Description of the REMIND model (Version 1.6)

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- Potsdam, November 2015 -

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Overview

This document describes the Integrated Assessment Model REMIND, which stands for "Regional Model of Investments and Development" in its version 1.6. It updates the documentation of the previous model version 1.5 (Luderer et al. 2013) The model was originally introduced by Leimbach et al. (2010b). 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**. Figure 1 illustrates its general structure. The macro-economic core of REMIND is a Ramsey-type optimal growth model in which inter-temporal welfare is maximized. REMIND divides the world 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) (see Figure 2). The model computes the market equilibrium either as a Pareto optimal solution in which global welfare is maximized (cooperative solution assuming all externalities are internalized), or as a non-cooperative Nash solution in which welfare is optimized on the regional level without internalization of interregional externalities. The model explicitly represents **trade** in final goods, primary energy carriers, and in the case of climate policy, emissions allowances. **Macro-economic production** factors are capital, labor, and final energy. REMIND uses economic **output** 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. A production function with constant elasticity of substitution (nested **CES production function**) determines the final energy demand. 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.

REMIND uses reduced-form emulators derived from the detailed land-use and agricultural model MAgPIE to represent land-use and agricultural emissions as well as bioenergy supply and other land-based mitigation options. REMIND can also be run in fully coupled mode with the MAgPIE model (Lotze-Campen et al. 2008).

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

The model accounts for the full range of anthropogenic greenhouse gas (GHG) emissions, most of which are represented by source. The MAGICC 6 (Meinshausen et al. 2011b) climate model is used to translate emissions into changes in atmospheric composition, radiative forcing and climate change.

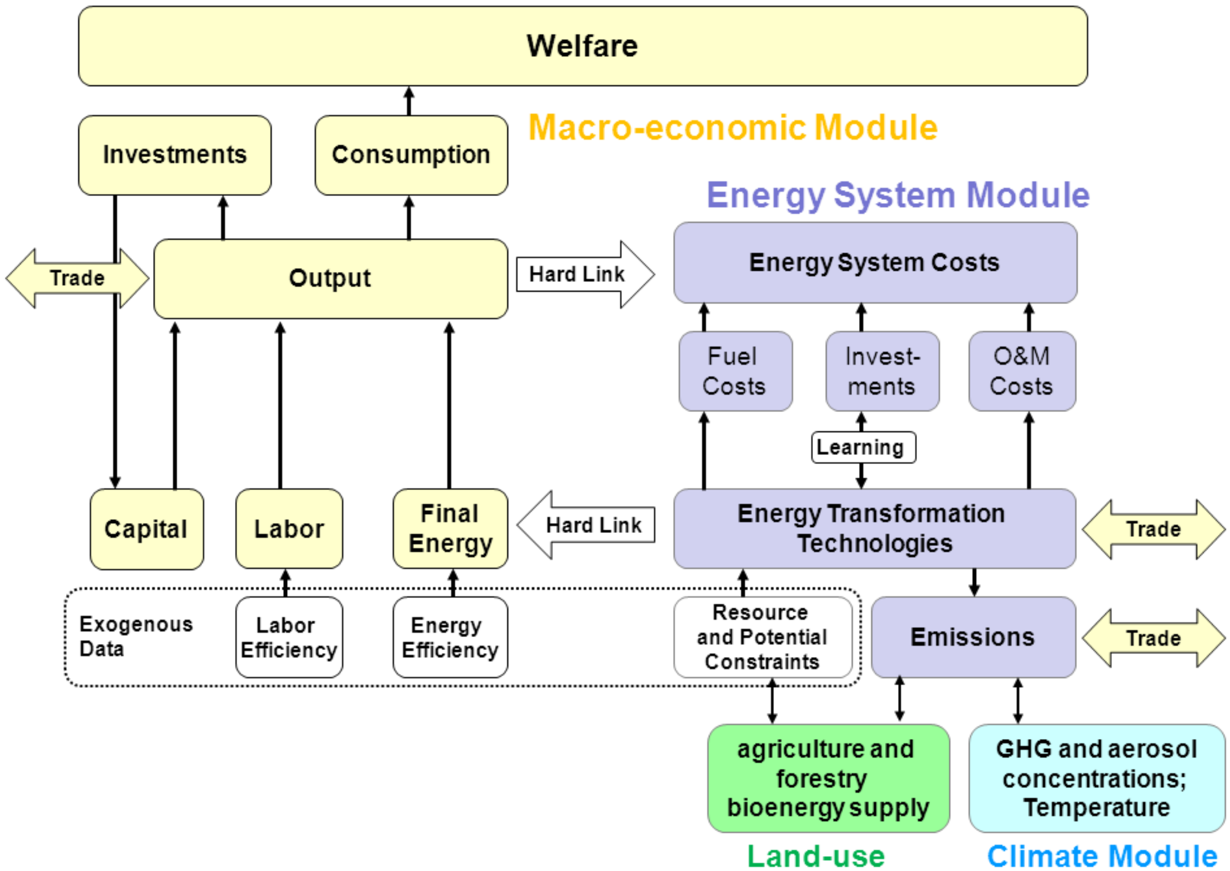

Figure 1. General structure of the REMIND model.

In terms of its macro-economic formulation, REMIND resembles other well established integrated assessment models such as RICE (Nordhaus and Yang 1996) and MERGE (Manne et al. 1995). However, REMIND is broader in scope and features a substantially higher level of detail in the representation of energy-system technologies, trade, and global capital markets. In contrast to RICE, REMIND does not monetize climate damages, and therefore is not applied to determine a (hypothetical) economically optimal level of climate change mitigation ("cost-benefit mode"), but rather efficient strategies to attain an exogenously prescribed climate target ("cost-effectiveness mode").

Table 1 provides an overview of REMIND's key features. Sections 2–5 describe individual modules, along with the relevant parameters and assumptions. Section 6 lists the model's strength and limits.

Table 1. Key features of REMIND, and reference to the relevant sections in this documentation.

Key feature	REMIND	Section
Macro-economic solution concept	Ramsey-type growth model with inter-temporal optimization of welfare	2.3
Discounting	Endogenous interest rate in the international capital market reflects the pure time preference rate (default 3%), as well as the marginal utility of consumption which diminishes with increasing per-capita consumption in line with the Keynes-Ramsey-Rule. This gives rise to a model endogenous interest rate of around 5-6%.	2.3.1
Expectation formation	Default: perfect foresight.	1.3
Cooperation	Either cooperative pareto-optimal solution with maximization of global welfare (*Negishi*), or non-cooperative *Nash* solution maximizing welfare for each individual regional.	2.3
Economic sectors, macro-economic production system	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.	2.3.2
International macro-economic linkages / Trade	Single market for all commodities (energy resources, final good, permits).	2.3.3
Investment dynamics	Capital motion equations, vintages for energy supply technologies, adjustment costs for acceleration of capacity expansion.	2.3.2; 3.2
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.	3.3 -3.4
Representation of end-use sectors	Stationary (which aggregates industry, residential and commercial), transport.	3.3 -3.4
Energy production system and 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 with a global learning curve for wind, solar PV and solar CSP (cf. Section 3.2.1), as well as hybrid, electric and fuel cell vehicle technologies (cf. Section 3.3.1). Labor productivity and energy efficiency improvements are calibrated to reproduce historic patterns.	2.2 ; 2.4; 3.2.1; 3.3.1
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, greenhouse gas taxes .	1.4
Land-use	Representation of bioenergy supply, land use CO_2 and agricultural non-CO_2 emissions based on a detailed land use model.	4

1 Model scope and methods

1.1 Model concept, solver and details

REMIND (Regional Model of Investments and Development) (Leimbach et al. 2010a; Luderer et al. 2012; Bauer et al. 2012a; Bauer et al. 2012b; Luderer et al. 2013) is a global multi-regional model incorporating the economy, the climate system, and a detailed representation of the energy sector. It solves for an inter-temporal Pareto optimum in economic and energy investments in each model region, fully accounting for inter-regional trade in goods, energy carriers and emissions allowances. REMIND allows for the analysis of technology options and policy proposals for climate change mitigation as well as related energy-economic transformation pathways.

