To pdf - REMIND

From IAMC-Documentation

Reference card - REMIND

Contents

The reference card is a clearly defined description of model features. The numerous options have been organized into a limited amount of default and model specific (non default) options. In addition some features are described by a short clarifying text.

Legend:

☐ <u>not</u> implemented
☑ **implemented**
☑ **implemented (not default option)**

About

Name and version	REMIND 1.7
Institution and users	Potsdam Institut für Klimafolgenforschung (PIK), Germany, https://www.pik-potsdam.de/research/sustainable-solutions/models/remind.
Documentation	REMIND documentation consists of a referencecard and detailed model documentation

Model scope and methods

Model documentation: Model scope and methods - REMIND

Objective	REMIND is a global multi-regional model incorporating the economy, the climate system and a detailed representation of the energy sector. REMIND allows for a sophisticated analysis of technology options and policy proposals for climate mitigation. It accounts for economic and energy investments in the model regions, and interregional trade in goods, energy carriers and emissions allowances.
Concept	Hybrid Hybrid model that couples an economic growth model with a detailed energy system model and a simple climate model.
Solution method	Inter-temporal optimization that maximizes cumulated discounted global welfare: Ramsey-type growth model with Negishi approach to regional welfare aggregation.
Anticipation	Perfect Foresight
Temporal dimension	Base year:2005, time steps:flexible time steps but the default is 5-year time steps until 2050 and 10-year time steps until 2100; the period from 2100-2150 is calculated to avoid distortions due to end effects, but typically we only use the time span 2005-2100 for model applications, horizon: 2005-2150
Spatial dimension	Number of regions:11

1. AFR - Sub-Saharan Africa
2. CHN - China
3. EUR - European Union
4. JPN - Japan
5. IND - India

6. LAM - Latin America
7. MEA - Middle East, North Africa, and Central Asia
8. OAS - other Asian countries (mainly South-East Asia)

9. RUS - Russia
10. ROW - rest of the World
    (Australia, Canada, New

Zealand, Norway, South
Africa)
11. USA - United States of
    America

Policy implementation	Pareto-optimal achievement of policy targets on temperature, radiative forcing, GHG concentration, cumulative carbon budgets, or CO2 emissions over time under full when- and where-flexibility. Implementation of permit allocation rules among regions. Possibility of pre-specified carbon tax pathway. Fossil fuel subsidies and taxes.

Socio economic drivers

Model documentation: Socio-economic drivers - REMIND

Exogenous drivers	☐ Exogenous GDP	☐ Energy Technical progress
	☐ Total Factor Productivity	☐ Materials Technical progress
	☑ **Labour Productivity**	☐ GDP per capita
	☐ Capital Technical progress	

Note: Calibration of energy efficiency parameters of the production function. Endogenous learning-by-doing for wind and solar power as well as electric and fuel cell vehicle technologies (global learning curve, internalized spillovers).

Development	☑ **GDP per capita**	☐ Education level
	☐ Income distribution in a region	☐ Labour participation rate
	☐ Urbanisation rate	

Macro economy

Model documentation: Macro-economy - REMIND

Economic sectors	☐ Agriculture	☐ Transport
	☐ Industry	☐ Services
	☐ Energy	

Note: The macro-economic part contains a single sector representation of the entire economy. A generic final good is produced from capital, labor, and different final energy types.

Cost measures	☑ **GDP loss**	☐ Area under MAC
	☑ **Welfare loss**	☐ Energy system costs
	☑ **Consumption loss**	

Trade	☑ **Coal**	☑ **Bioenergy crops**
	☑ **Oil**	☐ Food crops
	☑ **Gas**	☑ **Capital**
	☑ **Uranium**	☑ **Emissions permits**
	☐ Electricity	☑ **Non-energy goods**

Energy

Model documentation: Energy - REMIND

Behaviour	Price response through CES production function. No explicit modeling of behavioural change. Baseline energy demands are calibrated in such a way that the energy demand patterns in different regions slowly converge when displayed as per capita energy demand over per capita GDP"

Resource use

☑ **Coal** ☑ **Uranium**
☑ **Oil** ☑ **Biomass**
☑ **Gas**

Electricity technologies

☑ **Coal** ☑ **Solar PV**
☑ **Gas** ☑ **CCS**
☑ **Oil** ☑ **Solar CSP**
☑ **Nuclear** ☑ **Hydropower**
☑ **Biomass** ☑ **Geothermal**
☑ **Wind**

Conversion technologies

☑ **CHP** ☑ **Fuel to gas**
☑ **Heat pumps** ☑ **Fuel to liquid**
☑ **Hydrogen** ☑ **Heat plants**

Grid and infrastructure

☑ **Electricity** ☑ **CO2**
☑ **Gas** ☑ **H2**
☑ **Heat**

Note: Generalized transmission and distribution costs are included, but not modeled on an explicit spatial level. Regionalized additional grid and storage costs for renewable integration are included.

Energy technology substitution

☑ **Discrete technology choices** ☑ **System integration constraints**
☑ **Expansion and decline constraints**

Note: Expansion and decline, and system integration are influenced though cost markups rather than constraints.

Energy service sectors

☑ **Transportation** ☑ **Residential and commercial**
☑ **Industry**

Note: Industry and Residential and Commercial are not treated separately but represented jointly by one Stationary sector (referred to as 'Other Sector').

Land-use

Model documentation: Land-use - REMIND; Non-climate sustainability dimension - REMIND

Land-use *Note: Bioenergy supply from the land-use sector is represented by an emulation of the land-use model MAgPIE. The emulator focuses on bioenergy supply costs and agricultural emissions.*

Other resources

Model documentation: Non-climate sustainability dimension - REMIND

Other resources
☐ Water   ☑ **Cement**
☐ Metals

Note: Cement production is not explicitly modeled, but emissions from cement production are accounted for.

Emissions and climate

Model documentation: Emissions - REMIND; Climate - REMIND

Green house gasses
☑ **CO2**   ☑ **HFCs**
☑ **CH4**   ☑ **CFCs**
☑ **N2O**   ☑ **SF6**

Pollutants
☑ **NOx**   ☑ **Ozone**
☑ **SOx**   ☑ **CO**
☑ **BC**   ☑ **VOC**
☑ **OC**

Note: Ozone is not modeled as emission, but is an endogenous result of atmospheric chemistry.

Climate indicators
☑ **CO2e concentration (ppm)**   ☑ **Temperature change (°C)**
☑ **Radiative Forcing (W/m^2)**   ☐ Climate damages $ or equivalent

Note: Different emissions are accounted for with different levels of detail depending on the types and sources of emissions (directly by source, via MAC curves, by econometric estimates, exogenous).

Model Documentation - REMIND

This document describes the Integrated Assessment Model REMIND, which stands for "Regional Model of Investments and Development", in its version 1.7. It updates the documentation of the previous model version 1.6. 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). 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).

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.
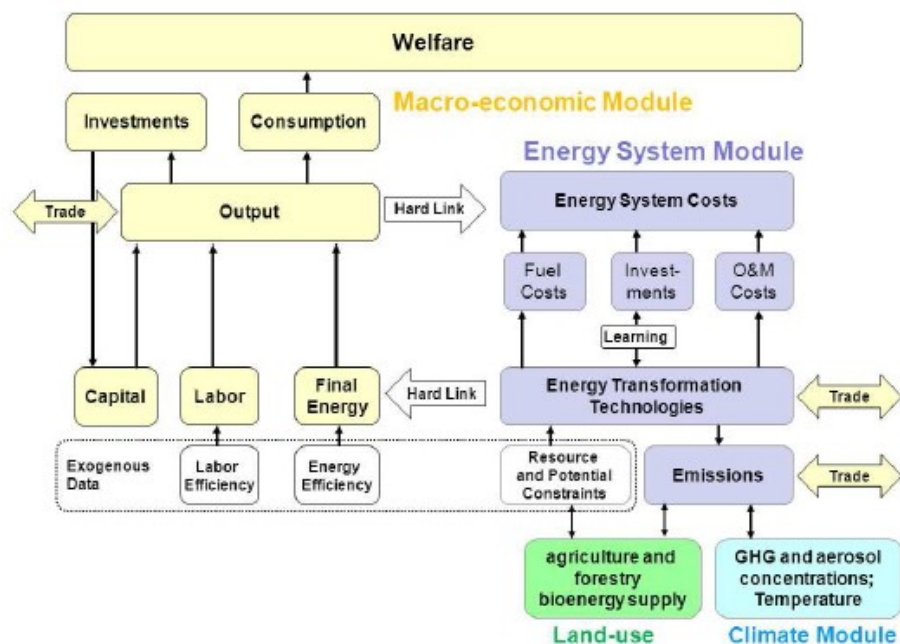
Figure 1. General structure of the REMIND model.

