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Report

2 November 2020

The REMIND-MAgPIE model and scenarios for transition risk analysis

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Based on the REMIND-MAgPIE model documentation and inputs of all authors of underlying documents:

Luderer G, Leimbach M, Bauer N, Kriegler E, Baumstark L, Bertram B, Giannousakis A, Hilaire J, Klein D, Levesque A, Mouratiadou I, Pehl M, Pietzcker R, Piontek F, Roming N, Schultes A, Schwanitz VJ, Strefler J (2016) Description of the REMIND model https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2697070

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This research project "Support for the Task-Force for Climate Related Financial Disclosures (TCFD) Banking Pilot Phase II" was funded by the United Nations Environment Program Finance Initiative (UNEP-FI) under grant nr. 1500003755

Citation suggestion:

Hilaire, J., Bertram, C. (2020): The REMIND-MAgPIE model and scenarios for transition risk analysis. A report prepared by PIK for the UNEP-FI Banking Pilot project (Phase 2), Potsdam: Potsdam-Institut für Klimafolgenforschung, 20 p.

https://doi.org/10.2312/pik.2020.006

The REMIND-MAgPIE model and scenarios for transition risk analysis

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2 November 2020

Abstract

This technical report documents the REMIND-MAgPIE model and the REMIND-MAgPIE scenarios that were selected to support transition risk analysis for the Task-Force for Climate Related Financial Disclosures (TCFD) Banking Pilot Phase II. REMIND-MAgPIE is an optimisation model that integrates the macroeconomic, agriculture and land-use, energy, water and climate systems. It describes, in a forward-looking fashion, the complex and non-linear dynamics in and between these systems. In line with the TCFD recommendations, the scenarios generated with this model can be integrated into risks assessments frameworks to identify and evaluate the risks related to a transition to a low-carbon economy.

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Acknowledgments

The authors would like to thank David Carlin (UNEP-FI) for leading the UNEP-FI TCFD Banking Pilot Phase 2, and the teams of UNEP-FI, Oliver Wyman and participating banks for fruitful discussions of climate scenarios and their analysis.
Special thanks go to Bas van Ruijven (IIASA) and Jihoon Min (IIASA) for the pleasant and fruitful collaboration, Elmar Kriegler (PIK) for his advice and the entire REMIND team for its support.

The REMIND-MAgPIE integrated assessment modelling framework

REMIND-MAgPIE is a comprehensive integrated assessment modelling (IAM) framework that quantifies, in a forward-looking fashion, the complex and non-linear dynamics within and between the energy, land-use, water, economy and climate systems. The model was created a decade ago (Leimbach, Bauer, Baumstark, and Edenhofer 2010; Lotze-Campen et al. 2008) and is continually being improved to generate up-to-date insights for scientific publications, and provide scientific evidence to decision and policy makers and other relevant stakeholders on climate change mitigation and further sustainability dimensions.

The REMIND-MAgPIE framework consists of four main components (see Figure 1). First the REMIND model combines a macro-economic module with an energy system module. The macro-economic core of REMIND is a Ramsey-type optimal growth model in which inter-temporal welfare is maximised. The energy system module includes a detailed representation of energy supply and demand sectors. Second the MAgPIE model represents land-use dynamics. The MAgPIE model is linked to the dynamic global vegetation model LPJmL (Bondeau et al. 2007; Müller and Robertson 2014; Schaphoff et al. 2017). For some applications that do not require detailed land-use information, a MAgPIE-based emulator is used to make the scenario generation process more efficient. The REMIND model is linked to the climate model MAGICC to account for changes in climate-related variables like global surface mean temperature. In addition, REMIND can be linked to other models to allow the analysis of other environmental impacts such as water demand, air pollution and health effects.

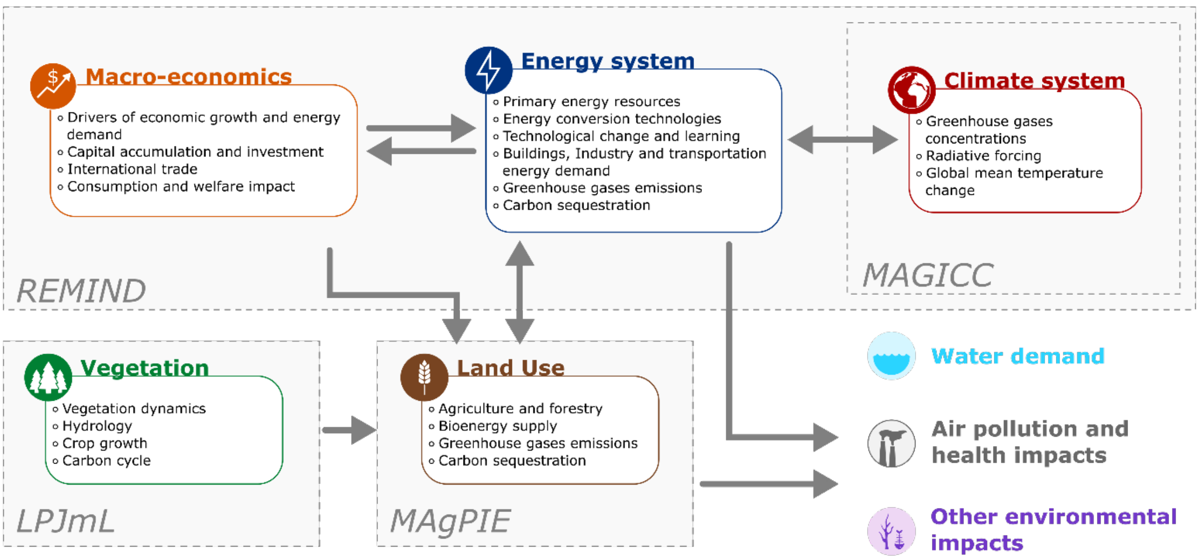

Figure 1 *Overview of the REMIND-MAgPIE integrated assessment modelling framework*