The macro-economic core of REMIND in each region is a Ramsey-type optimal growth model, where the inter-temporal welfare of each region is maximized. 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. It is possible to compute the co-operative Pareto-optimal global equilibrium including inter-regional trade as the global social optimum using the Negishi method (Negishi 1972), or the non-cooperative market solution among regions using the Nash concept (Leimbach et al. 2015). In the absence of non-internalized externalities between regions, these two solutions coincide. The inclusion of inter-regional externalities (in particular technology spillovers) causes a difference between the market and the socially optimal solution.

The macro-economic core and the energy system module are hard-linked via the final energy demand and costs incurred by the energy system (see Bauer et al. (2008) for further details). Economic activity results in demand for final energy such as transport energy, electricity, and non-electric energy for stationary end uses. A production function with constant elasticity of substitution (nested CES production function) determines final energy demand. The energy system module accounts for regional 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). REMIND determines non-CO_2 GHG emissions by applying marginal abatement costs curves relative to baseline emission levels that depend on activity variables or by assuming exogenous scenarios. For numerical reasons, we use a reduced-form climate module, which is calibrated to the MAGICC-6 model (Meinshausen et al. 2011a), to translate emissions into changes in atmospheric GHG concentrations, radiative forcing, and global mean temperature. For a more detailed evaluation, the model can be linked to the full MAGICC-6 climate model in an ex-post mode. REMIND is solved as a non-linear programming model. It is programmed in GAMS (Brooke et al. 1992) and uses the CONOPT solver (Drud 1994) by default.

1.2 Regional Detail

REMIND is a multi-regional model of global coverage, that divides the world into 11 regions (Figure 2). There are 5 individual 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 among others Australia, Canada, New Zealand, Norway, Turkey, and the Republic of South Africa).

REMIND explicitly represents trade in the composite good (aggregated output of the macro-economic system), primary energy carriers (coal, gas, oil, biomass, uranium), and in the case of climate policy, emissions allowances (cf. Section 2.3.3).

Global learning curves represent endogenous technological change through learning-by-doing for wind and solar power, as well as electric and fuel cell vehicle technologies. The spillovers among regions caused by this global learning are not internalized in the non-cooperative market solution, whereas in the socially optimal cooperative solution they are.

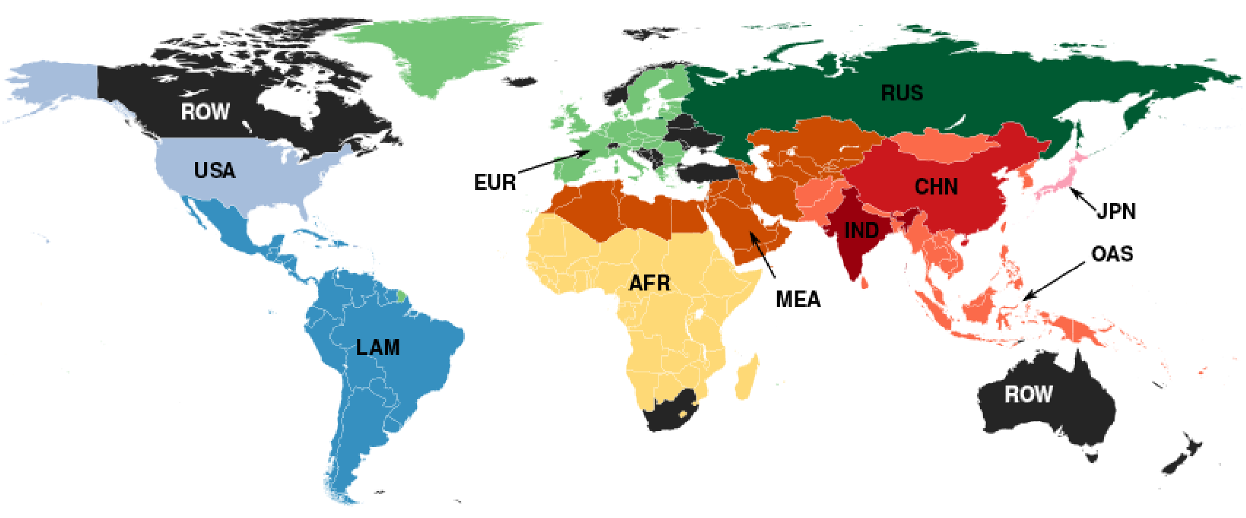

Figure 2. Regional definitions used in the REMIND model.

1.3 Temporal process

REMIND is an inter-temporal optimization model, solving for the perfect-foresight equilibrium 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 2060, ten-year time steps until 2100 and twenty-year time steps after that. We typically focus analysis on the time span 2005-2100, but run the model until 2150 to avoid distortions due to end effects.

1.4 Policy

In the climate policy mode, REMIND imposes an additional climate policy constraint 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. REMIND calculates the corresponding mitigation costs as a reduction of consumption or GDP with respect to the baseline case.

We can also study the impact of a pre-specified carbon tax pathway. For such scenarios, REMIND implements the tax as a penalty on emissions. Since it assumes full recycling of tax-revenues, the solution algorithm for such scenarios is less straightforward. It counterbalances the tax expenditure as part of each region's budget constraint by a fixed amount of tax revenue that is recycled in a lump-sum manner. It then runs iteratively with adjusted tax revenues until it matches the level of tax payments.

REMIND also accounts for subsidies and taxes in the energy sector and implements them 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 per year. The development of fossil fuel subsidies and taxes over REMIND's time horizon is prescribed by scenario assumptions. In the default case, subsidies phase out by 2050. Historical data are based on the IEA subsidies database and the International Energy Database, ENERDATA (Schwanitz et al. 2014).

2 Economy and demand drivers

2.1 Population and GDP

Population and GDP are main drivers of future energy demand and, thus, GHG emissions in REMIND. We base population and GDP inputs on the Shared Socio-economic Pathway (SSP) scenarios (KC and Lutz 2014; Dellink et al. 2015). By default, we apply the population projections (both total population as well as working age population) from IIASA and the GDP scenarios from the OECD (https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=about). Individual projections are available for each of the five SSP scenarios. By default, we use SSP2 scenario data as they represent a middle-of-the road scenario. To calibrate GDP, which is an endogenous result of the growth engine in REMIND, we calibrate labor productivity parameters in an iterative procedure so as to reproduce the OECD's GDP reference scenarios. Within REMIND GDP is measured in market exchange rates (MER).

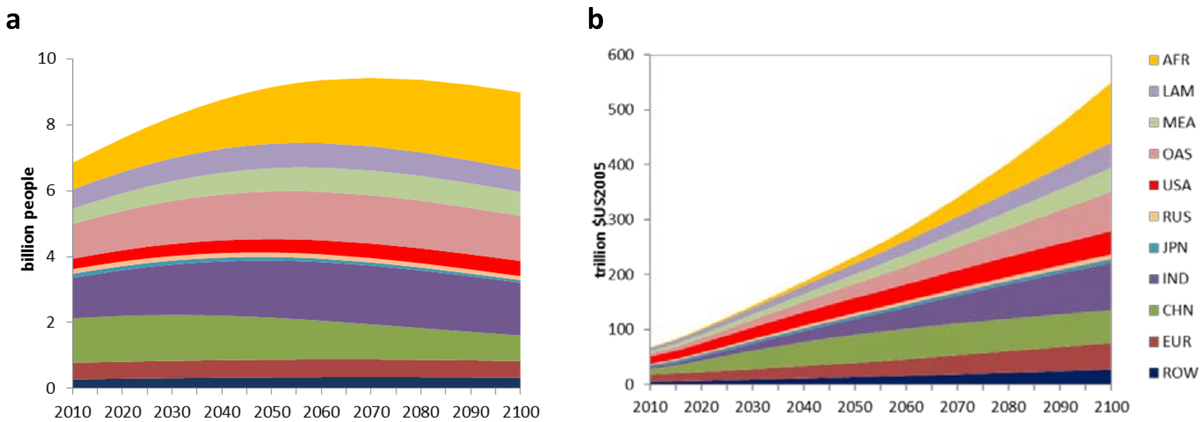

Figure 3. Projections of (a) population and (b) GDP used in the REMIND SSP2 (“Middle-of-the-Road”) scenario.