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 diminishing marginal utility of consumption diminishes with increasing per-capita consumption in line 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 regiona	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 (fossil fuels, final good, permits).	2.3.3
Investment dynamics	Capital motion equations, vintages for energy supply technologies, adjustment costs for acceleration of capacity expansion.	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
Representation of end-use sectors	Three energy end-use sectors: electricity production, stationary non-electric, transport.	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 so as to reproduce historic patterns.	2.4
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 - REMIND

REMIND (Regional Model of Investments and Development)[2][3][4][5][6][7]is a global multi-regional model incorporating the economy, the climate system, and a detailed representation of the energy sector.

1. See https://www.pik-potsdam.de/research/sustainable-solutions/models/remind for further documentation on REMIND. The model is programmed in GAMS.
2. Leimbach M, Bauer N, Baumstark L, et al (2010a) Technological Change and International Trade - Insights from REMIND-R. The Energy Journal 31:109–136. doi: 10.5547/ISSN0195-6574-EJ-Vol31-NoSI-5
3. Leimbach M, Bauer N, Baumstark L, Edenhofer O (2010b) Mitigation Costs in a Globalized World: Climate Policy Analysis with REMIND-R. Environ Model Assess 15:155–173. doi: 10.1007/s10666-009-9204-8
4. Luderer G, Pietzcker RC, Kriegler E, et al (2012) Asia's role in mitigating climate change: A technology and sector specific analysis with ReMIND-R. Energy Economics 34:S378–S390
5. Bauer N, Baumstark L, Leimbach M (2012a) The REMIND-R model: the role of renewables in the low-carbon transformation—first-best vs. second-best worlds. Climatic Change 114:145–168. doi: 10.1007/s10584-011-0129-2
6. Bauer N, Brecha RJ, Luderer G (2012b) Economics of nuclear power and climate change mitigation policies. PNAS 109:16805–16810. doi: 10.1073/pnas.1201264109
7. Luderer G, Leimbach M, Bauer N, et al (2013) Description of the REMIND Model (Version 1.5). SSRN Working Paper 2312844

1.1) Model concept, solver and details - REMIND

REMIND 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. The model 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 [1] , or the non-cooperative market solution among regions using the Nash concept [2],[3]. 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 [4] 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 [5], 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 [6] and uses the CONOPT solver [7] by default.

1. Negishi T (1972) General equilibrium theory and international trade. North-Holland Publishing Company Amsterdam, London
2. Leimbach M, Baumstark L, Luderer G (2015) The role of time preferences in explaining long-term pattern of international trade. Global Economy Journal 15:83–106. doi: 10.1515/gej-2014-0035
3. Leimbach M, Schultes A, Baumstark L, et al (2016) Solution algorithms of large-scale Integrated Assessment models on climate change. Annals of Operations Research, doi:10.1007/s10479-016-2340-z.
4. Bauer N, Edenhofer O, Kypreos S (2008) Linking energy system and macroeconomic growth models. CMS 5:95–117. doi: 10.1007/s10287-007-0042-3
5. Meinshausen M, S. C. B. Raper, T. M. L. Wigley (2011a) Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6–Part 1: Model description and calibration. Atmos Chem Phys 11:1417–1456. doi: 10.5194/acp-11-1417-2011
6. Brooke A, Kendrick D, Meeraus M (1992) GAMS - A User's Guide, Release 2.25. The Scientific Press, San Francisco
7. Drud AS (1994) CONOPT - A Large-Scale GRG Code. ORSA Journal on Computing 6:207–216.

1.3) Temporal dimension - REMIND

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) Spatial dimension - REMIND

REMIND is a multi-regional model of global coverage, that divides the world into 11 regions (see Figure 2 below). 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 Trade).

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.
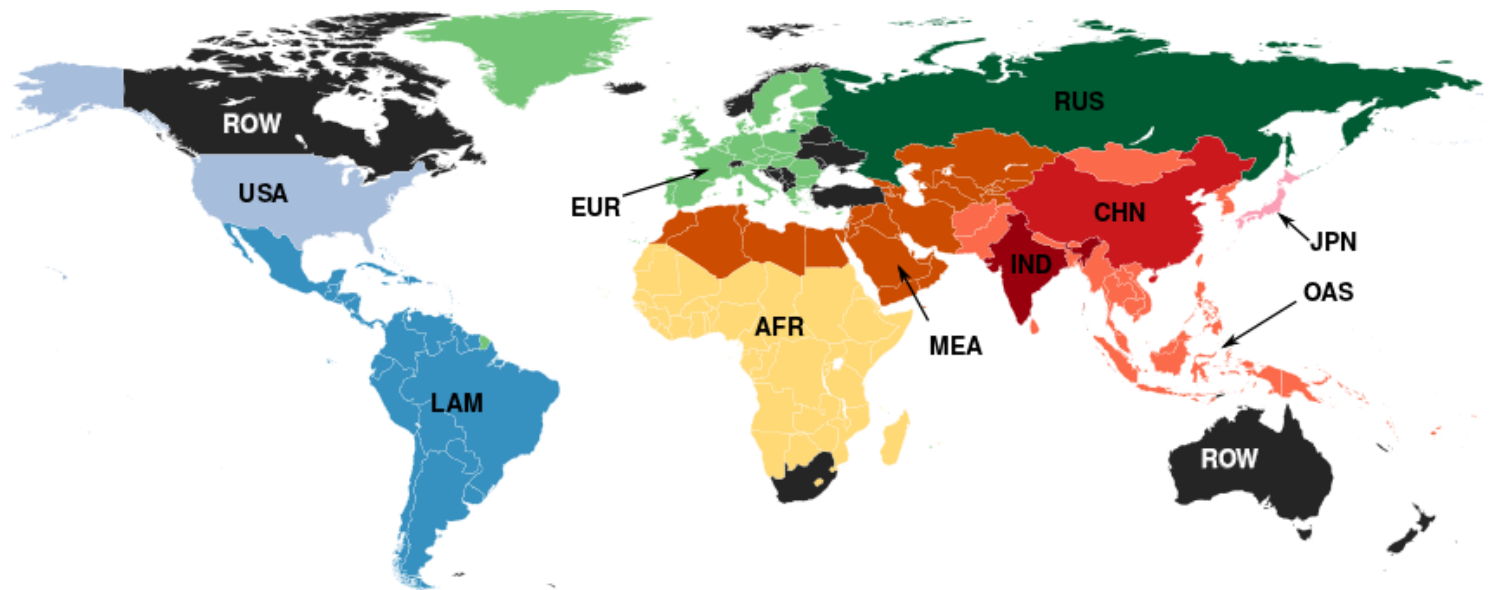
Figure 1. Regional definitions used in the REMIND model.

REMIND Region Code	Country Code	Country Name
LAM	ABW	Aruba
OAS	AFG	Afghanistan
AFR	AGO	Angola
LAM	AIA	Anguilla
EUR	ALA	Aland Islands
ROW	ALB	Albania
ROW	AND	Andorra
MEA	ARE	United Arab Emirates
LAM	ARG	Argentina
MEA	ARM	Armenia
OAS	ASM	American Samoa
ROW	ATA	Antarctica
OAS	ATF	French Southern Territories
LAM	ATG	Antigua and Barbuda
ROW	AUS	Australia
EUR	AUT	Austria
MEA	AZE	Azerbaijan
AFR	BDI	Burundi
EUR	BEL	Belgium
AFR	BEN	Benin
LAM	BES	Bonaire, Sint Eustatius and Saba
AFR	BFA	Burkina Faso
OAS	BGD	Bangladesh
EUR	BGR	Bulgaria
MEA	BHR	Bahrain
LAM	BHS	Bahamas
ROW	BIH	Bosnia and Herzegovina
LAM	BLM	Saint Barthelemy
ROW	BLR	Belarus
LAM	BLZ	Belize
LAM	BMU	Bermuda
LAM	BOL	Bolivia, Plurinational State of
LAM	BRA	Brazil
LAM	BRB	Barbados
OAS	BRN	Brunei Darussalam
OAS	BTN	Bhutan
ROW	BVT	Bouvet Island
AFR	BWA	Botswana
AFR	CAF	Central African Republic
ROW	CAN	Canada
OAS	CCK	Cocos (Keeling) Islands
ROW	CHE	Switzerland
LAM	CHL	Chile
CHN	CHN	China