Specifically, REMIND (Regional Model of Investment and Development) is an energy-economy general equilibrium model linking a macro-economic growth model with a bottom-up engineering-based energy system model. It covers eleven world regions (see Figure 2), differentiates various energy carriers and technologies and represents the dynamics of economic growth and international trade (Leimbach, Bauer, Baumstark, and Edenhofer 2010; Leimbach, Bauer, Baumstark, Luken, et al. 2010; Leimbach et al. 2017; Mouratiadou et al. 2016). A Ramsey-type growth model with perfect foresight serves as a macro-economic core projecting growth, savings and investments, factor incomes, energy and material demand. The energy system representation differentiates between a variety of fossil, biogenic, nuclear and renewable energy resources (Bauer, Calvin, et al. 2016; Bauer, Brecha, and Luderer 2012; Bauer, Hilaire, et al. 2016; Klein et al. 2014; 2014; Robert C. Pietzcker et al. 2014). The model accounts for crucial drivers of energy system inertia and path dependencies by representing full capacity vintage structure, technological learning of emergent new technologies, as well as adjustment costs for rapidly expanding technologies (Robert C. Pietzcker et al. 2017). The emissions of greenhouse gases (GHGs) and air pollutants are largely represented by source and linked to activities in the energy-economic system (Strefler, Luderer, Aboumahboub, et al. 2014; Strefler, Luderer, Kriegler, et al. 2014). Several energy sector policies are represented explicitly (Bertram et al. 2015; 2018; Kriegler et al. 2018), including energy-sector fuel taxes and consumer subsidies (Jewell et al. 2018; Schwanitz et al. 2014). The model also represents trade in energy resources (Bauer et al. 2015). More details on REMIND are provided in the next section.

MAgPIE (Model of Agricultural Production and its Impacts on the Environment) is a global multi-regional economic land-use optimization model designed for scenario analysis up to the year 2100. It is a partial equilibrium model of the agricultural sector that is solved in recursive dynamic mode. The objective function of MAgPIE is the fulfilment of agricultural demand for ten world regions at minimum global costs under consideration of biophysical and socio-economic constraints. Major cost types in MAgPIE are factor requirement costs (capital, labor, fertilizer), land conversion costs, transportation costs to the closest market, investment costs for yield-increasing technological change (TC) and costs for GHG emissions in mitigation scenarios. Biophysical inputs (0.5° resolution) for MAgPIE, such as agricultural yields, carbon densities and water availability, are derived from a dynamic global vegetation, hydrology and crop growth model, the Lund-Potsdam-Jena model for managed Land (LPJmL) (Bondeau et al. 2007; Müller and Robertson 2014; Schaphoff et al. 2017). Agricultural demand includes demand for food (Benjamin L. Bodirsky and Popp 2015), feed (Weindl et al. 2015), bioenergy (Humpenöder et al. 2018, 2011; A. Popp et al. 2010, 2011), material and seed. For meeting the demand, MAgPIE endogenously decides, based on cost-effectiveness, about intensification of agricultural production, cropland expansion and production relocation (intra-regionally and inter-regionally through international trade) (Dietrich et al. 2014; Lotze-Campen et al. 2010; Schmitz et al. 2012). MAgPIE derives cell specific land-use patterns, rates of future agricultural yield increases(Dietrich et al. 2014), food commodity and bioenergy prices as well as GHG emissions from agricultural production (B. L. Bodirsky et al. 2012; A. Popp et al. 2010, 2010) and land-use change (Humpenöder et al. 2014; Alexander Popp et al. 2014; 2017, 201).

The coupling approach between REMIND and MAgPIE is designed to derive scenarios with equilibrated bioenergy and emissions markets. In equilibrium, bio-energy demand patterns computed by REMIND are fulfilled in MAgPIE at the same bioenergy and emissions prices that the demand patterns were based on. Moreover, the emissions in REMIND emerging from pre-defined climate policy assumptions account for the GHG emissions from the land-use sector derived in MAgPIE under the emissions pricing and bioenergy use mandated by the same climate policy. The simultaneous equilibrium of bioenergy and emissions markets is established by an iteration of REMIND and MAgPIE simulations in which REMIND provides emissions prices and bioenergy demand to MAgPIE and receives land use emissions and bioenergy prices from MAgPIE in return. The coupling approach with this iterative process at its core is explained elsewhere (Bauer et al. 2014).

MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) is a reduced-complexity climate model that is connected to REMIND and calculates atmospheric concentrations of GHGs and other atmospheric climate drivers, radiative forcing and global annual-mean surface air temperature (Meinshausen, Wigley, and Raper 2011). Emission pathways of greenhouse gases, greenhouse gas precursors and air pollutants computed by REMIND are fed to MAGICC to estimate future changes in climate-related variables.

In addition, REMIND can be linked to other models to allow the analysis of other environmental impacts such as water demand, air pollution and health effects.

More detailed information on the REMIND model can be found in the next sections. A comprehensive documentation of the model is available at this URL:
https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_REMIND

The different sections of the documentation are provided in Table 1.

