency of 33%;* [#] *technologies with exogenously improving efficiencies. 2005 values are represented by the lower end of the range. Long-term efficiencies (reached after2045) are represented by high-end ranges.*

Emissions from fossil fuel combustion can be curbed by deploying carbon capture and storage (CCS). In REMIND, CCS technologies exist 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 (e.g., biomass integrated gasification combined cycle power plant), biofuels (e.g., biomass liquefaction), hydrogen, and syngas production. The sequestration of captured CO_2 is explicitly represented in the model by accounting for transportation and storage costs (Bauer 2005) . There are regional constraints on CO_2 storage potentials. In total, the global storage potential amounts to 1000 GtC. It is smallest for EUR with 50 GtC, Japan with 20 GtC, and India with 50 GtC. The yearly injection rate of CO_2 cannot exceed 0.5% of total storage capacity due to technical and geological constraints. This creates an upper limit of 5 GtC per year for global CO_2 injection.

Only one technology converts secondary energy into secondary energy, which is the production of hydrogen from electricity via electrolysis.

3.3 Final energy supply to sectors

3.3.1 Final energy demand sector

The distribution of energy carriers to end-use sectors forms the interface between the macro-economic module and the energy system module. REMIND distinguishes between the stationary end-use sector (aggregating industry and residential/commercial) and the transport end-use sector. Table 5 maps secondary energy supply to end-use sectors. The transport and distribution of secondary energy carriers is represented capacities that require investments and incur costs for operation and maintenance.

Table 5. Overview of energy carriers used in end-use sectors.

Sector	Power	Gases	Liquids	Hydrogen	Solids	Heat
Stationary	X	x	X	x	x	X
Transport	X	no	X	x	no	no

3.3.2 Final energy demand scenarios

The demand for final energy is determined by the macro-economic production function (cf. Figure 3). This gives rise to three mechanisms for reductions in energy intensity, i.e., a decline in the use of energy for energy service input per unit of economic output.

First, the efficiency parameters of the production function (exogenous) lead to autonomous reductions in energy intensity, which also occur in the absence of climate policy interventions. For 2005, the parameters are calibrated based on IEA energy balance sheets (IEA 2007a, 2007b). Energy-related CES-efficiency parameters are assumed to change at the same rate as labor efficiency, including an additional adjustment factor. This factor is separately chosen for each region and each final energy type. Therefore, the reference trajectories for final energy are obtained in scenarios without climate policies. The following guidelines are used:

- Short- and mid-term final energy demand follows the trend for the years 2005–2010, which mimics most of the regional projections shown in the "current policy scenario" of IEA WEO 2010.
- Per-capita energy use for the end-use of transport, non-electric stationary, and stationary electricity follow a converging trend between regions (EJ/capita over GDP in PPP/cap).

Second, the CES production function allows for substitutions between aggregated energy and capital (substitution elasticity of 0.5). Final energy is lower in comparison to the reference trajectories if additional constraints on the supply side are introduced (e.g., carbon taxes, resource, or emission constraints). This is partially balanced by increasing investments in macroeconomic capital. A reduction in final energy results in a lower GDP and, subsequently, lower consumption and welfare values.

Third, the model can endogenously improve end-use efficiency by investing in more efficient technologies for the conversion of final energies into energy services. For example, three vehicle technologies with different efficiencies are implemented in the light duty vehicle (LDV) mode of the transport sector, including internal combustion engine vehicles, battery-electric vehicles, and fuel cell vehicles.