AFR	CIV	Cote d Ivoire
AFR	CMR	Cameroon
AFR	COD	Congo, the Democratic Republic of the
AFR	COG	Congo
OAS	COK	Cook Islands
LAM	COL	Colombia
AFR	COM	Comoros
AFR	CPV	Cape Verde
LAM	CRI	Costa Rica
LAM	CUB	Cuba
LAM	CUW	Curacao
OAS	CXR	Christmas Island
LAM	CYM	Cayman Islands
EUR	CYP	Cyprus
EUR	CZE	Czech Republic
EUR	DEU	Germany
AFR	DJI	Djibouti
LAM	DMA	Dominica
EUR	DNK	Denmark
LAM	DOM	Dominican Republic
MEA	DZA	Algeria
LAM	ECU	Ecuador
MEA	EGY	Egypt
AFR	ERI	Eritrea
MEA	ESH	Western Sahara
EUR	ESP	Spain
EUR	EST	Estonia
AFR	ETH	Ethiopia
EUR	FIN	Finland
OAS	FJI	Fiji
LAM	FLK	Falkland Islands (Malvinas)
EUR	FRA	France
EUR	FRO	Faroe Islands
OAS	FSM	Micronesia, Federated States of
AFR	GAB	Gabon
EUR	GBR	United Kingdom
MEA	GEO	Georgia
ROW	GGY	Guernsey
AFR	GHA	Ghana
EUR	GIB	Gibraltar
AFR	GIN	Guinea
LAM	GLP	Guadeloupe
AFR	GMB	Gambia
AFR	GNB	Guinea-Bissau
AFR	GNQ	Equatorial Guinea

EUR	GRC	Greece
LAM	GRD	Grenada
EUR	GRL	Greenland
LAM	GTM	Guatemala
LAM	GUF	French Guiana
OAS	GUM	Guam
LAM	GUY	Guyana
CHN	HKG	Hong Kong
ROW	HMD	Heard Island and McDonald Islands
LAM	HND	Honduras
ROW	HRV	Croatia
LAM	HTI	Haiti
EUR	HUN	Hungary
OAS	IDN	Indonesia
EUR	IMN	Isle of Man
IND	IND	India
OAS	IOT	British Indian Ocean Territory
EUR	IRL	Ireland
MEA	IRN	Iran, Islamic Republic of
MEA	IRQ	Iraq
ROW	ISL	Iceland
MEA	ISR	Israel
EUR	ITA	Italy
LAM	JAM	Jamaica
EUR	JEY	Jersey
MEA	JOR	Jordan
JPN	JPN	Japan
MEA	KAZ	Kazakhstan
AFR	KEN	Kenya
MEA	KGZ	Kyrgyzstan
OAS	KHM	Cambodia
OAS	KIR	Kiribati
LAM	KNA	Saint Kitts and Nevis
OAS	KOR	Korea, Republic of
MEA	KWT	Kuwait
OAS	LAO	Lao People's Democratic Republic
MEA	LBN	Lebanon
AFR	LBR	Liberia
MEA	LBY	Libya
LAM	LCA	Saint Lucia
ROW	LIE	Liechtenstein
OAS	LKA	Sri Lanka
AFR	LSO	Lesotho
EUR	LTU	Lithuania
EUR	LUX	Luxembourg

EUR	LVA	Latvia
CHN	MAC	Macao
ROW	MAF	Saint Martin (French part)
MEA	MAR	Morocco
ROW	MCO	Monaco
ROW	MDA	Moldova, Republic of
AFR	MDG	Madagascar
OAS	MDV	Maldives
LAM	MEX	Mexico
OAS	MHL	Marshall Islands
ROW	MKD	Macedonia, the former Yugoslav Republic of
AFR	MLI	Mali
EUR	MLT	Malta
OAS	MMR	Myanmar
ROW	MNE	Montenegro
OAS	MNG	Mongolia
OAS	MNP	Northern Mariana Islands
AFR	MOZ	Mozambique
AFR	MRT	Mauritania
LAM	MSR	Montserrat
LAM	MTQ	Martinique
AFR	MUS	Mauritius
AFR	MWI	Malawi
OAS	MYS	Malaysia
AFR	MYT	Mayotte
AFR	NAM	Namibia
OAS	NCL	New Caledonia
AFR	NER	Niger
OAS	NFK	Norfolk Island
AFR	NGA	Nigeria
LAM	NIC	Nicaragua
OAS	NIU	Niue
EUR	NLD	Netherlands
ROW	NOR	Norway
OAS	NPL	Nepal
ROW	NRU	Nauru
ROW	NZL	New Zealand
MEA	OMN	Oman
OAS	PAK	Pakistan
LAM	PAN	Panama
OAS	PCN	Pitcairn
LAM	PER	Peru
OAS	PHL	Philippines
OAS	PLW	Palau
OAS	PNG	Papua New Guinea

EUR	POL	Poland
USA	PRI	Puerto Rico
OAS	PRK	Korea, Democratic People's Republic of
EUR	PRT	Portugal
LAM	PRY	Paraguay
MEA	PSE	Palestine, State of
OAS	PYF	French Polynesia
MEA	QAT	Qatar
AFR	REU	Reunion
EUR	ROU	Romania
RUS	RUS	Russian Federation
AFR	RWA	Rwanda
MEA	SAU	Saudi Arabia
AFR	SDN	Sudan
AFR	SEN	Senegal
OAS	SGP	Singapore
ROW	SGS	South Georgia and the South Sandwich Islands
AFR	SHN	Saint Helena, Ascension and Tristan da Cunha
ROW	SJM	Svalbard and Jan Mayen
OAS	SLB	Solomon Islands
AFR	SLE	Sierra Leone
LAM	SLV	El Salvador
ROW	SMR	San Marino
AFR	SOM	Somalia
ROW	SPM	Saint Pierre and Miquelon
ROW	SRB	Serbia
AFR	SSD	South Sudan
AFR	STP	Sao Tome and Principe
LAM	SUR	Suriname
EUR	SVK	Slovakia
EUR	SVN	Slovenia
EUR	SWE	Sweden
AFR	SWZ	Swaziland
LAM	SXM	Sint Maarten (Dutch part)
AFR	SYC	Seychelles
MEA	SYR	Syrian Arab Republic
LAM	TCA	Turks and Caicos Islands
AFR	TCD	Chad
AFR	TGO	Togo
OAS	THA	Thailand
MEA	TJK	Tajikistan
OAS	TKL	Tokelau
MEA	TKM	Turkmenistan
OAS	TLS	Timor-Leste
OAS	TON	Tonga

LAM	TTO	Trinidad and Tobago
MEA	TUN	Tunisia
ROW	TUR	Turkey
OAS	TUV	Tuvalu
OAS	TWN	Taiwan, Province of China
AFR	TZA	Tanzania, United Republic of
AFR	UGA	Uganda
ROW	UKR	Ukraine
OAS	UMI	United States Minor Outlying Islands
LAM	URY	Uruguay
USA	USA	United States
MEA	UZB	Uzbekistan
ROW	VAT	Holy See (Vatican City State)
LAM	VCT	Saint Vincent and the Grenadines
LAM	VEN	Venezuela, Bolivarian Republic of
LAM	VGB	Virgin Islands, British
LAM	VIR	Virgin Islands, U.S.
OAS	VNM	Viet Nam
OAS	VUT	Vanuatu
OAS	WLF	Wallis and Futuna
OAS	WSM	Samoa
MEA	YEM	Yemen
ROW	ZAF	South Africa
AFR	ZMB	Zambia
AFR	ZWE	Zimbabwe

1.5) Policy - REMIND

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 [1].

1. Schwanitz VJ, Piontek F, Bertram C, Luderer G (2014) Long-term climate policy implications of phasing out fossil fuel subsidies. Energy Policy 67:882–894. doi: 10.1016/j.enpol.2013.12.015

2) Socio-economic drivers - REMIND

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. REMIND's default population projections (both total population as well as working age population) are based on IIASA [1] (and the GDP scenarios from the OECD [2]. Both Population and GDP scenario data are available at https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=about. These projections are available for all five different SSP scenarios [3]. For default scenarios, 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).
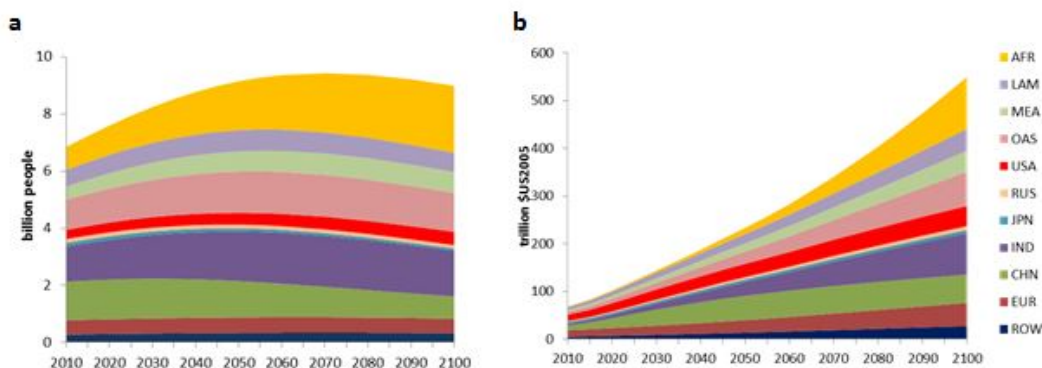
Figure 1. Projections of (a) population and (b) GDP used in the REMIND SSP2 ("Middle-of-the-Road") scenario.