2.2 Final Energy Demand

Economic activity results in demand for final energy determined by the macro-economic production function. REMIND distinguishes between the stationary end-use sector (aggregating industry and residential & commercial) and the transport end-use sector. The distribution of energy carriers to end-use sectors forms the interface between the macro-economic module and the energy system module. Table 2 maps secondary energy supply to end-use sectors. REMIND represents transport and distribution of secondary energy carriers in terms of capacities that require investments and incur costs for operation and maintenance. These costs shift the final energy supply curves and depend on the mode of transportation.

In REMIND, there are 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; IEA 2007b). We assume energy-related CES-efficiency parameters to change at the same rate as labor efficiency, including an additional adjustment factor. The model calibrates this factor separately for each region and each final energy type, so as to induce a gradual shift from solids and liquids to gases, transportation fuels and electricity, reflecting patterns of modernization observed in the past. We derive the reference trajectories for baseline scenarios without climate policy based on the following guidelines:

- Short- and mid-term final energy demand follows the trend for the years 2000-2010, which is consistent with 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/capita).

Second, the CES production function allows for price-dependent substitutions between aggregated energy and capital (substitution elasticity of 0.5). The introduction of additional constraints on the supply side (e.g., carbon taxes, resource, or emission constraints) results in higher energy prices and thus lower final energy consumption compared to the reference trajectories. As a consequence, the share of macro-economic capital input in the production function increases. In absence of distortions, 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.

Table 2. 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

2.3 Macro-economy

2.3.1 Objective function

REMIND models each region *r* 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 can compute maximum regional utility (welfare) by two different solution concepts – the Negishi approach and the Nash approach (Leimbach et al. 2015). In the Negishi approach, which computes a cooperative solution, the objective of the Joint Maximization Problem is the weighted sum of regional utilities, maximized subject to all other constraints:

$$W = \sum_r n_r U_r$$

An iterative algorithm adjusts the weights so as to equalize the intertemporal balance of payments of each region over the entire time horizon. This convergence criterion 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.

The Nash solution concept, by contrast, arrives at the Pareto solution not by Joint Maximization, but by maximizing the regional welfare subject to regional constraints and international prices that are taken as exogenous data for each region. The intertemporal balance of payments of each region has to equal zero and is one particular constraint imposed on each region. The equilibrium solution is found by iteratively adjusting the international prices until global demand and supply are balanced on each market. The choice of the solution concept is also important for the representation of trade, as discussed in Section 2.3.3.

In contrast to the Negishi approach, which solves for a co-operative Pareto solution, the Nash approach solves for a non-cooperative Pareto solution. The cooperative solution internalizes interregional spillovers between regions by optimizing the global welfare by using Joint Maximization. The non-cooperative solution considers spillovers as well, but they are not internalized. The relevant externalities are the technology learning effects in the energy sector.

2.3.2 Production structure

REMIND uses a nested production function with constant elasticity of substitution (CES) to determine a region's gross domestic product (GDP) (see Figure 4). Inputs at the upper level of the production function include labor, capital, and final energy. We use the population at working age to determine labor. 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. In turn, these two energy types are determined by the nested CES functions of more specific final energy carriers. REMIND assumes substitution elasticities between 1.5 and 3 for the lower levels of the CES nest. It assigns an efficiency parameter to each production factor in the various macroeconomic CES functions. The changes of efficiency parameters over time are tuned such that baseline economic growth and energy intensity improvements match exogenous scenario specifications, such as the shared socio-economic pathways SSP (O'Neill et al. 2014).

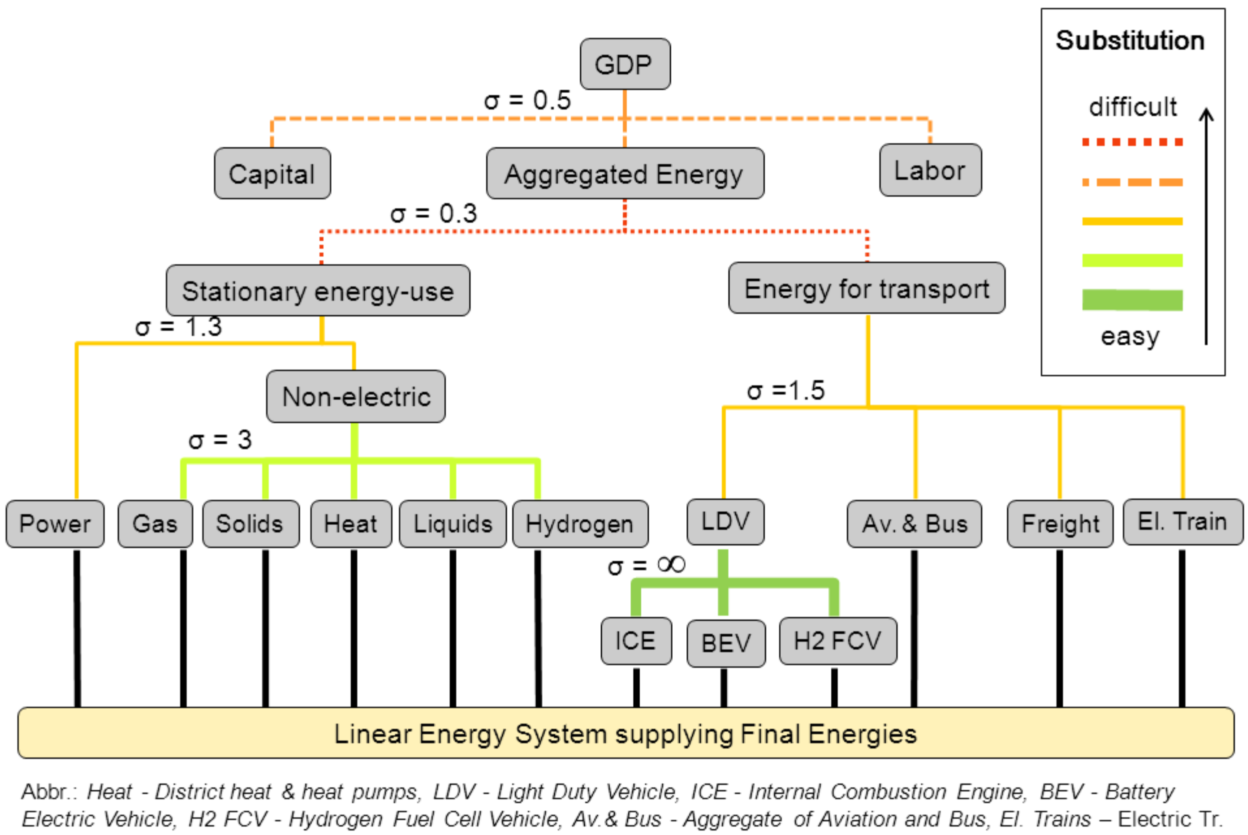

Figure 3. Production structure of REMIND. Linear production functions describe the conversion of primary energy (lowest level) to final energy carriers. Nested CES structures describe the aggregation of final energy carriers for end-use.

The macro-economic budget constraint for each region ensures 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%)[2], energy system expenditures E_{rt} and the export of composite goods M^G_{rt}. Energy system expenditures consist of investment costs, fuel costs, and operation and maintenance costs.

$$Y_{rt} - X_{rt}^{G} + M_{rt}^{G} \geq C_{rt} + I_{rt} + E_{rt}$$

The balance of demand from the macro-economy and supply from the energy system delivers equilibrium prices at the final energy level.

2.3.3 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). It assumes that renewable energy sources (other than biomass) and secondary energy carriers are non-tradable across regions. As an exception, REMIND can consider bilateral trade in electricity between specific region pairs (e.g., Europe and North Africa / Middle East), but this is not part of the default scenario. According to energy statistics, trade in refined liquid fuels does take place in the real world, but to a smaller extent than crude oil. Since REMIND considers crude oil trade, the liquid fuel trade only has a small share and is attributed to crude oil trade. To be consistent with trade statistics, REMIND allocates the trade in petroleum products to crude oil trade.