REMIND also accounts for subsidies and taxes on fossil fuels. These are implemented as a price mark-up on a region's final demand of solids, heating oil, diesel, and petrol used in transport, as well as gas and electricity used in the stationary sector. The global total amounts to approximately 450 billion USD. The development of fossil fuel subsidies and taxes over REMIND's time horizon is prescribed by the scenarios. In the default case, subsidies phase out by 2050. Historical data are based on the IEA subsidies database and the International Energy Database, ENERDATA.[3]

4 Climate module

4.1 Representation of the climate system

REMIND includes a reduced-form climate model similar to the one used in the DICE model. It comprises (1) an impulse-response function with three time scales for the carbon cycle, (2) an energy balance temperature model with a fast mixed layer, and (3) a slow deep ocean

[3] www.iea.org./subsidy/index.html and http://www.enerdata.net/ .

temperature box. Equations in the carbon-cycle temperature model describe concentration and radiative forcing that result from CH4, N2O, sulphate aerosols, black carbon, and organic carbon (Tanaka and Kriegler 2007). Sulfate emissions are directly linked to the combustion of fossil fuels in the energy sector. CO_2 emissions from land-use changes as well as CH4 and N2O emissions are derived from marginal abatement cost curves (Lucas et al. 2007). The climate module determines the atmospheric concentrations of CO_2, CH4, and N2O and computes the resulting radiative forcing and mean temperature at the global level. The most important parameter of the climate module is climate sensitivity, which is set to 3.0°C. More complex climate modules such as ACC2 (Tanaka and Kriegler 2007) and MAGICC (Meinshausen et al. 2011) can be coupled with REMIND via post-processing, i.e., not being part of the optimization routine. The advantages of these models are a more detailed representation of the carbon cycle, temperature change processes, and aerosol characteristics.

4.2 Representation of GHG and air pollutant emissions

REMIND simulates emissions from long-lived GHGs (**CO_2, CH_4, N_2O, F-gases, Montreal gases**), short-lived GHGs (**CO, NOx, VOC**), aerosols, and aerosol precursors (**SO_2, BC, OC, nitrate, mineral dust**). These emissions are accounted for with different levels of detail depending on the types and sources of emissions (Table 8).

CO_2, SO_2, BC, and OC emissions from fuel combustion are calculated based on sources. The energy system provides information on the regional consumption of fossil fuels and biomass for each time step and technology. For each fuel, region, and technology, an emission factor is applied to the specific gas in order to calculate the emissions.

CH_4, N_2O, and CO_2 from land-use change have mitigation options that are independent of energy consumption. However, costs are associated with these emissions. Therefore, the mitigation options are derived from marginal abatement cost (MAC) curves, which describe the percentage of abated emissions as a function of the costs. Baseline emissions—to which the MAC curves are applied—can be obtained by three different methods: by source (as described above), by an econometric estimate, or exogenously. The econometric estimate is used for CO_2 emissions from cement production as well as CH_4 and N_2O emissions from waste handling. In both cases, the driver of emissions depends on the development of the GDP (as a proxy for the amount of waste) or capital investment (as a proxy for cement production in infrastructure).

Other emissions are exogenous and are taken from the RCP scenarios (Van Vuuren et al. 2011). There are no abatement options; therefore, emissions from the RCP scenario best matching the target of the specific model are used.

Table 6. Overview of the treatment of GHG and air pollutant emissions.

GHG and air pollutant emissions	Treatment in REMIND	Percentage of 2005 CO_2 emissions
CO_2 fuel combustion	By source	56.6 %
Other CO_2 industry	Econometric estimate, coupled with capital investments per capita	2.8 %
CO_2 LUC	Marginal abatement cost curves, baseline from MAgPIE	17.3 %
CH_4 fossil fuel extraction	Marginal abatement cost curves, baseline by source	14.3 %
CH_4 land use (agriculture)	Marginal abatement cost curves, baseline from MAgPIE	
CH_4 land use change (open burning)	Exogenous	
CH_4 and N_2O from waste handling	Marginal abatement cost curves, baseline econometric estimate, coupled to GDP per capita	7.9 %
N_2O land use (agriculture)	Marginal abatement cost curves	
N_2O land use change (open burning)	Exogenous	
CFCs	Exogenous	1.1 %
PFCs	Exogenous	
SF_6	Exogenous	
Montreal gases	Exogenous	N/A
CO	Exogenous	
NO_x	Exogenous	
VOC	Exogenous	
SO_2 fuel combustion	By source	
SO_2 other sources	Exogenous	
Fossil fuel burning BC	By source	
Fossil fuel burning OC		
Biomass burning BC	Exogenous	
Biomass burning OC	Exogenous	
Nitrate	Exogenous	
Mineral dust	Exogenous	