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3. O'Neill BC, Kriegler E, Riahi K, et al (2014) A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change 122:387–400. doi: 10.1007/s10584-013-0905-2

2.1) Population - REMIND

Population is an exogenous input for REMIND (see description under Socio-economic drivers). It enters the model in just two forms: total population and working age population. While the welfare measuring is based on total population, the working age population is used as labor input in the macroeconomic production function. The exogenous labor input affects the dynamics of other macroeconomic production factors (capital, energy) since the model seeks an optimal allocation of production factors.

Total population is also used for generating energy demand scenarios that are mainly based on assumptions about the development of per capita demand on different energy types (see description under Energy demand)

2.2) Economic activity - REMIND

The three main components of GDP are capital, labor and energy. The energy sector is split into different final, secondary and primary components nested through a CES function (see more detailed description under Production system and representation of economic sectors and in Figure 1: 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. (http://themasites.pbl.nl/models/advance/index.php/Production_system_and_representation_of_economic_sectors_-_REMIND)). REMIND is calibrated so that the output matches exogenous GDP projections subject to exogenous labor and final energy demand projections through an adjustment of labor productivity and energy efficiency parameters. Energy efficiencies are time, region and energy-type specific, labor productivity is time and region-specific.

3) Macro-economy - REMIND

Objective function

REMIND models each region r as a representative household with a utility function Ur 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(r,t) is the consumption of region r at time t, and P(r,t) 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 rho. 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 [1]. 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 [2]; see also [3] for a discussion of the extension. Other models such as MERGE [4] and RICE [5] 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 the section on Trade.

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.

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5. Nordhaus WD, Yang Z (1996) A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies. The American Economic Review 86:741–765

3.1) Production system and representation of economic sectors - REMIND

REMIND uses a nested production function with constant elasticity of substitution (CES) to determine a region's gross domestic product (GDP) (see Figure 6 bleow). 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 [1].
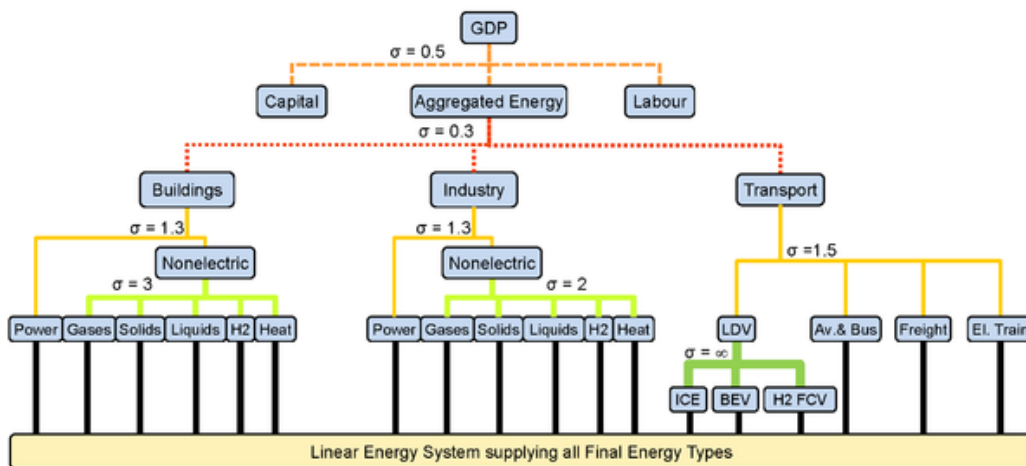
Figure 1. Production structure of REMIND. Linear production functions describe the conversion of primary energy (lowest level) to final energy carriers. Nested CES structures describe the aggregation of final energy carriers for end-use.

The macro-economic budget constraint for each region ensures that, in each region and for every time step, the sum of GDP Y(r,t) and imports of composite goods M_G(r,t) can be spent on consumption C(r,t), investments into the macroeconomic capital stock I(r,t), energy system expenditures E(r,t) and the export of composite goods X_G(r,t). 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. Macroeconomic capital depreciates at 5% per year, and investments are subject to adjustment costs that scale with the square of the rate of change in investments relative to the capital stock.

1. O'Neill BC, Kriegler E, Riahi K, et al (2014) A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change 122:387–400. doi: 10.1007/s10584-013-0905-2

3.4) Trade - REMIND

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. To be consistent with trade statistics, trade in petroleum products is subsumed under crude oil trade.

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

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

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 [1], 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. 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_{ir} 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.

Two solution concepts for the treatment of trade exist, called Nash and Negishi approach. The Negishi approach includes 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. Prices are derived from the shadow prices of the trade balances in each iteration. In contrast, the Nash approach adjusts goods prices until demand and supply of traded goods are equalized. There are no explicit market clearning conditions, and regions optimize separately, facing their individual intertemporal balance of payments. In each iteration, the international prices are exogenous parameters for all regions. In the absence of inter-regional externalities, both solution approaches converge to the same solution.

Table 1. 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

1. Heckscher EF, Ohlin B, Flam H, Flanders MJ (1991) Heckscher-Ohlin trade theory. MIT Press, Cambridge, Massachusetts

4) Energy - REMIND

Energy is a factor input demanded by the economy, as different final energy types are inputs to GDP generation in the nested CES production function as described in Figure 1: 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. (http://themasites.pbl.nl/models/advance/index.php/Production_system_and_representation_of_economic_sectors_-_REMIND). This chapter explains the different primary energy resources modelled and their potentials (Section Energy resource endowments). REMIND considers more than 40 technologies for the conversion of these resources into different secondary energy types (Sections Electricity, Heat, Other conversion) and the conversion of secondary to final energy (Section Grid and infrastructure). The subsequent subsections explain the use of those final energy types in the different demand sectors (Sections Transport and Stationary sector).

4.1) Energy resource endowments - REMIND

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.

4.1.1) Fossil energy resources - REMIND

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 [1]. Extraction costs increase over time as low-cost deposits become exhausted [2], [3]; [4]; [5]; [6]. In REMIND, we use region-specific extraction cost curves that relate production cost increases to cumulative extraction [7]; [8].

Figure 10 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 [9]. 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 [10].

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 [11]; [12]. 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 [13]; [14]; [15].
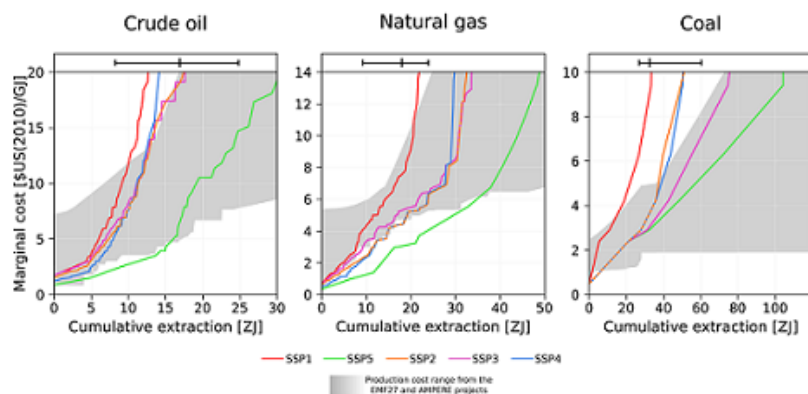
Figure 1: Global aggregate Cumulative Availability Curves of coal, oil and gas for the different SSPs. The bars at the top indicate the minimum, median and maximum extraction in baseline scenarios in the EMF-27 study; the shaded area covers the range of extraction cost functions given in the EMF-27 and 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.