Table 1 Sections and URLs of the REMIND documentation

Section	**Link**
Overview	https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_REMIND
Model scope and methods	https://www.iamcdocumentation.eu/index.php/Model_scope_and_methods_-_REMIND
Socio-economic drivers	https://www.iamcdocumentation.eu/index.php/Socio-economic_drivers_-_REMIND
Macro-economy	https://www.iamcdocumentation.eu/index.php/Macro-economy_-_REMIND
Energy	https://www.iamcdocumentation.eu/index.php/Energy_-_REMIND
Land use	https://www.iamcdocumentation.eu/index.php/Land-use_-_REMIND
Emissions	https://www.iamcdocumentation.eu/index.php/Emissions_-_REMIND
Climate	https://www.iamcdocumentation.eu/index.php/Climate_-_REMIND
Non-climate sustainability dimension	https://www.iamcdocumentation.eu/index.php/Non-climate_sustainability_dimension_-_REMIND

The source code of the model is open-source and available at this URL:
https://github.com/remindmodel/remind

A primer on climate mitigation scenarios and integrated assessment models is available at the following URL: https://climatescenarios.org/primer/ and further material can be accessed in the SENSES Toolkit : https://climatescenarios.org.

The REMIND model

Spatial and temporal definitions

REMIND version 1.7 used for the UNEP-FI banking pilot divides the world into 11 regions (see Figure 2). There are 5 individual countries (CHN – China; IND – India; JPN – Japan; USA – United States of America; and RUS – Russia) and 6 aggregated regions (AFR – Sub-Saharan Africa excluding Republic of South Africa; EUR – Members of the European Union; LAM – Latin America; MEA – including countries from the Middle East, North Africa, and central Asia; OAS – other Asian countries mainly located in South East Asia; and ROW – the rest of the world including among others Australia, Canada, New Zealand, Norway, Turkey, and the Republic of South Africa).

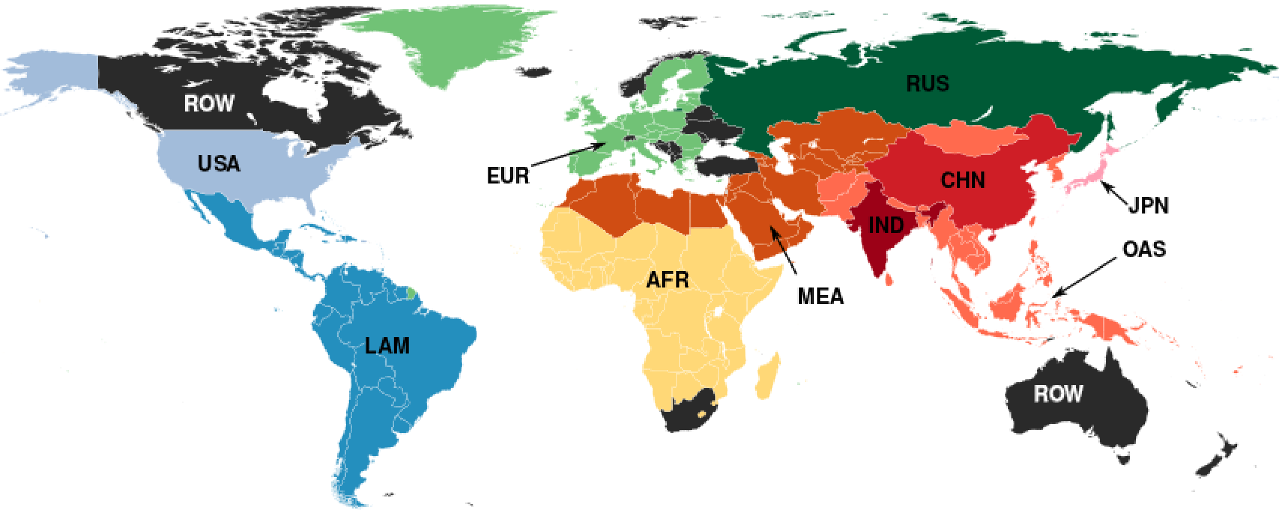

Figure 2 *Regional definition in the REMIND model*

Regarding the temporal dimension, the model outputs data every five years between 2005 and 2060 and every ten years between 2060 and 2100.

Structure and modules

The structure of the REMIND model is depicted in Figure 3. The macro-economic core of REMIND is a Ramsey-type optimal growth model in which intertemporal welfare is maximised. The model explicitly represents regional trade in final goods, primary energy carriers, and in the case of climate policy, emissions allowances. Macro-economic production factors are capital, labour 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 and energy system modules are linked via the following two channels: final energy demand and costs incurred by the energy system (Bauer, Edenhofer, and Kypreos 2008). Economic activity results in demand for final energy in the transportation, industry and buildings sectors[1]. A production function with constant elasticity of substitution (nested CES production function, see next section) 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 fifty technologies are available for the conversion of primary energy into