Within the Negishi approach, for each good *i* a global trade balance equation ensures that markets are cleared:

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

REMIND models regional trade via a common pool, with the exception of the bilateral electricity trade mentioned above. 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. In line with the classical Heckscher-Ohlin and Ricardian models (Heckscher et al. 1991), trade between regions is induced by differences in factor endowments and technologies. REMIND also represents the additional possibility of inter-temporal trade. This can be interpreted as capital trade or borrowing and lending.

[2] Macro-economic investments are subject to adjustment costs, which scale with the square of the rate of change in investments, relative to the existing capital stock.

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, where π^i_r is the present value price of good *i*.

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

In this equation discounting is implicit by using present value prices.

Inter-temporal trade and the capital mobility implied by trade in the composite good, cause prices of mobile factors to equalize, thus providing the basis for an inter-temporal and inter-regional equilibrium. Since no capital market distortions are considered, the interest rates equalize across regions. Similarly, permit prices equalize across regions, unless their trade is restricted. By contrast, final energy prices and wages can differ across regions because these factors are immobile. Prices for traded primary energy carriers differ according to the transportation costs.

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

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 surplus balance regions with a current account deficit. The inter-temporal budget constraints clear debts and assets that accrue through trade over time. 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. REMIND models trading of emissions permits 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 freely traded among world regions. A permit-constraint equation ensures that an emissions certificate covers each unit of GHG emissions. Trade 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.

The treatment of trade in REMIND depends on the solution concept (Nash vs. Negishi). The two approaches are in a dual relationship. The Negishi approach considers the trade balances of all goods explicitly and adjusts the welfare weights in order to guarantee that the intertemporal balance of payments of each region is settled. REMIND derives the prices of traded goods from the optimal solution in each iteration. The Nash approach adjusts goods prices until demand and supply of traded goods are equalized. In each iteration, the international prices are exogenous parameters for all regions. Furthermore, each region is subject to an intertemporal budget constraint, i.e. the intertemporal balance of payments has to be equal to zero.

Table 3. Characterization of the treatment of trade in the two alternative Negishi and Nash solution concepts.

	Negishi	Nash
Global trade balances in each period	Exogenous constraint	Prices are adjusted until supply (export) and demand (import) equalize
Prices of internationally traded goods	Endogenously determined by the optimal solution	Exogenous parameter, adjusted between iteration
Regional intertemporal balance of payments	Negishi weights adjusted until all payment balance have converged to zero	Constraint of the regional optimization problem

2.4 Technological change

REMIND assumes endogenous technological change through learning-by-doing for wind and solar power, electric (BEV) and fuel cell vehicle (FCV) technologies, as well as variable renewable energy (VRE) storage, through global learning curves and internalized spillovers. The specific investment costs for wind, solar PV, and solar CSP decrease by 12, 20, and 9%, respectively, for each doubling of cumulated capacity. The capital costs of the generalized storage units for VRE, as well as of advanced vehicle technologies (BEV, FCV), decrease with a 10% learning rate. REMIND reduces learning rates as capacities increase such that the investment costs asymptotically approach exogenously prescribed floor costs (cf. Table 6 and Table 8).

As discussed in Section 2.2, REMIND represents energy efficiency improvements via an exogenously prescribed increase in the efficiency parameters of the CES production function, as well as price induced reductions in energy demand and changes in technology choice.

REMIND represents investment dynamics in terms of capital motion equations, vintages for energy supply technologies and adjustment costs related to the acceleration of capacity expansion (for further details see Section 3.2).

3 Energy

Energy is an input factor demanded by the economy, as different final energy types are inputs to GDP generation in the nested CES production function as described in Figure 4. This chapter explains the different primary energy resources modelled and their potentials (Section 3.1).

REMIND considers more than 40 technologies for the conversion of these resources into different secondary energy types (Sections 3.2.1, 3.2.2) and the conversion of secondary to final energy (Section 3.2.3). The subsequent subsections explain the use of those final energy types in the different demand sectors (Sections 3.3 and 3.4).

3.1 Energy resource endowments

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. It is possible to trade coal, oil, gas, uranium, and biomass across regions, but the trading of resources is subject to regional and resource-specific trade costs.

3.1.1 Exhaustible resources

REMIND characterizes exhaustible resources such as coal, oil, gas, and uranium in terms of extraction cost curves. Fossil resources (e.g., oil, coal, and gas) are further defined by decline rates and adjustment costs (Bauer et al. 2013). 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, we use region-specific extraction cost curves that relate production cost increases to cumulative extraction (IHS CERA 2012; Rogner et al. 2012).

Figure 5 shows extraction cost curves at the global level as implemented for various SSPs. More details on the underlying data and method will be presented in a separate pape (Bauer et al. under review). The default scenario used in REMIND is SSP2 (“Middle-of-the-Road”). In the model, these fossil extraction cost input data are approximated by piecewise linear functions that are employed for fossil resource extraction curves. Additionally, as a scenario choice, it is possible to make oil and gas extraction cost curves 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.

For uranium, extraction costs follow a third-order polynomial parameterization. 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).

REMIND prescribes decline rates 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 2008a; IEA 2009). An additional dynamic constraint limits the extraction growth of coal, oil, and gas to 10% per year. In addition, we use adjustment costs to represent short-term price markups resulting from rapid expansion of resource production (Dahl and Duggan 1998; Krichene 2002; Askari and Krichene 2010).

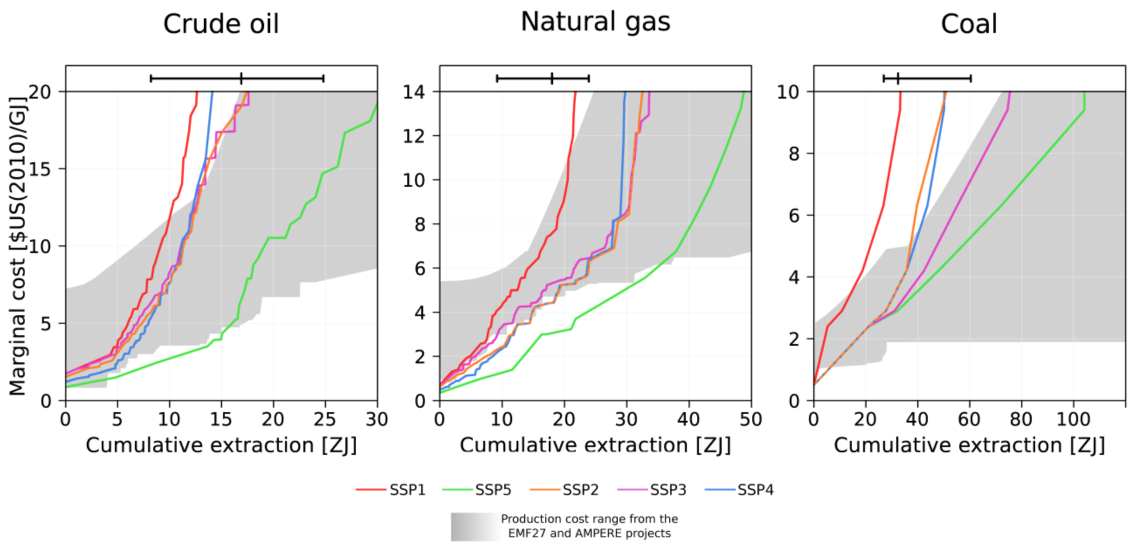

Figure 4: Global aggregate Cumulative Availability Curves of coal, oil and gas for the different SSPs. The bars at the top indicate the minimum, median and maximum extraction in baseline scenarios in the EMF-27 study; the shaded area covers the range of extraction cost functions given in the EMF-27 and AMPERE studies.

Trade costs in REMIND are both 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 Bioenergy

REMIND represents three types of bioenergy feedstocks:

(a) First-generation biomass produced from sugar, starch, and oilseeds (typically small in quantity, based on an exogenous scenario);

(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.