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11. IEA (2008a) World Energy Outlook 2008. International Energy Agency
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4.1.2) Uranium and other fissile resources - REMIND

A comparison of regularly up-dated assessments of global uranium availability is given in Figure 11. Conventional identified resources of uranium are differentiated into recovery cost categories. The assessment by the Nuclear Energy Agency [1] comprises 6.3Mt of uranium, which equals approximately one hundred times current reactor requirements. The estimates of World Energy Council [2] and German Geological Survey [3] mainly rely on the numbers of NEA but apply different interpretations for identified uranium resources. The more uncertain category of conventional undiscovered uranium resources are also assessed differently by the three institutions.

For the default version the assumption is that 23MtUr are ultimately available with increasing extraction costs up to 260$US per tUr. The implementation uses a quadratic extraction cost function for each region that starts at 25US$ per kg uranium and cuts off at the same marginal costs (300$US per kg uranium), if - at the global level - 23MtUr are reached. The shape parameter of the regional extraction cost functions depend on the regional availability of uranium resources. The default version does not represent reprocessing and fast breeding reactors integrated into the nuclear fuel cycle. Given the optimistic assessment of uranium resources this assumption is economically reasonable in the near-term[4].

Figure 1. Overview of assessments on global uranium in Mt uranium. Identified resources are differentiated by cost categories; undiscovered resources are differentiated by geological certainty.

			BGR	NEA	WEC
Conventional resource	Identified resource	<80 $US per kg	2.5	3.7	
		<130 $US per kg		1.7	5.4
		<260 $US per kg	3.8	0.9	0.9
	Undiscovered resource	Prognostic	2.9	2.9	6.8
		Speculative	3.9	7.5	3.6
Unconventional resource				<22	10-22

1. Nuclear Energy Agency NEA (2010): Uranium 2009. Resources, Production, and Demand. Nuclear Energy Agency and Organization of Economic Co-operation and Development. Paris, France.
2. World Energy Council WEC (2010): 2010 Survey of energy resources. London, UK.
3. Bundesanstalt für Geowissenschaften und Rohstoffe BGR (2010): Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen. Hannover, Germany.
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4.1.3) Bioenergy - REMIND

REMIND models three types of bioenergy feedstocks:

1. First-generation biomass produced from sugar, starch, and oilseeds (typically small in quantity, based on an exogenous scenario);
2. Ligno-cellulosic residues from agriculture and forest; and
3. 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 can either be run in standalone mode or soft-coupled to the land-use model MAgPIE (Model of Agricultural Production and its Impact on the Environment) [1]; [2]; [3], see also Section "Land Use" . In standalone mode, REMIND draws on an emulator of MAgPIE, which describes bioenergy supply costs and total agricultural emissions as a function of bioenergy demand, as described in detail in Klein [4]. 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 [5], based on Haberl [6].

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 [7]. 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 [8]; [9]. 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.

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3. Lotze-Campen H, Popp A, Beringer T, et al (2010) Scenarios of global bioenergy production: The trade-offs between agricultural expansion, intensification and trade. Ecological Modelling 221:2188–2196. doi: 10.1016/j.ecolmodel.2009.10.002
4. Klein D, Humpenöder F, Bauer N, et al (2014) The global economic long-term potential of modern biomass in a climate-constrained world. Environ Res Lett 9:074017. doi: 10.1088/1748-9326/9/7/074017
5. Chum H, Faaij A, Moreira J, et al (2011) Bioenergy. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P
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4.1.4) Non-biomass renewables - REMIND

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 12). 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 [1]. 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 [2] 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 [3]. 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 [4]; [5]; [6]; [7]. 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 [8], but is less than one fifth of the potential in Lu [9].
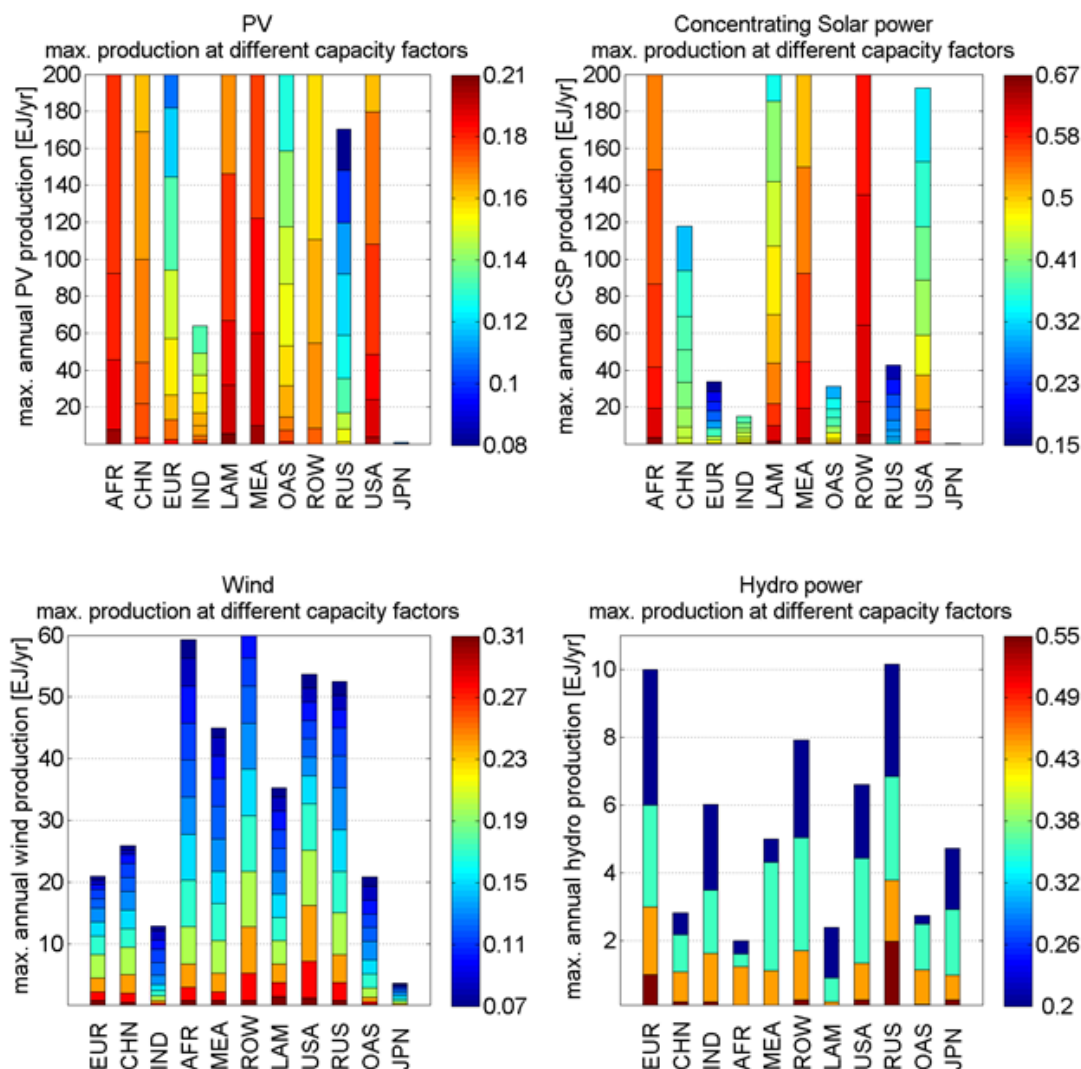
Figure 1. Regionalized resource potentials for solar PV, CSP, wind and hydro power as a function of resource quality expressed in terms of attainable capacity factors.

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).

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4.2) Energy conversion - REMIND

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 various secondary energy carriers included in REMIND are:

- Electricity
- Gases
- Liquids
- Hydrogen
- Solid fuels
- District heat and local renewable heat

Table 3 gives an overview over which energy carriers are used in which end use sector.

Table 1. Overview of energy carriers used in end-use sectors

Sector	Electricity	Gases	Liquids	Hydrogen	Solids	Heat
Residential and Commercial	X	x	X	X	X	X
Industry	X	x	X	X	X	X
Transport	X	no	X	X	no	no

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 (maximum 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 [1]; [2]. 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 two technologies convert secondary energy into secondary energy, namely the production of hydrogen from electricity via electrolysis and the opposite route, the production of electricity from a hydrogen turbine.

Technology choice for energy supply 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.

1. IEA (2007a) Energy Balances of OECD Countries. International Energy Agency, Paris
2. IEA (2007b) Energy Balances of non-OECD Countries. International Energy Agency, Paris

4.2.1) Electricity - REMIND

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 1. Energy Conversion Technologies for Electricity (Note: † indicates that technologies can be combined with CCS).