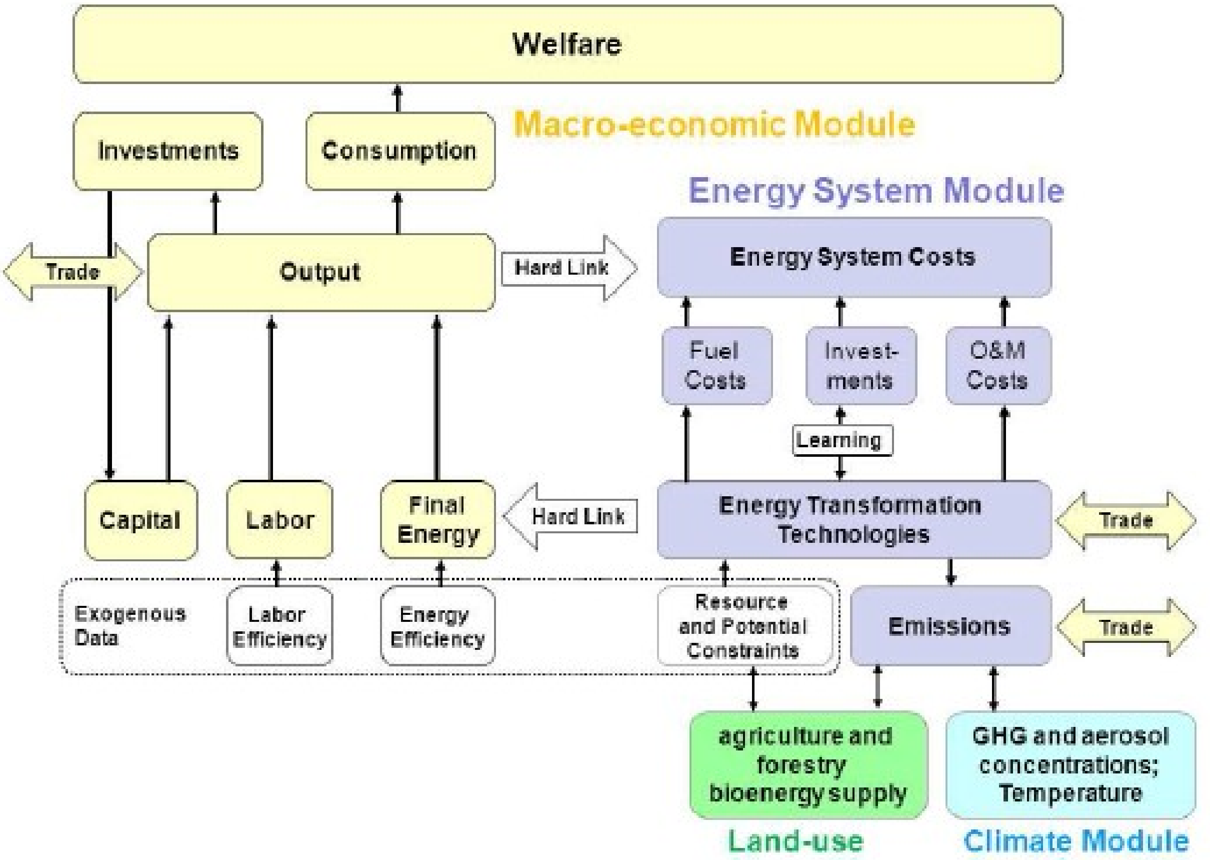

***Figure 3** Overview of the structure of the REMIND model*

secondary energy carriers as well as for the distribution of secondary energy carriers into final energy.

Macro-economics

Optimal growth model and solution algorithm

REMIND models each region as a representative household with a utility function that depends upon per-capita consumption. Following welfare economic theory, utility increases with per-capita consumption though at decreasing rates (diminishing marginal utility). The calculation of utility is also subject to a discounting of 3%. The logarithmic relationship between per-capita consumption and regional utility implies an elasticity of marginal consumption of 1. Thus, in line with the

[1] Note that this sectoral division is typically used in energy models and does not match perfectly other classifications often used in economic circles (e.g. BICS, GICS, ISIC and NACE)

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 relies on a non-cooperative Nash algorithm to converge to the optimal solution (Leimbach et al. 2017) and do so by maximising the regional welfare subject to regional constraints and international prices. The non-cooperative nature of this algorithm is characterized by the non-internalisation of interregional externalities like global spillovers from learning-by-doing in the energy sector (e.g. innovations in solar PV and wind technologies). The intertemporal balance of payments of each region is constrained to equal zero. The equilibrium solution is found by iteratively adjusting the international prices until global demand and supply are balanced in each market.

CES production function

REMIND uses a nested production function with constant elasticity of substitution (CES) to determine a region's gross domestic product (GDP) (see Figure 4). Inputs at the upper level of the production function include labour, capital and final energy (also called aggregated energy). We use the population at working age to determine the labour force. Final energy input to the upper production level forms a CES nest which comprises energy for transportation, industry and buildings coupled with a substitution elasticity of 0.3. In turn, these three 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. In addition, an energy efficiency parameter is assigned to each production factor which allows efficiency improvements to be accounted for. These parameters are tuned such that baseline economic growth and energy intensity improvements match exogenous scenario specifications (e.g. The Shared Socio-Economic Pathway (SSP) assumptions, see O'Neill et al. (2014) for more details).

