Annex C: Scenarios and modelling methods

Coordinating Lead Authors: Celine Guivarch (France), Elmar Kriegler (Germany), Joana Portugal Pereira (Brazil).

Lead Authors: Valentina Bosetti (Italy), James Edmonds (the United States of America), Manfred Fischedick (Germany), Petr Havlik (Austria), Paulina Jaramillo (the United States of America), Volker Krey (Austria), Franck Lecocq (France), André Lucena (Brazil), Sebastian Mirasgedis (Greece), Glen Peters (Norway/Australia), Yamina Saheb (France/Algeria), Goran Strbac (United Kingdom), Anders Hammer Strømman (Norway), Detlef van Vuuren (the Netherlands), Nan Zhou (the United States of America).

Contributing Authors: Cornelia Auer (Germany), Nico Bauer (Germany), Edward Byers (Austria/Ireland), Bruno Cunha (Brazil), Stefan Frank (Austria), Jan Fuglestvedt (Norway), Mathijs Harmsen (the Netherlands), Alan Jenn (the United States of America), Jarmo Kikstra (Austria/the Netherlands), Paul Kishimoto (Canada), Robin Lamboll (United Kingdom), Julien Lefèvre (France), Eric Masanet (the United States of America), Craig Michael (the United States of America), Malte Meinshausen (Australia/Germany), Zebedee Nicholls (Australia), Aleksandra Novikova (Germany), Brian O'Neill (the United States of America), Simon Parkinson (Canada), Pedro Rochedo (Brazil), Joeri Rogelj (Belgium/United Kingdom), Steve Rose (the United States of America), Sasha Samadi (Germany), Yeh Sonia (Sweden/the United States of America), David Vérez (Spain/Cuba).

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Preamble

The use of scenarios and modelling methods are key pillars in IPCC WG III Assessment Reports. Past WG III assessment report cycles identified knowledge gaps about the integration of modelling across scales and disciplines, mainly between global integrated assessment modelling methods and bottom-up modelling insights of mitigation responses. Future research also recognised the need to improve the transparency of model assumptions and enhance the communication of scenario results.

This annex on *Scenarios and modelling methods* aims to address some of these gaps by detailing the modelling frameworks applied in the WG III AR6 chapters and disclose scenario assumptions and its key parameters. It was been explicitly included in the Scoping Meeting Report of the WG III contribution to the AR6 and approved by the IPCC Panel in the 46th Session of the Panel.

The annex includes two parts: Part I. on *modelling methods* summarises methods and tools available to evaluate sectorial, technological and behavioural mitigation responses as well as integrated assessment models (IAMs) for the analysis of “whole system” transformation pathways; Part II on *scenarios* sets out the portfolio of climate change scenarios and mitigation pathways assessed in the WG III AR6 chapters, its underneath principles and interactions with scenario assessments by WG I and WG II.

[To be updated before FGD submission.]

Part I Modelling methods

I.1. Overview of modelling tools

Modelling frameworks vary vastly amongst themselves, and several key characteristics can be used as basis for model classification (Scrieciu et al. 2013; Hardt and O'Neill 2017; Capellán-Pérez et al. 2020; Dodds et al. 2015). One of the most basic aspects of a modelling tool is how it approaches the system modelled from a solution perspective. **Simulation models** are based on the evaluation of the dynamic behaviour of a system (Lund et al. 2017). They can be used to determine the performance of a system under alternative options of key parameters in a realistic manner. Most often, simulation models require comprehensive knowledge of each parameter, in order to choose a specific path under several alternatives. On the other hand, **optimisation models** seek to maximise or minimise a mathematical objective function under a set of constraints (Iqbal et al. 2014; Baños et al. 2011). Most often, the objective function represents the total cost or revenue of a given system or the total welfare of a given society. One major aspect of optimisation models is that the solution in achieved by simultaneously binding a set of constraints, which can be used to represent real life limitation on the system, such as: constraints on flows, resource and technology availability, labour and financial limitations, environmental aspects, and many other characteristics that the model may require (Fazlollahi et al. 2012; Cedillos Alvarado et al. 2016; Pfenninger et al. 2014). Specifically, when modelling climate mitigation responses, limiting carbon budgets is often used to represent future temperature level pathways (Gidden et al. 2019a; Rogelj et al. 2016; Millar et al. 2017; Peters 2018).

Another major distinction amongst modelling tools is related to the solution methodology from a temporal perspective. They can have a perfect foresight intertemporal assumption or a recursive-dynamic assumption. Intertemporal optimisation with **perfect foresight** is an optimisation method for achieving an overall optimal solution over time. It is based on perfect information on all future states of a system and assumptions (such as technology availability and prices) and, as such, today's and future decisions are made simultaneously, resulting in a single path of optimal actions that lead to the overall optimal solution (Keppo and Strubegger 2010; Gerbaulet et al. 2019). Such modelling approach can present an optimal trajectory of the set of actions and policies that would lead to the overall first-best solution. However, real-life decisions are not always based on optimal solutions (Ellenbeck and Lilliestam 2019) and, therefore, solutions from perfect foresight models can be challenging to be implemented by policymakers (Pindyck 2013, 2017). For instance, perfect foresight implies perfect knowledge of the future states of the system, such as future demand on goods and products and availability of production factors and technology.