Table 4: Energy Conversion Technologies for Electricity

Energy Carrier	Technology
Primary exhaustible resource	
Coal	- Conventional coal power plant - Integrated coal gasification combined cycle† - Coal combined heat and power plant
Oil	Diesel oil turbine
Gas	- Gas turbine - Natural gas combined cycle† - Gas combined heat and power plant
Uranium	Light water reactor
Primary renewable resource	
Solar	- Solar photovoltaic - Concentrating solar power
Wind	Wind turbine
Hydropower	Hydropower
Biomass	- Integrated biomass gasification combined cycle† - Biomass combined heat and power plant
Geothermal	Hot dry rock
Secondary energy type	
Hydrogen	Hydrogen turbine

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 2. Techno-economic characteristics of technologies based on exhaustible energy sources and biomass [1]; [2]; [3]; [4]; [5]; [6]; [7]; [8]; [9]; [10]; [11]; [12]; [13].

		Life-time	Overnight investment costs		O&M costs (fix & variable)		Conversion efficiency		CCS capture rate	Capacity factor	
		Years	$US2015/kW		$US2015/GJ		%		%		
			No CCS	With CCS	No CCS	With CCS	No CCS	With CCS	With CCS	No CCS	With CCS
Coal	PC	40	1600		3		41-46#			0.75	
	IGCC	35	2200	2800	4.0	5.3	42-50#	33-43#	90	0.75	0.80
	C2H2*	35	1510	1720	1.9	2.1	59	57	90	0.8	0.8
	C2L*	35	1740	1820	4.2	5.0	40	40	70	0.85	0.85
	C2G	35	1440		1.4		60			0.9	
Gas	NGT	30	500		6.0		36-41#			0.09	
	NGCC	35	950	1350	2.1	2.9	56-63#	49-56	90	0.55	0.65
	SMR	35	600	660	0.6	0.7	73	70	90	0.9	0.9
Biomass	BIGCC*	40	2450	3150	5.1	6.9	37-46#	28-35#	90	0.75	0.75
	BioCHP	40	3000		6.0		35			0.75	
	B2H2*	35	1680	2040	5.7	6.8	61	55	90	0.9	0.9
	B2L*	35	3000	3600	4.2	5.4	40	41	50	0.9	0.9
	B2G	40	1200		1.9		55			0.9	
Nuclear	TNR	40	4700		6.7		33§			0.8	

Abbreviations: PC - pulverized coal, IGCC - integrated coal gasification combined cycle, CHP - coal combined heat and power plant, C2H2 - coal to hydrogen, C2L - coal to liquids, C2G - coal gasification, NGT - natural gas turbine, NGCC - natural gas combined cycle, SMR - steam methane reforming, BIGCC – Biomass IGCC, BioCHP – biomass combined heat and power, B2H2 – biomass to hydrogen, B2L – biomass to liquids, B2G – biogas, TNR - thermo-nuclear reactor; * 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 Grid and Infrastructure. To represent the general need for flexibility even in a thermal power system, we included a further flexibility constraint based on Sullivan [14].

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

Table 3. Techno-economic characteristics of technologies based on non-biomass renewable energy sources [15]; [16]; [17]; [18]; [19].

	Lifetime	Overnight Investment costs in 2005	Overnight Investment costs in 2015	Floor costs	Learn Rate 2003-2013	Cumulative capacity 2005	Yearly fix O&M costs	Capacity factor
	Years	$US2015/ kW	$US2015/ kW	$US2015/ kW		GW	% of Inv.Costs	Share of a year
Hydro	70	2300	2300	-	-	-	2%	0.15-0.55
Geo HDR	30	3000	3000	-	-	-	4%	1
Wind	25	2400	1850	1100	12%	60	2%	0.09-0.48
SPV	30	5900	1750	450	20%	5	1.5%	0.1-0.2
CSP	30	10300	6950	1550	10%	0.5	2.5%	0.15-0.67

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19. Pietzcker et al. 2014

4.2.2) Heat - REMIND

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 1. 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)

4.2.6) Grid, pipelines and other infrastructure - REMIND

General distribution costs

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

Variable renewable energy sources

Variable renewable electricity (VRE) sources such as wind and solar PV require storage to guarantee a stable supply of electricity [1]. Since the techno-economic parameters applied to CSP include the cost of thermal storage to continue electricity production 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[2].

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

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.

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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 $_{VRE}$. 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 [3].

Carbon capture and Storage

REMIND represents several carbon capture and storage (CCS) applications. First, 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 and gas. Secondly, 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. Thirdly, CCS can be used to reduce atmospheric CO2 emissions from the industry sector.

The sequestration of captured CO2 is explicitly represented in the model by accounting for transportation and storage costs [4]. There are regional constraints on CO2 storage potentials which are largely based on IEA [5]. 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 CO2 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 CO2 injection.

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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.
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4.3) Energy end-use - REMIND

Since version 1.7, REMIND represents the transport, industry and residential/commercial end use sectors. In former REMIND versions, residential/commercial and industry were represented as an aggregate stationary sector.

Table 1. Overview of energy carriers used in the various end-use sectors

Sector	Electricity	Gases	Liquids	Hydrogen	Solids	Heat
Residential and Commercial	X	x	X	X	X	X
Industry	X	x	X	X	X	X
Transport	X	no	X	X	no	no

4.3.1) Transport - REMIND

REMIND models the transport sector by using a hybrid approach combining top-down and bottom-up elements (see Figure 1. 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. (http://themasites.pbl.nl/models/advance/index.php/Production_system_and_representation_of_economic_sectors_-_REMIND)). Specifically, mobility demands for the 4 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 [1] 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 Energy Conversion.

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).

Table 1. 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

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4.3.2) Residential and commercial sectors - REMIND

In REMIND, the residential and commercial sectors are modeled together within the buildings sector. The demand and the supply of energy for buildings follow different modelling approaches:

Demand for energy types used in the buildings 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.

Supply 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 bottom-up energy model is described in full detail in Section "Energy conversion".

The buildings sector differentiates between two explicit energy functions: electricity, and all energy inputs used for heating purposes (gas, solids, district heat, liquids, and hydrogen). It is easier to substitute one energy carrier for another in the latter group, than it is to substitute electricity for another energy carrier (see Figure 3 for the full CES production function with all substitution elasticity values).

The main energy demand drivers are GDP growth, the autonomous efficiency improvements (efficiency parameters of CES production function), the elasticities of substitution between capital and energy and between the buildings, industry, and transport energy sectors. 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.

The indirect energy use and material needs for production of appliances or houses is not explicitly represented, only implicitly accounted for by the main CES production function, which is calibrated to the total historical energy demand of a region.

Inside a model run, different FE prices (due to climate policy, different resource assumptions, etc.) can lead to substitution of different buildings energy types inside the CES function, or a total reduction of buildings energy demand. There is no single 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 buildings sector generates direct emissions – from fuel combustion in buildings and is responsible for indirect emissions (emissions from the energy supply sector) that go into the climate model and, depending on the scenario, are taxed or limited by a budget.

4.3.3) Industrial sector - REMIND

Demand for final energy carriers used in the industry sector (solids, liquids, gases, hydrogen, district heat and electricity) is modeled in a top-down fashion: they are input to a nested CES production function that produces GDP. **Supply** 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 bottom-up energy model supplying the energy carriers is described in full detail in Section "Energy conversion".

The industry sector differentiates between two types of energy functions supplied by the final energy carriers: electricity, and energy inputs used for heating purposes (solids, liquids, gas, hydrogen, and district heat).

The industry sector 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.

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The indirect energy use and material needs for construction of factories and machinery is not explicitly represented, only implicitly accounted for by the main CES production function, which is calibrated to the total historical energy demand of a region.

The main determinants of final energy demand in the industry sector are GDP growth, the autonomous efficiency improvements (efficiency parameters of CES production function), the elasticities of substitution between capital and energy and between industry, residential/commercial and transport energy use. These factors influence demand in a similar manner as described for the residential/commercial and transport sectors, i.e., final energy types are inputs to a CES function, the output of which is combined with energy from other sectors 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.

Emissions of the three largest industry sub-sectors (cement, chemicals and steel production) can partially be abated by the use of CCS. To that end, emissions of the sub-sectors are calculated based on region-specific sub-sector shares in the use of CO2-emitting final energy carriers (solids, liquids and gases). The share of emissions abated by CCS is determined via sub-sector specific marginal abatement cost (MAC) curves; according to the explicit or implicit CO2 price total emissions are reduced and sequestered CO2 is increased accordingly, while additional abatement costs are incurred and accounted for in the budget.