To represent supply of purpose-grown bioenergy from the land-use sector, REMIND draws on an emulation of the land-use model MAgPIE (Model of Agricultural Production and its Impact on the Environment) (Lotze-Campen et al. 2008; Popp et al. 2010; Lotze-Campen et al. 2010). The emulator describes supply costs and total agricultural emissions as a function of bioenergy demand, as described in detail in Klein et al. (2014). The supply curves capture the time, scale and region dependent change of bioenergy production costs, as well as path dependencies 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, we assume that the use of traditional biomass (supplied by residues) is phased out, as modern and less harmful fuels are increasingly used with rising incomes (Sims et al. 2010). We also assume that first generation modern biofuels are phased out, reflecting their high costs and accounting for concerns about land-use impacts, co-emissions, and competition with food production from first-generation biofuels (Fargione et al. 2008; Searchinger et al. 2008). As a consequence, the main sources of bioenergy in REMIND scenarios are second-generation purpose-grown biomass and ligno-cellulosic agricultural and forestry residues.

To further reflect concerns about the sustainability of large-scale deployment of lingo-cellulosic bioenergy, REMIND assumes an ad valorem tax on bioenergy. The tax increases linearly from 0 to 100% between 2030 and 2100 and is applied to the bioenergy price given by the emulator (see above). Based on the current public debate, we consider this tax to be a reflection of the potential institutional limitations on the widespread-use of bioenergy.

3.1.3 Non-biomass renewables

REMIND models resource potentials for non-biomass renewables (hydro, solar, wind, and geothermal) using region-specific potentials. For each renewable energy type, we classify the potentials into different grades, specified by capacity factors (Figure 6). Superior grades have higher capacity factors, which correspond to more full-load hours per year. This implies higher energy production 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 (Luderer et al. 2014). 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 were developed in Pietzcker et al. (2014b) in cooperation with the German Aerospace Center DLR. In total, the solar potential is almost unlimited, with a total amount of 6500 EJ/year for PV and 2000EJ/year for CSP. However, the resource quality differs strongly across regions, so that some regions have mostly sites with low full-load hours. To account for the competition between PV and CSP for the same sites with good irradiation, an additional constraint for the combined deployment of PV and CSP was introduced in REMIND (Pietzcker et al. 2014b). This implies that the sum of the area used by both technologies is smaller than the total available area.

The regionally aggregated wind potentials were developed based on a number of studies (Hoogwijk 2004; Brückl 2005; Hoogwijk and Graus 2008; 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 WGBU (2003), but is less than one fifth of the potential in Lu et al. (2009).

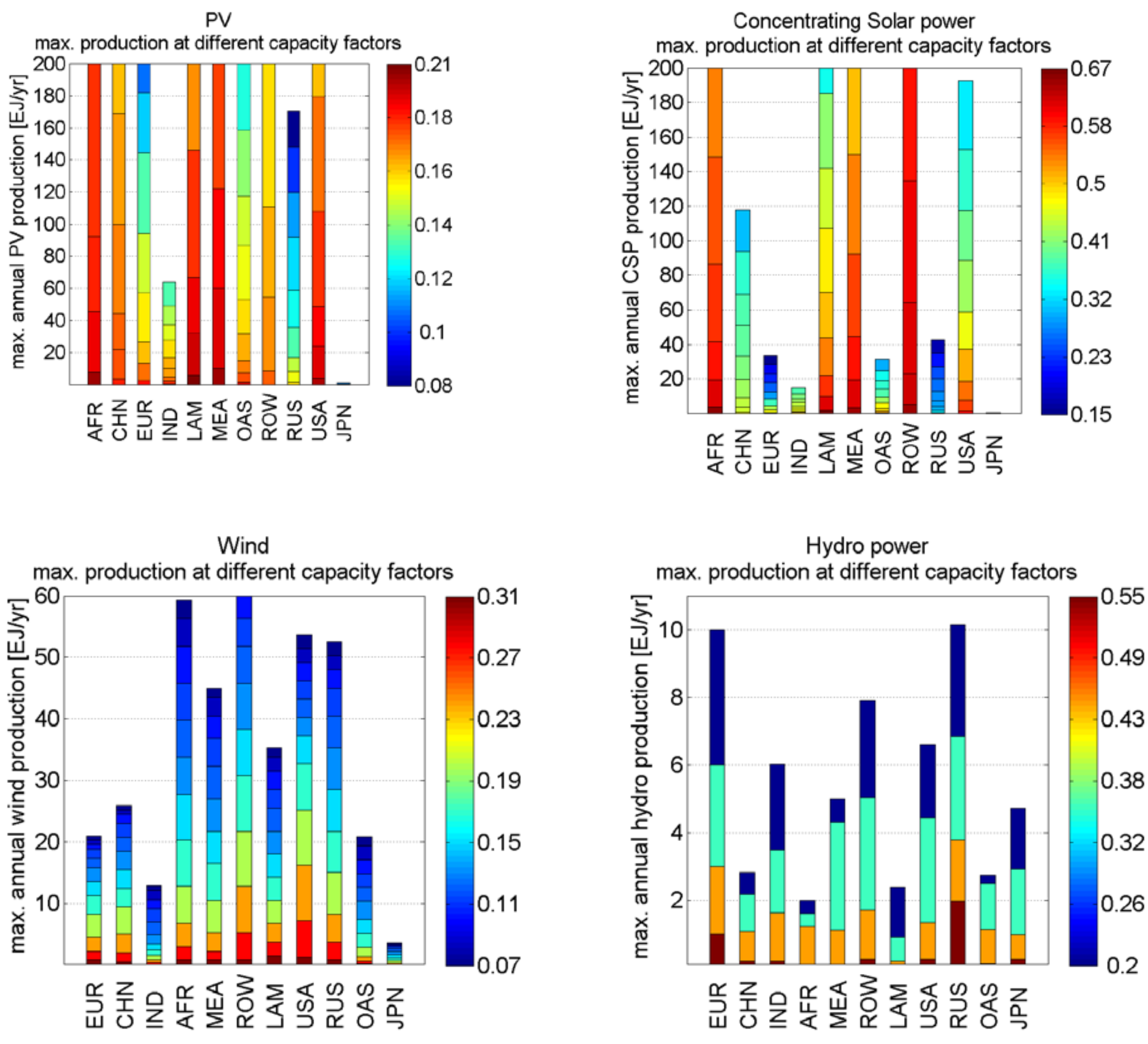

Figure 5. Regionalized resource potentials for solar PV, CSP, wind and hydro power as a function of resource quality expressed in terms of attainable capacity factors.

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

3.2 Energy conversion

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. In general, technologies providing a certain secondary energy type compete linearly against each other, i.e. technology choice follows cost optimization based on investment costs, fixed and variable operation and maintenance costs, fuel costs, emission costs, efficiencies, lifetimes, and learning rates. REMIND assumes full substitutability between different technologies producing one energy type.

The secondary energy carriers included in REMIND are:

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

REMIND specifies each technology through a number of characteristic parameters

- Specific overnight investment costs that are constant for most technologies and decrease due to learning-by-doing for some relatively new technologies (see below).
- Cost markups due to financing costs over the construction time.
- Fixed yearly operating and maintenance costs in percent of investment costs.
- Variable operating costs (per unit of output, excluding fuel costs).
- Conversion efficiency from input to output.
- Capacity factor (aaximum utilization time per year). This parameter also reflects maintenance periods and other technological limitations that prevent the continuous operation of the technology.
- Technical lifetime of the conversion technology in years.
- If the technology experiences learning-by-doing: initial learn rate, initial cumulative capacity, as well as floor costs that can only be approached asymptotically.

REMIND represents all technologies 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 out of technologies is achieved. The model allows for pre-mature retirement of capacities before the end of their technological life-time (at a maximum rate of 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; IEA 2007b). 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, REMIND adjusts by-production coefficients of combined power-heat technologies (CHP) by region to meet the empirical conditions of the base year.

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

3.2.1 Electricity

Around twenty electricity generation technologies are represented in REMIND, see Table 4, with several low-carbon (CCS) and zero carbon options (nuclear and renewables).