4.3 Climate policy analysis

REMIND is typically run in two modes: In the **climate policy mode** an additional climate policy constraint is imposed on the welfare maximization. Examples include limits on temperature, forcing (from Kyoto gases or all radiative substances), CO_2 concentration, cumulative carbon budget, and CO_2 emissions over time. The corresponding mitigation costs are calculated as a percentage reduction of the net present value consumption or GDP, with respect to the business-as-usual case.

The impact of a **pre-specified carbon tax pathway** can also be studied. For such scenarios, the tax is implemented as a penalty on emissions. Since full recycling of tax-revenues is assumed, the solution algorithm for such scenarios is less straightforward. The tax expenditure as part of each region's budget constraint is counterbalanced by a fixed amount of tax revenues. The model is solved iteratively with adjusted tax revenues until it matches the level of tax payments.

5 Key strengths and caveats

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

The central strength of REMIND 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 features:

- Full *where-flexibility* due to interregional trade of goods and emissions permits;
- Full *when-flexibility* due to the inter-temporal optimization and endogenous choice of a welfare-optimizing emissions 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 GHGs is under development.

Due to the simultaneous solution of the macro-economy and the energy system, as well as inter-temporal optimization, the computational effort for solving REMIND is very high. The level of computational complexity limits the amount of detail 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 in time and space. The challenges associated with the integration of variable renewable energies are only represented at an aggregated level (cf. Section 3.2.1).

- The representation of final energy demand lacks detail on the level of energy-consuming activities and technologies. Consequently, inertias from significant turnover rates for end-use equipment in some sectors, climate policy-relevant feedbacks from knowledge accumulation as well as technological spillovers and consumer choice of technologies are only represented in a stylized manner.

- Trading of composite goods is a free, unrestricted variable. The emerging trade pattern shows that trade flows from "North" to "South" in the base year, 2005. While this is in accordance with the theory, it contrasts the empirics in some regions (particularly China and USA). This can only be corrected by calibrating regionally differentiated time preference rates. Therefore, we do not use this variable as a default. The inaccurate reproduction of trade patterns in non-energy goods only has a limited influence on climate policy analyses because it applies to baseline and climate policy scenarios alike.

6 Model Applications

REMIND 1.5 is currently deployed in a number of major model inter-comparison exercises (e.g., EMF27, AMPERE, LIMITS) as well as stand-alone analyses. These studies are not yet available in the peer-reviewed literature. Therefore, this section summarizes the applications and results achieved with previous REMIND model versions.

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 its ability to analyze these interactions in an integrated framework. For instance, REMIND has been used to analyze decarbonization pathways in a number of studies. Leimbach et al. (2010a) used REMIND to assess the interrelations of climate policy and trade, and Bauer et al. (2012a) studied the role of renewables in mitigating climate change. A detailed analysis of the interplay between decarbonization strategies in different sectors and regions was performed in the context of the AME project (Luderer et al. 2012b). The change of investment patterns required for a low-carbon transition was also analyzed in this study.

6.2 Regional distribution of mitigation costs

Leimbach et al. (2008) presented the first analyses of regional mitigation costs for different climate policy regimes. The analysis in the RECIPE project (Luderer et al. 2012a) shows that regional mitigation costs can depart substantially from the global mean. The cost distribution can be broken down 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, e.g., renewable potentials. The second component is particularly important for the large exporters of fossil fuels, e.g., Russia and the Middle East. The third component depends not only on the international burden of sharing and institutional frameworks, but also on the price of carbon, which in turn, depends on stabilization targets and low-carbon technological innovations. Based on an analysis using REMIND, Lüken et al. (2011) showed that the portfolio of technologies strongly influences the regional distribution of mitigation costs. One conclusion is that under a restricted technology portfolio, the initial allocation of emissions permits among nations has a greater influence on mitigation costs than the full availability of all relevant low-carbon options.