Process emissions from cement production are calculated based either on per capita GDP or on per capita investments, based on the level of economic development of a region. REMIND reduces cement emissions when CO2 prices increase and thereby drive up clinker/cement prices. This reduction of cement emissions represents both a reduction in demand through improved molds and structural redesign and a reduction of emissions from changing the composition of cement. These options are represented by a MAC curve (exemplary points: 10% reduction at 30$/tCO2, 40% reduction at 200$/tCO2, 60% reduction at 600$/tCO2), and the costs for reducing cement emissions are fully accounted for in the budget equation. Additionally, process emissions from cement production can be further reduced by using CCS – the model employs the same MAC curve as for energy-use emissions in the cement sub-sector.

4.4) Energy demand - REMIND

Baseline final energy in REMIND is calibrated to projections from theEDGE2 model (Energy Demand Generator, version 2). EDGE2 integrates econometric projections based on historical trends with scenario assumptions about long-term developments. The econometric projections play an important role in the short term while scenario assumptions rather influence the long-term behavior. The EDGE2 model covers six energy carriers— biomass, coal, electricity, liquids, gas, district heat —and six sectors —residential, commercial, industry, non-energy use, agriculture and fisheries, others.

The econometric regressions draw on the historical relationship between the per capita energy carrier demand in each sector and the GDP or sectoral value added per capita. The specification of the econometric model differs from one energy carrier to the other depending upon the observed relationship in historical data between the explained and the explanatory variables, or upon the regional heterogeneity. Each sectoral energy carrier is treated individually, which allows for a better control of the econometric fit, but has the disadvantage of ignoring the interdependencies between them. However, these interdependencies are partly reflected in the historical data.

The scenario assumptions follow the SSP framework and narratives [1]. In the SSP2 middle-of-the road scenario, EDGE 2 assumes a continuation of historical per-capita energy demand trends, and a regional partial convergence towards a global trend line over time. This global trend line relates globally averaged per capita demand for an energy carrier with per capita GDP. The convergence assumption differs across energy carriers and sectors. Typically, demand for electricity will assume greater convergence than demand for gas, liquids or district heat, which reflects the diverse regional heating requirements. The resulting demands were then user-adjusted to ensure that aggregated demand for energy carriers used to provide heat lies within a band of expected per-capita heat demand at a given per capita income.

To derive SSP1 and SSP5 demand trajectories, three types of modifications were performed relative to SSP2 to reflect the respective scenario narratives: (1) a change in the energy intensity in the end-use sectors transportation, industry, residential and commercial buildings, (2) a change in the energy carrier intensities (most importantly, electric vs. non-electric), and (3) a change in the regional convergence of trajectories.

The projections show agreement with several energy stylized facts [2]. In line with the energy-ladder concept [3], the share of solids decreases widely. Most notably, they exhibit a phase-out of traditional biomass in developing countries. By contrast, the share of grid-based energy carriers, in particular electricity, is projected to increase across all regions over the century. Following GDP per capita and population projections, developing regions' demands grow fast, while developed regions experience a slower increase. In line with other studies, we find that currently least-developed countries will account for the bulk of global energy demand in the long-term.

Once these projections are calculated, they are aggregated to the sectoral and energy carrier levels present in REMIND. Then, the macro-economic production function of REMIND is calibrated to meet these energy demand pathways in the baseline scenario .

In policy cases, REMIND can reduce energy intensity energy service input per unit of economic output through two mechanisms. First, 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. Second, 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.

1. O'Neill, Kriegler et al.
2. van Ruijven et al. 2008
3. Karekezi et al. 2012

4.5) Technological change in energy - REMIND

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 endogenously prescribed floor costs.

For variable renewable energies, we implemented two parameterized cost markup functions for storage and long-distance transmission grids - see Section "Electricity". To represent the general need for flexibility even in a thermal power system, we included a further flexibility constraint based on Sullivan [1].

The techno-economic parameters of power technologies used in the model are given in Table 2 Techno-economic characteristics of technologies based on exhaustible energy sources and biomass. (http://themasites.pbl.nl/models/advance/index.php/Electricity_-_REMIND) for fuel-based technologies and in Table 3 echno-economic characteristics of technologies based on non-biomass renewable energy sources. (http://themasites.pbl.nl/models/advance/index.php/Electricity_-_REMIND) for non-biomass renewables. For wind, solar and hydro, capacity factors depend on grades, see Section "Non-biomass renewables"

As discussed in Section "Macro-economy", 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 "Energy conversion").

1. Sullivan P, Krey V, Riahi K (2013) Impacts of considering electric sector variability and reliability in the MESSAGE model. Energy Strategy Reviews 1:157–163. doi: 10.1016/j.esr.2013.01.001)

5) Land-use - REMIND

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. In the default standalone mode, 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 [1]; [2]; [3]. 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.
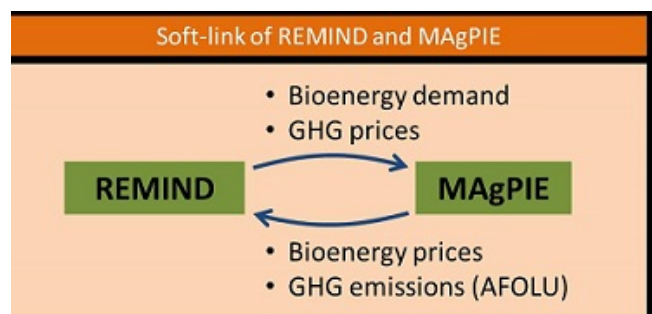
Figure 1. In the coupled mode REMIND is soft-linked to the land-use model MAgPIE. The models are run iteratively and exchange information about bioenergy demand and supply and about emission mitigation in the land-use system.

1. Lotze-Campen H, Müller C, Bondeau A, et al (2008) Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach. Agricultural Economics 39:325–338. doi: 10.1111/j.1574-0862.2008.00336.x
2. Popp A, Lotze-Campen H, Bodirsky B (2010) Food consumption, diet shifts and associated non-CO2 greenhouse gases from agricultural production. Global Environmental Change 20:451–462. doi: 10.1016/j.gloenvcha.2010.02.001
3. Lotze-Campen H, Popp A, Beringer T, et al (2010) Scenarios of global bioenergy production: The trade-offs between agricultural expansion, intensification and trade. Ecological Modelling 221:2188–2196. doi: 10.1016/j.ecolmodel.2009.10.002

5.1) Agriculture - REMIND

REMIND derives non-CO2 emissions in the absence of climate policies from various agricultural activities for given assumptions on socio-economic pathways from corresponding MAgPIE scenarios. An important nexus between the energy system and agriculture is bioenergy demand. In standalone mode, REMIND uses bioenergy supply costs derived from MAgPIE, see section "Bioenergy". To account for the sensitivity of resource potentials to carbon pricing, REMIND uses different supply curve parameterizations in baseline and climate policy scenarios. Bioenergy-induced emissions of N2O (fertilizer use) and CO2 (land-use change) are accounted for using specific per-unit emission coefficients.

In standalone mode, REMIND derives the economic mitigation potential of agricultural CH4 and N2O emissions is calculated using marginal abatement cost curves (MACCs) from Lucas [1]. For land-use related CO2, similar MACCs derived from MAgPIE are employed.

As described in Figure 1 (http://themasites.pbl.nl/models/advance/index.php/Land-use_-_REMIND), if run in coupled mode REMIND adopts consistent GHG emission projections and bioenergy supply curves from MAgPIE.

1. Lucas PL, van Vuuren DP, Olivier JGJ, den Elzen MGJ (2007) Long-term reduction potential of non-CO2 greenhouse gases. Environmental Science & Policy 10:85–103. doi: 10.1016/j.envsci.2006.10.007

5.2) Forestry - REMIND

If run in stand-alone mode, REMIND relies on 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.

6) Emissions - REMIND

6.1) GHGs - REMIND

REMIND simulates emissions from long-lived GHGs (CO2, CH4, N2O), short-lived GHGs (CO, NOx, VOC) and aerosols (SO2, BC, OC). REMIND accounts for these emissions with different levels of detail depending on the types and sources of emissions (see Table 10). It calculates CO2 emissions from fuel combustion, CH4 emissions from fossil fuel extraction and residential energy use and N2O 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 [1].