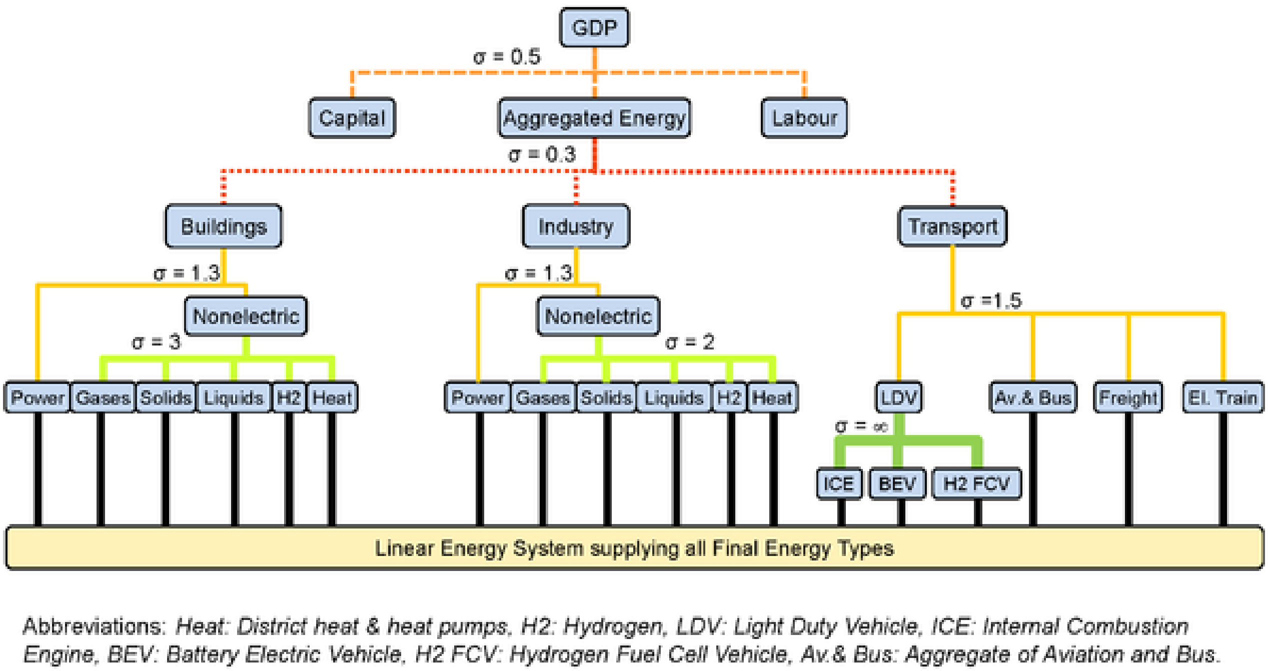

Figure 4 *Overview of the nested CES production function in REMIND*

Energy demand

Baseline final energy in REMIND is calibrated to energy demand projections. These result from the combination of short-term econometric projections of historical trends with long-term development assumptions (e.g SSP2 scenario assumptions). In the short-term, the econometric regressions estimate the future demand of six energy carriers (i.e. biomass, coal, electricity, liquids, gas, district heat) across six sectors (i.e. residential, commercial, industry, non-energy use, agriculture and fisheries, others). They draw from the relationship between the per capita energy carrier demand in each sector and the GDP or sectoral value added per capita. In the long-term, the scenario assumptions follow the SSP framework and narratives. In the SSP2 middle-of-the road scenario, continuation of historical per-capita energy demand trends is assumed as well as 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.

The projections show agreement with several energy stylized facts (Van Ruijven et al. 2008). In line with the energy-ladder concept (Karekezi et al. 2012), 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.

Once these projections are calculated, they are aggregated to the sectoral (i.e. buildings, industry and transportation) and energy carrier levels (e.g. electricity, liquids, gas, heat, solids, H2) defined 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 via 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 the 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 are implemented in the light duty vehicle (LDV) mode of the transport sector: internal combustion engine vehicles, battery-electric vehicles, and fuel cell vehicles.

Energy technologies

Around fifty different energy conversion technologies are represented in REMIND. The core part of the energy system corresponds to the conversion of primary energy into secondary energy carriers via specific energy conversion technologies (e.g. power plants, refineries). These technologies compete with each other and are chosen to minimise the costs of the system 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 (e.g. power plants). The various secondary energy carriers included in REMIND are electricity, gases, liquid fuels, hydrogen, solid fuels, district heat and local renewable heat.

Exhaustible energy resources

Exhaustible energy resources comprise coal, oil, gas and uranium. They are represented as region-specific extraction cost curves that relate cumulative extraction to production cost increases (Bauer, Hilaire, et al. 2016; IHS CERA 2012; Hans-Holger Rogner et al. 2012). Extraction costs increase over time as low-cost deposits become exhausted (Herfindahl 1967; H-H Rogner 1997; Aguilera et al. 2009; BGR 2010; Hans-Holger Rogner et al. 2012). Fossil resources (e.g. coal, oil and gas) are further defined by decline rates and adjustment costs (Bauer, Mouratiadou, et al. 2016; IEA 2008; 2009; Dahl and Duggan 1998; Krichene 2002; Askari and Krichene 2010). The regional trade of exhaustible energy resources is subject to regional- and resource-specific trade costs.

Renewable resources

Renewable resources include biomass and non-biomass renewables like water (hydro), wind, solar, geothermal.

Regarding biomass, three types of bioenergy feedstocks are considered in REMIND, namely first-generation biomasss (e.g. sugar, starch), ligno-cellulosic residues and second-generation purpose-grown biomass (e.g. grassy and woody biomass). 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 et al. (2014). The supply curves capture the time, scale and region dependent change of bioenergy production costs, as well as path dependencies resulting from past land conversions and induced technological changes in the land-use sector, all of which are simulated in MAgPIE.

As for non-biomass renewables, the resource potentials for hydro, solar, wind, and geothermal are represented by using region-specific potentials (Luderer et al. 2014; Robert Carl Pietzcker et al. 2014; Robert C. Pietzcker et al. 2017). For each renewable energy type, the potentials are classified into different grades, specified by capacity factors. 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 optimisation.

Emissions of greenhouse gases and air pollutants

REMIND simulates emissions from long-lived GHGs (CO_2, CH_4, N_2O, fluorinated gases), short-lived GHGs and precursors (CO, NO_x, VOC) and aerosols and precursors (SO_2, BC, OC, NH_3). REMIND accounts for these emissions with different levels of detail depending on the types and sources of emissions. It calculates CO_2 emissions from fuel combustion, CH_4 emissions from fossil fuel extraction and residential energy use and N_2O emissions from energy supply based on sources. The energy system provides information on the regional consumption of fossil fuels and biomass for each time step and technology. For each fuel, region and technology, REMIND applies specific emissions factors, which are calibrated to match base year GHG inventories.