Table 4. Energy Conversion Technologies for Electricity (Note: * indicates that technologies can be combined with CCS)

Primary Exhaustible Resources	Technology
Coal	Coal combined heat and power plant Conventional coal power plant* Integrated coal gasification combined cycle* Oxyfuel*
Oil	Diesel oil turbine
Gas	Gas combined heat and power plant Gas turbine Natural gas combined cycle*
Uranium	Light water reactor
Primary Renewable resources	**Technology**
Solar	Solar photovoltaic Concentrated solar power
Wind	Wind turbine
Hydropower	Hydro power
Geothermal	Hot dry rock
Biomass	Biomass combined heat and power plant Integrated biomass gasification combined cycle*

Table 5. Techno-economic characteristics of technologies based on exhaustible energy sources and biomass (Iwasaki 2003; Hamelinck 2004; Bauer 2005; Ansolabehere et al. 2007; Gül et al. 2007; Ragettli 2007; Schulz 2007; Uddin and Barreto 2007; Rubin et al. 2007; Takeshita and Yamaji 2008; Brown et al. 2009; Klimantos et al. 2009; Chen and Rubin 2009)

		Life-time	Overnight investment costs		O&M costs		Conversion efficiency		Capture Rate	Capacity factor	
		Years	$US/kW		$US/GJ		%		%		
			No CCS	With CCS	No CCS	With CCS	No CCS	With CCS	With CCS	No CCS	With CCS
Coal	PC	40	1400	2400	2.8	5.1	45-51#	36	90	0.75	0.85
	Oxyfuel	40		2150		4.7		37	99		0.75
	IGCC	35	1650	2050	3.4	4.6	43-52#	38-48#	90	0.75	0.75
	C2H2*	35	1260	1430	1.9	2.1	59	57	90	0.8	0.8
	C2L*	35	1450	1520	4.2	5.0	40	40	70	0.85	0.85
	C2G	35	1200		1.4		60			0.9	
	NGT	30	350		1.5		38-43#			0.4	
Gas	NGCC	35	650	1100	1.0	1.7	56-64#	48/59	90	0.75	0.85
	SMR	35	500	550	0.6	0.7	73	70	90	0.9	0.9
Biomass	BIGCC*	40	1860	2560	4.2	6.0	42	31	90	0.8	0.8
	BioCHP	40	1375		5.0		43			0.46	
	B2H2*	35	1400	1700	5.7	6.8	61	55	90	0.9	0.9
	B2L*	35	2500	3000	3.8	4.9	40	41	50	0.9	0.9
	B2G	40	1000		1.9		55			0.9	
Nuclear	TNR	40	3000		5.2		33§			0.8	

For abbreviations see Table "Acronyms and Abbreviations" ; * 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 after 2045) are represented by high-end ranges.*

For variable renewable energies, we implemented two parameterized cost markup functions for storage and long-distance transmission grids - see Section 3.2.3. To represent the general need for flexibility even in a thermal power system, we included a further flexibility constraint based on Sullivan et al. (2013).

The techno-economic parameters of power technologies used in the model are given in Table 5 for fuel-based technologies and in Table 6 for non-biomass renewables. For wind, solar and hydro, capacity factors depend on grades, see Section 3.1.3.

Table 6. Techno-economic characteristics of technologies based on non-biomass renewable energy sources (Neij et al. 2003; Nitsch et al. 2004; IEA 2007a; Junginger et al. 2008; Pietzcker et al. 2014)

	Lifetime	Overnight Investment costs	Floor costs	Learning Rate	Cumulative capacity 2005	O&M costs	Capacity factor
	Years	**$US/kW**	**$US/kW**	**%**	**GW**	**% of Inv.Costs**	
Hydro	70	2300	-	-	-	2	0.2-0.5
Geo HDR	30	3000	-	-	-	4	1
Wind	25	1400	900	12	60	2	0.07-0.31
SPV	30	4900	500	20	5	1.5	0.1-0.2
CSP	30	8600	1300	9	0.5	2.5	0.2-0.67

3.2.2 Conversion to non-electric energy carriers

REMIND also features a broad range of technologies for the supply of non-electric secondary energy carriers, such solids, liquids, gases, heat and hydrogen, as listed in Table 7. Note that biomass is the main non-fossil feedstock for the supply of non-electric energy.

Table 7. Conversion Technologies for non-electric energy carriers (Note: * indicates that technologies can be combined with CCS)

		RESOURCE	
		Fossil resources	**Renewable resources and electricity**
SECONDARY ENERGY CARRIERS	**Solids**	CoalTR	BioTR
	Liquid fuels	Coal to liquids* Crude oil refining	B2L Bioethanol
	Gases	Coal gasification Gas transformation	Biomass gasification
	Heat	Coal heating plant Coal combined heat and power (CHP) plant Gas heating plant Gas combined heat and power (CHP) plant	Geothermal heat pump, Biomass heating plant Biomass CHPplant
	Hydrogen	Coal to hydrogen* Steam methane reforming*	Biomass to hydrogen Electrolysis (from electricity)

3.2.3 Grid and infrastructure

3.2.3.1 General distribution costs

REMIND represents electricity/gas/hydrogen grids as well as distribution costs for solids and liquids in terms of linear cost-markups on final energy use.

3.2.3.2 Variable renewable energy sources

Variable renewable electricity (VRE) sources such as wind and solar PV require storage to guarantee a stable supply of electricity (Pietzcker et al. 2014b). Since the techno-economic parameters applied to CSP include the cost of thermal storage to continue electricity generation at nighttime, REMIND assumes that CSP requires 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[3]. As a measure of the demand for balancing, the model calculates a time-, region-, and VRE-specific scale-factor α_{VRE}, where E is the total electricity produced by the renewable energy source, S_{VRE} is the market share of the renewable energy source after storage losses and curtailment.

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

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 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 α_{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. REMIND assumes that grid requirements increase with market share. Furthermore, since resource potentials for PV (suitable for decentralized installation) are not as localized as those for wind and CSP, REMIND assumes that grid costs for PV are 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%, marginal integration costs (including storage, curtailment and grid costs) are in a range of 19-25 USD/MWh for wind, 20-35 USD/MWh for PV, and 8-15 USD/MWh for CSP. For more details on the modeling of VRE integration in REMIND, see Pietzcker et al. (2014b).

[3] 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.

3.2.3.3 Carbon capture and Storage

Deployment of carbon capture and storage (CCS) can curb emissions from fossil fuel combustion. In REMIND, CCS technologies exist for generating electricity as well as for the production of liquid fuels, gases, and hydrogen from coal. Moreover, it is possible to combine biomass 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 which are largely based on IEA (2008b). In total, the global storage potential amounts to around 1000 GtC . It is smaller for EUR with 50 GtC, Japan with 20 GtC, and India with 50 GtC. The yearly injection rate of CO_2 is assumed not to 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.

3.3 Transport

REMIND models the transport sector by using a hybrid approach combining top-down and bottom-up elements (see Figure 4). Specifically, mobility demands for the four modeled transport sub-sectors (passenger-light duty vehicles (LDV), freight, electric rail, passenger-aviation and buses) are derived in a top-down fashion, since they are input to a nested CES production function that ultimately produces GDP. For the LDV mode, three different technology options (internal combustion engine, battery electric vehicle, and fuel cell vehicle) compete against each other in a linear bottom-up technology model.

The transport sector requires input of final energy in different forms (liquids, electricity and hydrogen) and requires investments and operation and maintenance payments into the distribution infrastructure (infrastructure capacity grows linearly with distributed final energy) as well as into the vehicle stock. It generates emissions that go into the climate model and, depending on the scenario, can be taxed or limited by a budget. Furthermore, it is possible to consider taxes and subsidies on fuels. Material needs and embodied energy are not considered.