Recursive-dynamic models, also known as myopic or limited foresight models, make decisions over sequential periods of time. For each time step, the solution is achieved without information of future time steps. Therefore, the solution path is a series of solutions in short trajectories that, ultimately, are very unlikely to achieve the overall optimal solution over the whole time period considered (Fuso Nerini et al. 2017). Nonetheless, the solution represents a set of possible and plausible policies and behavioural choices of the agents that could be taken in short-term cycles, without perfect information (Hanna and Gross 2020; Heuberger et al. 2018). In between, some models consider **imperfect or adaptive expectations,** where economic decisions are based on past, current and imperfectly anticipated future information (Keppo and Strubegger 2010; Löffler et al. 2019; Kriegler et al. 2015a). Modelling tools can also be differentiated by their level of representation of economic agents and sectors (Section I.2). Full economy models, such as **general equilibrium** models, have a full representation of all agents of the economy and their interactions with each other. Such models are valuable for assessing first and second-order effects of policies, technological changes or other impacts over time (Babatunde et al. 2017). **Partial equilibrium** models focus on the representation of a subset of economic sector and agents. Typically, partial equilibrium models have a more detailed representation of a specific sector, such as policies packages and technology portfolio (Cheng et al. 2015; Hanes and Carpenter 2017; Sanchez et al. 2018; Guedes et al. 2019; Pastor et al. 2019).

Due to their own limitations, it is common for general equilibrium models and partial equilibrium models to be used in a **hybrid modelling framework**. This allows for partial equilibrium model to incorporate macroeconomic impacts of policies and changes in a specific agents or sectors, such as changes in prices and demands. On the other hand, general equilibrium models can take advantage of a more detailed model for assessing changes in this sector, such as resources and technology changes or specific agent behavioural patterns (Section I.2 Economic modelling).

The most basic aspect to differentiate models is their main objective function, which include the detail at which they represent key sectors, systems and agents. This affects the decision on methodology and other coverage aspects. Several models have been developed for different sectorial representation, such as the energy (Section I.3 Energy system modelling), buildings (Section I.4 Building sector models), transports (Section I.5 Transport models), industry (Section I.6 Industry sector models), and land use (Section I.7 Land use modelling).

Modelling exercises vary considerable in terms of key characteristics, including geographical scales, time coverage, environmental variables, technologies portfolio, and socioeconomic assumptions. A detailed comparison of key characteristics of global and national models used in this report is presented in Section I.9. Geographical coverage ranges from sub-national (Cheng et al. 2015; Feijoo et al. 2018; Rajão et al. 2020), national (Vishwanathan et al. 2019; Li et al. 2019; Sugiyama et al. 2019; Schaeffer et al. 2020; Baptista et al. 2020), regional (Vrontisi et al. 2016; Hanaoka and Masui 2020) and global models (McCollum et al. 2018a; Gidden et al. 2018; Kriegler et al. 2018a; Rogelj et al. 2019b; Drouet et al. 2020). Even models with the same geographical coverage can still be significantly different from each other, for instance, due to the number of regions within the model. Models can also have spatially implicit and explicit formulations, which in turn can have different spatial resolution. This distinction is especially important for land use models, which account for changes in land use and agricultural practices (see Section I.7 Land use modelling). The time horizon, time steps and time resolution are major aspects that differ across models. Model horizon can range from short- to long-term, typically reaching from a few years to up until the end of the century (Fujimori et al. 2019b; Rogelj et al. 2019a; Ringkjøb et al. 2020; Gidden et al. 2019b). Time resolution is particularly relevant for specific applications, such as power sector models, which have detailed representation of power technologies dispatch and operation (Soria et al. 2016; Abujarad et al. 2017; Guan et al. 2020).

Furthermore, technology representation varies greatly for each model. Not only the level of detail, which can be specific for a given sector or region, but also how technological change is accounted for. There are two approaches: exogenous and endogenous technological change. They primarily differ on how policy and investment decisions affect technological development and diffusion.

Finally, **Integrated Assessment Model** (IAM) are simplified representations of the complex physical and social systems, focusing on the interaction between economy, society and the environment (see Section I.9 Integrated assessment modelling). They represent the coupled energy-economy-land-climate system to varying degrees. In a way, IAM differ themselves in all the topics discussed in this section: significant variation in geographical, sectorial, spatial and time resolution; rely greatly on socioeconomic assumptions; different technological representation; partial or general equilibrium assumptions; differentiated between perfect foresight or recursive-dynamic methodology. The difficulty in fully representing the extent of climate damages in monetary terms may be the most important and challenging limitation of IAMs and it is mostly directed to cost benefit IAMs. However, both categories of IAMs present important limitations (see Section I.9 Integrated assessment modelling).