CH_4, N_2O, and CO_2 from land-use change have mitigation options that are independent of energy consumption. However, costs are associated with these emissions. Therefore, REMIND derives the mitigation options from marginal abatement cost (MAC) curves, which describe the percentage of abated emissions as a function of the costs. It is possible to obtain baseline emissions - to which the MAC curves are applied - by three different methods: by source (as described above), by an econometric estimate, or exogenously. REMIND uses the econometric estimate for CO_2 emissions from cement production as well as CH_4 and N_2O emissions from waste handling. In both cases, the driver of emissions depends on the development of the GDP (as a proxy for waste production) or capital investment (as a proxy for cement production in infrastructure). REMIND uses exogenous baselines for N_2O emissions from transport and industry.

Emissions of other GHGs (e.g. fluorinated gases) are exogenous and are taken from the SSP scenario data set from the IMAGE model. REMIND does not represent abatement options for these gases; therefore, emissions from IMAGE scenarios best matching the target of the specific model simulation are used.

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

For pollutant emissions of SO_2, BC, OC, NO_x, CO, VOC and NH_3 related to the combustion of fossil fuels, REMIND considers time- and region-specific emissions factors coupled to model-endogenous activity data. Emission factors for SO_2, BC, and OC are assumed to decline over time according to air pollution policies (Rao et al. 2017). 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.

Land-use model emulator

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. These are derived based on the state-of-the-art land use model MAgPIE (Lotze-Campen et al. 2008; Alexander Popp, Lotze-Campen, and Bodirsky 2010; Lotze-Campen et al. 2010).

REMIND-MAgPIE scenarios for transition risk analysis

Selected scenarios

In consultation with UNEP-FI and the participants of the banking pilot project, we selected a set of eight transition scenarios that cover a range of emission reductions of varying stringency and pace. They cover alternative assumptions on the dimensions of policy method (exploration of near-term policy consequences vs. long-term target pathways), policy timing (immediate policy vs. delayed implementation of policy), and technology availability (full availability of CDR vs. limited availability of CDR). We distinguish four types of scenarios containing the specific scenarios defined as follows:

1) Near-term policy extrapolation scenarios

- **NPi**: National implemented policies
- **NDC**: Nationally Determined Contributions for 2030 (conditional commitments)

2) Immediate global climate action based on carbon budget

- **Immediate2C**: global climate action after 2020 to limit cumulative emissions between 2011-2100 to 1000 GtCO2 (67% chance of limiting warming to 2 degrees Celsius)
- **Immediate1p5C**: global climate action after 2020 to limit cumulative emissions between 2011-2100 to 400 GtCO2 (67% chance of limiting warming to 1.5 degrees Celsius)

3) Delayed global climate action based on carbon budget

- **Delayed2C**: delayed global climate action after 2030 to limit cumulative emissions between 2011-2100 to 1000 GtCO2 (67% chance of limiting warming to 2 degrees Celsius), following NDCs until 2030
- **Delayed1p5C**: delayed global climate action after 2030 to limit cumulative emissions between 2011-2100 to 400 GtCO2 (67% chance of limiting warming to 1.5 degrees Celsius), following NDCs until 2030

4) Immediate global climate action based on carbon budget with alternative assumption on technology availability

- **LowCDR2C**: global climate action after 2020 to limit cumulative emissions between 2011-2100 to 1000 GtCO2 (67% chance of limiting warming to 2 degrees Celsius), assuming limited availability of carbon dioxide removal options
- **LowCDR1p5C**: global climate action after 2020 to limit cumulative emissions between 2011-2100 to 400 GtCO2 (67% chance of limiting warming to 1.5 degrees Celsius), assuming limited availability of carbon dioxide removal options

Motivation for the scenario choices

The selected scenarios cover a range of emission reductions and carbon prices that vary in stringency and pace (see Figure 5). These ranges reflect the different risk levels associated with the transition to a low-carbon future with 1.5 and 2 degrees Celsius of warming. These transition risks can be characterised by orderly and disorderly transition pathways (NGFS 2019).