The main drivers/determinants of transport demand are GDP growth, the autonomous efficiency improvements (efficiency parameters of CES production function), and the elasticities of substitution between capital and energy and between stationary and transport energy forms. In more detail, mobility from the different modes comes as an input to a CES function, the output of which is combined with stationary energy to generate a generalized energy good, which is combined with labor and capital in the main production function for GDP. Finally, inside a model run, different final energy prices (due to climate policy, different resource assumptions, etc.) can lead to substitution of different transport modes inside the CES function, or a total reduction of travel demand (see Pietzcker et al. (2014a) for a comparison of the different contributions to transport mitigation). For passenger transport, we consider LDV (powered by liquids, electricity or hydrogen), Aviation and Bus (aggregated, only powered by liquids) and Electric Trains (only powered by electricity). For freight transport, there is only one generic mode based on liquid fuels. For the conversion technologies of primary energy sources into these secondary energy carriers, see Section 3.2.

The distribution of vehicles inside the LDV mode follows cost optimization (perfect linear substitutability), although with different non-linear constraints (learning curve, upper limits of 70% on share of battery-electric vehicles and 90% on Fuel Cell vehicles) that in most realizations lead to a technology mix.

Efficiency, lifetime, investment costs, and fixed O&M costs parameters characterize all vehicle technologies. All these parameters, except investment costs for battery electric and fuel cell vehicles, are constant over time. Battery electric vehicles and fuel cell vehicles undergo learning-by-doing through a one-factor learning curve with floor costs that are asymptotically approached as cumulated capacity increases. Fuel prices are fully endogenous, as determined by the supply sector (intertemporal optimization with resource and capacity constraints as well as prices/constraints on emissions in policy scenarios).

REMIND calibrates the efficiencies of the transport CES leaves in such a way that when the baseline per-capita travel demand is plotted over per-capita GDP, travel demand in different regions shows a converging behavior. Regions with already very high affluence have mainly flat transport final energy per capita, in line with recent developments (USA, EU27, JPN), and a slow convergence towards a level in between that of the USA and EU27 today. REMIND assumes developed countries to show rising final energy per capita use with rising affluence, with some deviations in the exact path in the final energy per capita – GDP per capita – space due to differences in their recent history. They converge to a similar point like the average of OECD regions, but so slow that convergence would only happen after 2100.

Table 8. Overview of LDV technologies

	Life-time	Overnight Investment costs	Floor costs	Learn Rate	Cumulative capacity 2005	Fixed O&M costs	Efficiency
	Years	**1000$US/ unit**	**1000$US/ unit**	**%**	**Million units**	**% of investment costs**	**Relative to ICEV**
ICEV	13	11	-	-	-	10	1
BEV	13	26	15	10	3	10	3
H2-FCV	13	32	15	10	3	10	2.5

3.4 Stationary sector

In its present version, REMIND, represents an aggregate 'stationary sector' that embodies residential, commercial and Industrial energy demand (see Figure 4). We plan a disaggregation of the buildings (residential & commercial) and industry sectors for future REMIND versions.

Demand for energy types used in the stationary sector (electricity, solids, liquids, gas, district heat, and hydrogen) is modeled in a top-down fashion: they are input to a nested CES production function that produces GDP. Provision of these final energies is modeled in a bottom-up energy model, where detailed capital stocks of conversion technologies convert primary energies to secondary and final energies, with full substitutability between technologies.

The stationary sector requires inputs of final energy in different forms (electricity, solids, liquids, gas, district heat, and hydrogen) and requires investments and operation and maintenance payments into the distribution infrastructure (generic capacity constraint). It generates emissions that go into the climate model and, depending on the scenario, are taxed or limited by a budget.

The indirect energy use and material needs for production of appliances is not explicitly included, only implicitly embedded in the main CES production function via the total energy demand of a region. On the final energy provision side, REMIND represents all energy use for extraction and conversion up to the distribution of final energies.

The main drivers in the stationary sector are GDP growth, the autonomous efficiency improvements (efficiency parameters of CES production function), the elasticities of substitution between capital and energy and between stationary and transport energy forms. These drivers influence demand in a similar manner as described for the transport sector, i.e. final energy types are inputs to a CES function, the output of which is combined with transport energy in another CES function to generate a generalized energy good, which in turn is combined with labor and capital in the main production function for GDP. REMIND calibrates the efficiencies of the stationary CES leaves in such a way that, when the baseline per-capita stationary energy demand is plotted over per-capita GDP, stationary energy demand in different regions shows a converging behavior. REMIND assumes developing countries to show rising final energy per capita (FE/cap) use with rising affluence, with some deviations in the exact path in the FE/cap – GDP/cap space due to differences in their recent history. For electricity demand, the per-capita levels converge towards a similar point like the average of OECD regions, but convergence will only happen after 2100, i.e. outside the analysis time frame of REMIND. For heat demand, the per-capita heat demand of a region levels off at a point based on a rough estimation of climate/heating demand in a region. Inside a model run, different FE prices (due to climate policy, different resource assumptions, etc.) can lead to substitution of different stationary energy types inside the CES function, or a total reduction of stationary energy demand. There is no direct price elasticity of demand in the model, the nested CES function results in different price elasticities at different points in time/system configurations.

The stationary sector differentiates between two explicit energy functions: electricity used for appliances, and all other inputs (gas, solids, district heat, liquids, and hydrogen) used for heating purposes. Table 4 and Table 7 show the primary energy sources that can be used to supply electricity or the other carriers used for heating. Combined heat and power plants using coal, gas or biomass are cross cutting along these two energy uses.

Technology choice follows cost optimization based on investment costs, fixed and variable operation and maintenance costs, fuel costs, emission costs, efficiencies, lifetimes, and learning rates. Endogenous technological change (learning-by-doing) influences wind and solar investment costs. For fossil fuel power plants, some exogenous time-dependent improvement of efficiency parameters until 2050 and convergence of efficiencies that are regionally calibrated to observed 2005 values are implemented. REMIND assumes full substitutability between different technologies producing one final energy type.

4 Land use

There are a number of important interactions of the energy, economy and climate systems represented in REMIND with the land system, such as emissions from land use changes and agriculture, or bioenergy supply. By default, REMIND relies on reduced-form approaches to account for these inter-linkages between the energy and the agricultural and land-use sectors (stand-alone mode). These are derived based on the state-of-the-art land use model MAgPIE (Lotze-Campen et al. 2008; Popp et al. 2010; Lotze-Campen et al. 2010). For a detailed and fully consistent analysis of the integrated energy-economy-land use system, REMIND can also be soft-linked and run iteratively with MAgPIE as depicted in Figure 7 (coupled mode). The soft-link between REMIND and MAgPIE focuses on two crucial interactions: (i) bioenergy demand and supply, (ii) land use/land use change emissions and GHG prices. At the end-point of the iterative solution process, the markets for bioenergy and emission mitigation across the energy and land-use sector are in equilibrium.

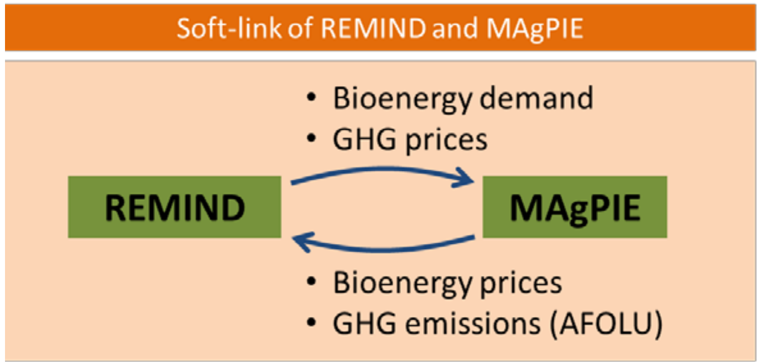

Figure 6. In the coupled mode REMIND is soft-linked to the land-use model MAgPIE. The models are run iteratively and exchange information about bioenergy demand and supply and about emission mitigation in the land-use system.

4.1 Agriculture

REMIND derives non-CO_2 emissions in the absence of climate policies from various agricultural activities for given assumptions on socio-economic pathways from corresponding MAgPIE scenarios. Unless coupled with MAgPIE, we use marginal abatement cost curves from Lucas et al. (2007) to derive economic abatement potentials.