CH4, N2O, and CO2 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 16). 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 CO2 emissions from cement production as well as CH4 and N2O 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 N2O 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.
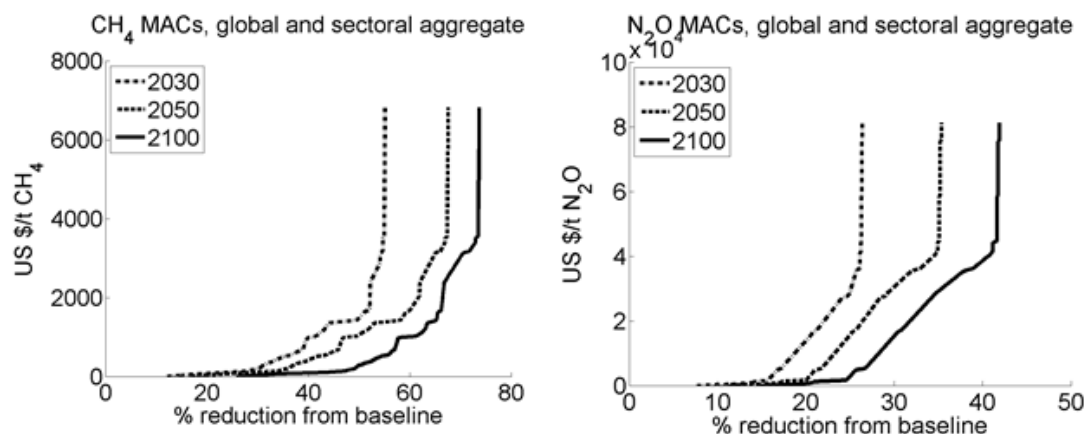

Figure 1. Globally and sectorally aggregated abatement costs and potentials for CH4 (left panel) and N2O (right panel) for different points in time. Marginal abatement cost curves are shifted over time such that more abatement is possible and the same level of abatement is available for a lower price. Adapted from Strefler, et al. (2014).

Table 1. Overview of the treatment of GHG and air pollutant emissions.

GHG and air pollutant emissions	Treatment in REMIND	Percentage of 2005 CO2e emissions
CO₂ fuel combustion	By source	56.6 %
Other CO₂ industry	Econometric estimate, coupled with capital investments per capita	2.8 %
CO₂ LUC	Marginal abatement cost curves, baseline from MAgPIE	17.3 %
CH₄ fossil fuel extraction	Marginal abatement cost curves, baseline by source	14.3 %
CH₄ residential energy use	By source	
CH₄ land use (agriculture)	Marginal abatement cost curves, baseline from MAgPIE	
CH₄ land use change (open burning)	Exogenous	
CH₄ and N₂O from waste handling	Marginal abatement cost curves, baseline econometric estimate, coupled to GDP per capita	7.9 %
N₂O transport and industry	Marginal abatement cost curves, baseline exogenous	
N₂O energy supply	By source	
N₂O land use (agriculture)	Marginal abatement cost curves, Baseline from MAgPIE plus emission factor on bioenergy	
N₂O land use change (open burning)	Exogenous	
CFCs	Exogenous	1.1 %
PFCs	Exogenous	
SF₆	Exogenous	
Montreal gases	Exogenous	N/A
CO	By source	
NOx	By source	
VOC	By source	
NH₃	By source	
SO₂ fuel combustion	By source	
SO₂ other sources	Exogenous	
Fossil fuel burning BC	By source	
Fossil fuel burning OC		
Biomass burning BC	Exogenous	
Biomass burning OC	Exogenous	

1. EDGAR (2011) Global Emissions EDGAR v4.2. http://edgar.jrc.ec.europa.eu/overview.php?v=42. Accessed 25 Jan 2013

6.2) Pollutants and non-GHG forcing agents - REMIND

REMIND calculates emissions of aerosols and ozone precursors (SO2, BC, OC, NOx, CO, VOC, NH3). It accounts for these emissions with different levels of detail depending on sources and species.

For pollutant emissions of SO2, BC, OC, NOx, CO, VOC and NH3 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 [1]. Emission factors for SO2, 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 [2]. Further, REMIND uses landuse emissions from the MAgPIE model, which in turn are based on emission factors from van der Werf [3]. Other emissions are exogenous and are taken from the RCP scenarios [4].

1. EDGAR (2011) Global Emissions EDGAR v4.2. http://edgar.jrc.ec.europa.eu/overview.php?v=42. Accessed 25 Jan 2013
2. Fujino et al. (2006)
3. Werf et al. (2010)
4. Van Vuuren D, Stehfest E, Gernaat DEHJ, et al (under review) Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm

7) Climate - REMIND

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 "Policy").

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 CH4, N2O, sulfate aerosols, black carbon, and organic carbon [1]. The climate module determines the atmospheric concentrations of CO2, CH4, and N2O 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.

1. Tanaka K, Kriegler E (2007) Aggregated Carbon Cycle, Atmospheric Chemistry, and Climate Model (ACC2)

8) Non-climate sustainability dimension - REMIND

Air pollution

Emissions of air pollutants are derived as described in section "GHGs".

Water

The water module of REMIND represents water demand for electricity production and is extensively described in Mouratiadou [1]; [2]. The description that follows is based on excerpts from these two papers. More extensive details on the methodology can be found in their Supplementary Online Materials, while a summary is provided below.

In REMIND, water demand for electricity production represents requirements associated to cleaning, cooling, and other process related needs (e.g. flue gas desulfurization). Both the water withdrawal and water consumption indicators are quantified. All four principal cooling systems are considered, those being once-through open systems (with freshwater or sea water), recirculating wet towers, pond cooling, and dry towers.

Based on these indicators and cooling systems, REMIND carries out an ex-post estimation of operational water demand for the electricity sector, by combining exogenous information on the water requirements per electricity and cooling technology with endogenous information on the electricity mix and technology vintages. Thermoelectric power plant cooling requirements are estimated as a function of excess heat, as opposed to a function of electricity output. Therefore, differences in water intensities in time or across regions due to differences in power plant thermal efficiencies and the age structure of thermal power plants are taken explicitly into account.

In sum, our estimate of water demand for electricity is based on the mix of electricity production technologies, the shares of cooling technologies, the water withdrawal and water consumption intensities, the vintage structures and the power plant thermal efficiencies. Global water withdrawal and consumption for thermal power technologies (WTt) are calculated by multiplying the excess heat from thermal power plants with the share of technology vintages (Vin), the vintage-specific share (csh) of different cooling technologies (cl), and the cooling technology specific water withdrawal or consumption coefficient for excess heat (cheat) and summing over regions, technologies and vintages.

$$WT_t = \sum_{r,elt,tb} \left(Vin_{r,t,elt,tb} \cdot Heat_{r,t,elt} \cdot \sum_{cl} \left(csh_{r,elt,tb,cl} \cdot cheat_{elt,cl} \right) \right)$$

Global water withdrawal and consumption for non-biomass renewable technologies elr (WRt) are estimated in a similar manner, only that they are based on electricity output (El) and electricity output-based coefficients instead of excess heat.

$$WR_t = \sum_{r,elr,tb} \left(Vin_{r,t,elr,tb} \cdot El_{r,t,elr} \cdot \sum_{cl} \left(csh_{r,elr,tb,cl} \cdot cel_{elr,cl} \right) \right)$$

Water withdrawal and consumption coefficients per electricity output are based on Macknick [3]; [4], and have been converted into the coefficients for excess heat for the thermal power plant technologies (cheat) by back calculating the respective value for the US for 2005. The shares of cooling technologies per electricity technology are deduced from Kyle [5].

Currently, the electricity water demand estimates do not include water demand for fossil fuel extraction or for the irrigation of bioenergy crops. Additionally, water quantity and quality constraints, or the costs and technical characteristics of various cooling technologies, are not taken explicitly into account.

1. Mouratiadou I, Biewald A, Pehl M, et al (2016) The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways. Environmental Science & Policy 64:48–58. doi: 10.1016/j.envsci.2016.06.007
2. Mouratiadou I, Bevione M, Bijl D, et al (submitted) The water-electricity nexus in deep decarbonization scenarios: a multi-model assessment)
3. Macknick J, Newmark R, Heath G, Hallett KC (2011) A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies. National Renewable Energy Laboratory, Golden, Colorado
4. Macknick J, Sattler, S., Averyt, K., et al (2012) The water implications of generating electricity: water use across the United States based on different electricity pathways through 2050. Environmental Research Letters 7:045803
5. Kyle P, Davies EGR, Dooley JJ, et al (2013) Influence of climate change mitigation technology on global demands of water for electricity generation. International Journal of Greenhouse Gas Control 13:112–123. doi: 10.1016/j.ijggc.2012.12.006

9) Appendices - REMIND

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

9.1) Mathematical model description - REMIND

The documentation of REMIND equations can be found at http://www.pik-potsdam.de/research/sustainable-solutions/models/remind/remind-equations.pdf

10) References - REMIND

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