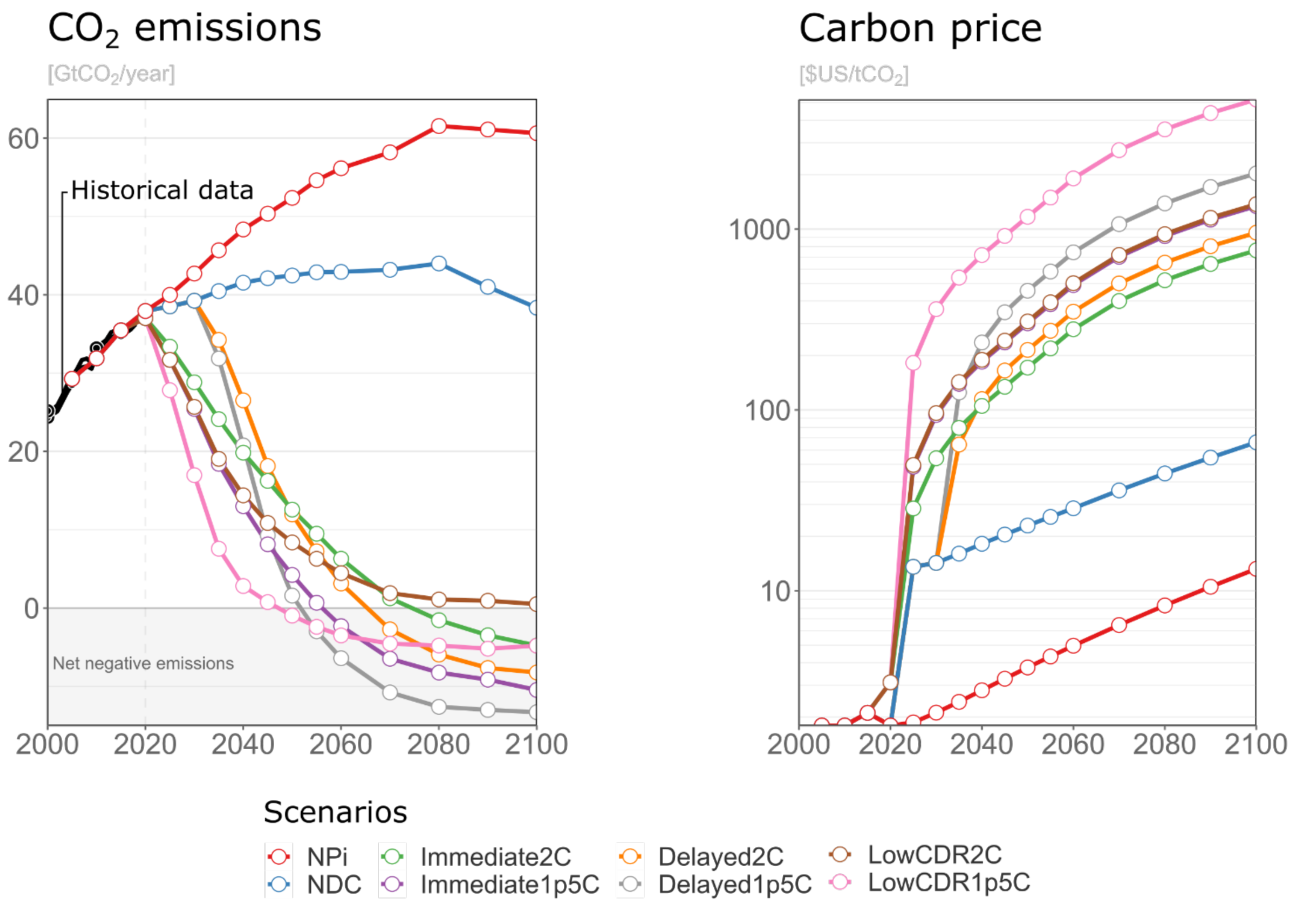

Figure 5 *Global CO_2 emissions from energy and industrial processes and carbon prices in the 8 REMIND-MAgPIE scenarios. Historical data include CEDS (Hoesly et al. 2017) and EDGAR 5.0 (Crippa et al. 2019).*

The most orderly transition pathways include the NPi and NDC scenarios which reflect currently implemented and planned policies, respectively. Concretely, NPi represents a scenario in which climate action is not becoming more stringent than that implied by currently implemented policies; whereas NDC includes announced greenhouse gas emission reductions for 2030 (e.g. country conditional NDCs). Announced longer-term targets like the 2050 net-zero emission commitments are excluded because their scope is too broad and uncertain. It is important to note that in these scenarios, as there is no transition to a low-carbon future over the course of this century, global mean temperature could rise above 3 degrees Celsius and entail severe physical climate risks.

Orderly transition pathways in line with the goals of the Paris Agreement include the Immediate2C and Immediate1p5C scenarios which represent globally coordinated transitions to a low-carbon future, taking a globally cost-optimal emission trajectory into account that compensates GHG emissions (particularly those in the short term) with carbon dioxide removal, most of which occurs in the second half of the century (though the global upscaling of CDR technologies starts as early as 2030 and is rapid). These scenarios are rather idealized in their assumption on both the immediate implementation of global emission reductions and the scale up of negative emissions technologies over the next few decades. These two scenarios should be interpreted as benchmark against which the delayed and limited CDR cases which are more disorderly can be compared.

The Delayed1p5C and Delayed2C scenarios feature a delay in global climate action until 2030, as countries first only live up to the NDCs and then converge on a global trajectory towards a low-carbon future. In order to limit warming to well-below 2 degrees in these scenarios, emission reductions after 2030 need to be steeper than in the immediate1p5C and immediate2C scenario. In addition, more negative emissions are required to compensate for the lack of emission reduction in the short term. The LowCDR1p5C and LowCDR2C scenarios feature also an immediate globally coordinated transitions to a low-carbon future but under limited CDR availability. In these scenarios, carbon removal from bioenergy with carbon capture and storage does not go beyond 6.5 GtCO2 per year over the 21st century in relatively good agreement with a recent systematic review of the CDR literature (Fuss et al. 2018).

Scenario descriptions

All REMIND-MAgPIE scenarios provided to UNEP-FI are based on the study by Kriegler et al. (2018).