4.2 Biofuels

REMIND represents a number of energy conversion technologies using bioenergy as feedstock. If REMIND is run in stand-alone mode, bioenergy resource potentials are represented as time-dependent and region-specific supply cost-curves derived from MAgPIE (Klein et al. 2014). To account for the sensitivity of resource potentials to carbon pricing, REMIND uses different supply curve parameterizations in baseline and climate policy scenarios. Direct and indirect GHG emissions (CO_2 and N_2O) induced by bioenergy production are accounted for by using specific emission factors.

Alternatively, the coupled REMIND-MAgPIE system allows for a detailed analysis of the impacts of bioenergy use for climate change mitigation and land use.

4.3 Forestry

If run in stand-alone mode, REMIND relies on exogenous results from MAgPIE to account for CO_2 emissions from land use, land use change and forestry. Reduced emissions from deforestation and forest degradation (REDD) as a mitigation option is represented via a climate policy dependent marginal abatement cost curve

The coupled REMIND-MAgPIE system allows for a detailed analysis of forestry-based mitigation options in the context of an integrated climate change mitigation scenario.

5 Climate module

5.1 GHGs

REMIND simulates emissions from long-lived GHGs (CO_2, CH_4, N_2O), short-lived GHGs (CO, NO_x, VOC) and aerosols (SO_2, BC, OC). REMIND accounts for these emissions with different levels of detail depending on the types and sources of emissions (see Table 9). It calculates CO_2 emissions from fuel combustion, CH4 emissions from fossil fuel extraction and residential energy use and N_2O emissions from energy supply 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, REMIND applies specific emissions factors, which are calibrated to match base year GHG inventories (EDGAR 2011).

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, REMIND derives the mitigation options from marginal abatement cost (MAC) curves, which describe the percentage of abated emissions as a function of the costs (see Figure 8). It is possible to obtain baseline emissions - to which the MAC curves are applied - by three different methods: by source (as described above), by an econometric estimate, or exogenously. REMIND uses the econometric estimate 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 waste production) or capital investment (as a proxy for cement production in infrastructure). REMIND uses exogenous baselines for N_2O emissions from transport and industry.

Emissions of other GHGs (e.g. F-gases, Montreal gases) are exogenous and are taken from the SSP scenario data set from the IMAGE model (Van Vuuren et al. under review). REMIND does not represent abatement options for these gases; therefore, emissions from the corresponding SSP/RCP scenario best matching the target of the specific model simulation are used.

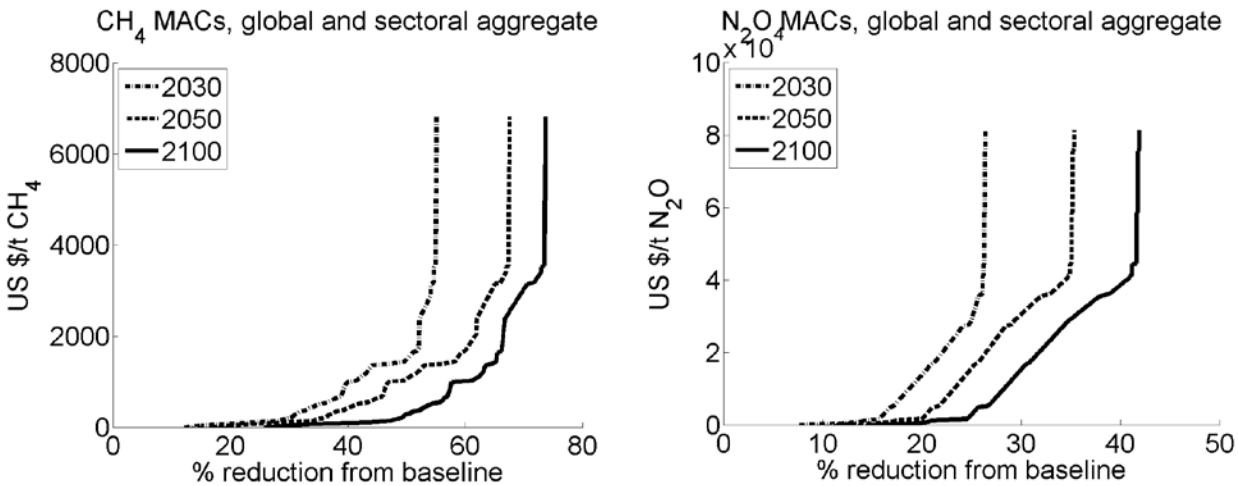

Figure 7. Globally and sectorally aggregated abatement costs and potentials for CH_4 (left panel) and N_2O (right panel) for different points in time. Marginal abatement cost curves are shifted over time such that more abatement is possible and the same level of abatement is available for a lower price. Adapted from Strefler, et al. (2014).

Table 9. Overview of the treatment of GHG and air pollutant emissions

GHG and air pollutant emissions	Treatment in REMIND	Percentage of 2005 CO2e 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 residential energy use	By source	
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 transport and industry	Marginal abatement cost curves, baseline exogenous	
N_2O energy supply	By source	
N_2O land use (agriculture)	Marginal abatement cost curves, Baseline from MAgPIE plus emission factor on bioenergy	
N_2O land use change (open burning)	Exogenous based on MAgPIE	
CFCs	Exogenous based on	1.1 %
PFCs	Exogenous	
SF_6	Exogenous	
Montreal gases	Exogenous	N/A
CO	By source	
NOx	By source	
VOC	By source	
NH_3	By source	
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	

5.2 Pollutants and non-GHG forcing agents

REMIND calculates emissions of aerosols and ozone precursors (SO_2, BC, OC, NOx, CO, VOC, NH_3). It accounts for these emissions with different levels of detail depending on sources and species (see Table 9).

For pollutant emissions of SO_2, BC, OC, NO_x, CO, VOC and NH_3 related to the combustion of fossil fuels, REMIND considers time- and region-specific emissions factors coupled to model-endogenous activity data. BC and OC emissions in 2005 are calibrated to the GAINS model (Klimont et al. in prep.a; Amann et al. 2011). All other emissions from fuel combustion in 2005 are calibrated to EDGAR (2011). Emission factors for SO_2, BC, and OC are assumed to decline over time according to air pollution policies based on Klimont et al. (in prep.b). Current near-term policies are enforced in high-income countries, with gradual strengthening of goals over time and gradual technology RDD&D. Low-income countries do not fully implement near-term policies, but gradually improve over the century.

Emissions from international shipping and aviation and waste of all species are exogenous and taken from Fujino et al. (2006). Further, REMIND uses landuse emissions from the MAgPIE model, which in turn are based on emission factors from van der Werf et al. (2010).

5.3 Modelling of climate indicators

By default, REMIND is coupled with the MAGICC 6 climate model to translate emissions into changes in atmospheric composition, radiative forcing and temperature increase. Due to numerical complexity, after running REMIND we perform the evaluation of climate change using MAGICC. Iterative adjustment of emission constraints or carbon taxes allows meeting specific temperature or radiative forcing limits in case of mitigation scenarios (see Section 1.4).

In addition, REMIND includes a reduced-form climate model similar to the one used in DICE (Nordhaus and Boyer 2000) which can be used within the REMIND optimization to enable direct formulation of temperature or radiative forcing targets in climate mitigation scenarios. 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 temperature box. Equations in the carbon-cycle temperature model describe concentration and radiative forcing that result from CH_4, N_2O, sulfate aerosols, black carbon, and organic carbon (Tanaka and Kriegler 2007). The climate module determines the atmospheric concentrations of CO_2, CH_4, and N_2O and computes the resulting radiative forcing and mean temperature at the global level. Its key parameters are calibrated to reproduce MAGICC, with a climate sensitivity of around 3.0°C.

REMIND does not account for climate damages.

6 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.
- Trading of composite goods is a free, unrestricted variable. The emerging trade pattern shows 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). To correct this, it is necessary to calibrate regionally differentiated time preference rates (Leimbach et al. 2014). The limitations in reproducing 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.
- Electricity from renewables such as wind and solar is characterized by strong fluctuations of supply in time and space. Representation of the challenges associated with the integration of variable renewable energies only occurs at an aggregated level (cf. Section 3.2.3).

- The representation of final energy demand lacks detail on the level of energy-consuming activities and technologies. Consequently, representation of 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 only occurs in a stylized manner.

Acronyms and Abbreviations

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

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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