6.3 Exploration of very low stabilization targets

The international community is committed to limiting global warming to no more than 2°C. Achieving this target with a high probability requires stabilizing GHGs at less than 450 ppm CO_2eq. As part of the ADAM model inter-comparison exercise (Edenhofer et al. 2010), the cost and feasibility of an emissions reduction trajectory that aims for 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 various types of technology to generate negative emissions.

The results suggest that stabilization in line with the 2°C target is feasible in terms of technology and is moderate in cost. While a broad range of technologies are required for climate change mitigation, very low stabilization relies heavily on the availability of CCS in combination with biomass in order to remove 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 increases in mitigation costs and changes in decarbonization pathways under imperfect settings.

As part of the ADAM project, REMIND was used to assess the cost and achievability of climate mitigation targets under restricted technology portfolios for a 550 and 400 ppm CO_2eq stabilization target (Leimbach et al. 2010b). Similarly, technology constraints for a 450 ppm CO_2-only target were assessed in the context of the RECIPE project (Bauer et al. 2012a; Luderer et al. 2012a). A robust conclusion across different stabilization scenarios and models is that restricting the deployment of renewables and CCS results in substantially higher mitigation costs, while limiting the expansion of nuclear power has a comparatively small effect. By increasing the stringency of the target, biomass and CCS become increasingly important. This is because combining bioenergy with CCS can generate negative emissions and is, therefore, pivotal for low stabilization scenarios. Bauer et al. (2012b) present a detailed analysis of the economics of nuclear power in the context of climate change mitigation.

A further analysis performed by the RECIPE model addresses the consequences of delaying the setup of an international climate policy regime (Jakob et al. 2012). If no climate policies are enacted until 2020, the 450 ppm CO_2 target can still be achieved, albeit at a 40% higher cost than in the case of immediate action. The analysis also shows 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.

Acronyms and Abbreviations

Acronym/Abbreviation	Definition
CCS	Carbon capture and storage
CES	Constant elasticity of substitution
CO_2eq	CO_2 equivalent
DLR	Deutsches Zentrum für Luft- und Raumfahrt, German Aerospace
GDP	Gross domestic product
GHG	Greenhouse gases
ESM	Energy system module
F-gases	Fluorinated greenhouse gases
LbD	Learning by doing
ppm	Parts per million
MAC	Marginal abatement costs
REMIND	Regional Model of Investments and Development
MERGE	Model for Evaluating Regional and Global Effects
RICE	Regional Integrated Model of Climate and the Economy
RECIPE	Report on Energy and Climate Policy in Europe
AME	Asian Modeling Exercise
IEA	International Energy Agency
WEO	World Energy Outlook
HVDC	High-voltage, direct current
PV	Photovoltaic panel
CSP	Concentrated solar power
VRE	Variable renewable electricity

Chemical symbols

Symbol	Name
BC	Black carbon
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
N_2O	Nitrous oxide
NOx	Nitrogen oxides
OC	Organic carbon
SO_2	Sulphur dioxide
VOC	Volatile organic compounds

Definition and aggregation of REMIND regions

#	Region code	Region type	Definition
1	AFR	World region	Africa
2	CHN	Country	China
3	EUR	World region	Europe
4	IND	Country	India
5	JAP	Country	Japan
6	LAM	World region	Latin America
7	MEA	World region	Middle East
8	OAS	World region	Other Asian
9	ROW	World region	Rest of the World
10	RUS	Country	Russian federation
11	USA	Country	United States of America

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