Current policy scenarios

The **National implemented Policies scenario (NPi)** describes energy, climate and economic projections for the period until 2030, based on currently implemented national policies relevant for achieving the internationally pledged INDC (Intended Nationally Determined Contributions) targets. The emission development after 2030 assumes that countries will pursue equivalent effort. This is represented by assuming constant relative CO_2-equivalent emission reductions between NoPolicy (a scenario without any climate policies) and NPi between 2030 and 2100. The starting point for NPi scenario is the climate policy database containing climate, energy and development policies in G20 countries with cut-off year of 2015. These policies can be policy targets from national policy documents (e.g. National Communication, strategy documents) or policy instruments (e.g. ETS, feed-in-tariff, renewable portfolio standard). In practice, policy instruments are often implemented to achieve national (often aspirational) policy targets. As it might be difficult to implement specific policy instruments in IAMs, we included aspirational policy targets as currently implemented policies, but only if they are backed by effective policy instruments. If the policy instrument ends before the policy target year, we assume continuation of the policy instrument, but only for around five years. This leads to the definition of implemented policy as either a policy adopted by the government (through legislation), or a non-binding target backed by effective policy instruments.

The **NDC scenario (NDC)** assumes implementation of NDCs by 2030, but no further intensification of emission reduction commitments beyond the NDCs after 2030. The focus of this scenario is the year 2030, which is the target year of most submitted NDCs. However, we assume that post-2030, countries will implement equivalent effort in the same way as for NPi scenario (so by assuming constant relative CO_2-equivalent emission reductions between a NoPolicy (scenario without any climate policies) and INDCi between 2030 and 2100). It thus assumes a continuation of fragmented and highly diversified action and does not represent an intensification of efforts toward the achievement of the 1.5-2°C target as envisioned by the Paris Agreement, but rather the floor of ambition implied by the submitted INDCs. It thus represents a scenario of moderate, fragmented action in which the (conditional) commitments made in the INDCs are realized, but where the international community fails to ratchet-up 2030 targets and increase long-term ambition relative to the effort implied by the INDCs. This scenario will serve as a point of comparison for the 1.5°C and 2°C scenarios.

Climate change mitigation scenarios

There are three sub-groups of scenarios achieving 1.5-2°C limits under a set of long-term carbon budget constraints.

Immediate climate action scenarios

The **ImmediateXX** scenarios explore the feasibility of achieving of keeping warming below the 1.5-2°C-limits in the most cost-effective way, by starting from today's policies under the cumulative (between 2011-2100) budget constraint of 400-1000 Gt CO_2, respectively.

Delayed climate action scenario

The **DelayedXX** scenarios explore the feasibility of keeping warming below the 1.5-2°C-limits in a global cost-effective way, starting from INDC-based near-term pathways under the cumulative (between 2011-2100) budget constraint of 400-1000 Gt CO_2, respectively.

The immediate and delayed climate action pathways are composed of two distinct phases: in the first phase until 2020 (Immediate) or 2030 (Delayed), they follow the developments of the NPi or NDC scenario (i.e. **ImmediateXX** achieves the currently implemented policies included in NPi scenario up till the year 2020, and **DelayedXX** achieves the INDC targets up till 2030). In the second phase starting from 2020 (Immediate) or 2030 (Delayed), they assume stylized, comprehensive climate policies (CO_2 prices equalized across regions and sectors) limiting cumulative 2011-2100 CO_2 budgets at two discrete levels (400 and 1000 Gt CO_2 cumulative 2011-2100), in line with long-term stabilization in the 1.5-2°C range. The carbon budget of 1000 GtCO_2 for the period 2011-2100 would limit global warming below 2°C relative to pre-industrial levels with at least 67%. The budget of 400 GtCO_2 for the period 2011-2100 explores the effort necessary to limit global warming to 1.5°C with 66% probability by the end of the 21st century (in 2100). During the 21st century the probability of exceeding 1.5°C is generally higher than 33% (also known as temperature overshoot). The same CO_2 price is applied to non-CO_2 greenhouse gases (i.e. CH_4, N_2O, fluorinated gases) to ensure comparable mitigation efforts across gases.

Limited CDR scenarios

The low CDR scenarios are similar to the **ImmediateXX** scenarios in the sense that they also explore the feasibility of keeping warming below the 1.5-2°C-limits in a global cost-effective way, starting from INDC-based near-term pathways under the cumulative (between 2011-2100) budget constraint of 400-1000 Gt CO_2, respectively. However, carbon dioxide removal in particular afforestation and biomass with carbon capture and storage is limited in these scenarios, by implementing an explicit constraint on areas available for afforestation and halving the injection rate for geological reservoirs compared to default assumptions.

Mapping with NGFS scenarios

The REMIND-MAgPIE scenarios provided to the UNEP-FI banking pilot overlap with some of the scenarios used for the NGFS scenario study (NGFS 2020b; 2020a; 2020c). The mapping between these two sets of scenario names are provided in Table 1.

Table 2 Mapping between UNEP-FI and NGFS scenario names

Kriegler et al. (2018) and IPCC SR1.5	**NGFS scenario name**	**UNEP-FI scenario name**
PEP_NPi[2]	Current Policies	NPi
PEP_NDC[3]	Nationally determined contributions (NDCs)	NDC
PEP_2C_full_eff	Immediate 2C scenario with CDR	Immediate2C
PEP_1p5C_full_eff	Immediate 1.5C scenario with CDR	Immediate1p5C
PEP_2C_full_NDC	Delayed 2C scenario with CDR	Delayed2C
PEP_1p5C_full_NDC	*Not available*	Delayed1p5C
PEP_2C_red_eff	Immediate 2C scenario with limited CDR	LowCDR2C
PEP_1p5C_red_eff	Immediate 1.5C scenario with limited CDR	LowCDR1p5C
PEP_2C_red_NDC	Delayed 2C scenario with limited CDR	*Not Available*

[2] This scenario is not available in Kriegler et al. (2018) and the IPCC SR1.5 database but was generated using the model version described in Kriegler et al. (2018).
[3] Only available in Kriegler et al. (2018)

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