I.2 Economic modelling

Several types of economic models can be distinguished, as introduced in Section I.1. **General equilibrium models** in a broadest sense – often referred to as Computable General Equilibrium (CGE) models – represent the full economy through the economic interdependencies between multiple sectors and agents, and the interaction between supply and demand on multiple markets (Robinson et al. 1999). They capture the full circularity of economic flows through income and demand relationships and feedbacks including the overall balance of payments. Most CGE models are neoclassical supply-led models with market clearing based on price adjustment. Representative agents usually seek to minimise production costs or maximise utility under given production and utility function, although optimal behaviours are no preconditions per se. Most CGE models also include assumptions of perfect markets with full employment of factors although market imperfections and underemployment of factors (e.g. unemployment) can be assumed (Babiker and Eckaus 2007; Guivarch et al. 2011). CGE models can either be static or dynamic and represent pathways as a sequence of equilibria in the second case.

On the contrary, **partial equilibrium models** only represent a subset of economic sectors and markets disconnected from the rest of the economy. They basically represent sectoral market balance and adjustments – energy markets for instance through supply and demand interaction - under ceteris paribus assumptions about other markets (labour, capital, etc.), income, etc. ignoring possible feedbacks.

Macro-econometric models have the same full economy coverage and sector interdependence including balance of payments than general equilibrium models, and are sometimes considered a subset of them. They differ from standard neoclassical CGE models in the main that economic behaviours are not micro-founded optimising behaviours but represented by macroeconomic and sectoral functions estimated through econometric techniques (Barker and Scrieciu 2010). In addition, they usually adopt a demand-led post-Keynesian approach where final demand and investment determine supply and not the other way around. An important consequence is that investment in a given sector (e.g. low carbon energy) does not crowd-out investment in other sectors contrary to supply-led models. Finally, prices do not instantaneously clear markets and adjust with lag.

Macro-economic growth models are derived from aggregated Solow or Ramsey growth models. They are based on a single macroeconomic production function combining capital, labour and sometimes energy to produce a generic good for consumption and investment. They are used as the macroeconomic component of cost benefit IAMs (Nordhaus 1993) and some detailed-process IAMs.

The **coverage of economic actors and sectors and their interaction** differ across models. A main distinction is between models based on full Social Accounting Matrix (SAM) and compact growth approaches. On the one hand, SAM-based models – such as CGE and macroeconometric models - follow a multisector approach distinguishing from several to a hundred of different economic sectors or production goods and represent sector specific value-added, final consumption and interindustry relationships through an Input-Output framework of intermediary consumption (Robinson 1989). They also represent individual economic agents (firms, households, public administration, etc.) with specific behaviours and budget constraints. On the other hand, compact growth models are reduced to a single macroeconomic agent producing, consuming and investing a single macroeconomic good without considering interindustry relationships. In some detailed process IAMs, the compact growth approach is combined with a detailed representation of energy supply and demand systems that surmises different economic actors and subsectors. However, the energy system remains driven by a compact macroeconomic growth engine (Bauer et al. 2008). Partial equilibrium models usually distinguish several subsectors and economic agents for supply and demand of energy.

In most models the treatment of **economic growth** follows Solow or Ramsey growth approach based on the evolution through time of production factors endowment and productivity. Classically, labour endowment and demography are exogenous, and capital accumulates through investment. Partial equilibrium models do not model economic growth but use exogenous growth assumptions derived from compact growth models. Factors productivity evolution is assumed exogenous in most cases i.e. general technical progress is assumed to be an autonomous process. A few models feature endogenous growth aspects where factor productivity increase with cumulated macroeconomic investment. Models also differ about the content of technical progress and alternatively consider un-biased total factor productivity improvement or labour specific factor augmenting productivity. In multisector models aggregated economic growth is also the result of the endogenous sectoral composition of GDP known as structural change. **Structural change** is the result of the interaction between differentiated changes of productivity between sectors – through sector specific technical progress or substitution – and the structure of final demand as income grows (Herrendorf et al. 2014). If general technical progress is mostly assumed exogenous and autonomous at an aggregated level, **innovation in relation to energy demand and technical systems** follow more detailed specifications. Energy efficiency can be assumed an autonomous process at different levels – macroeconomic, sector or technology level – or energy technical change can be endogenous and induced as a learning by doing process or as a result of R and D investments (learning by searching) (Löschel 2002).

Multi region models consider interactions between regions through **trade** of energy goods, non-energy goods and services (energy goods only for partial equilibrium energy models) and emission permits in the context of climate policy. For each type of goods trade is usually represented as a common pool where regions interact with the pool through supply (exports) or demand (imports). A few models consider bilateral trade flows between regions. Traded goods can be assumed perfectly substitutable between regions of origin (Heckscher-Ohlin assumption) such as is often the case for energy commodities like oil or imperfectly substitutable (represented as Armington goods most of the time) for non-energy goods. The representation of trade and capital imbalances at the regional level and their evolution through time vary across model and imbalances are either not considered (regional current accounts are balanced at each point in time), or a constraint for intertemporal balance is included (an export surplus today will be balanced by an import surplus in the future) or else trade imbalances follow other rules such as a convergence towards zero in the long run (Foure et al. 2020).

Strategic interaction can also occur between regions especially in the presence of externalities such as climate change, energy prices or technology spill-overs. Intertemporal models can include two types of strategic interaction: i) a cooperative Pareto optimal solution where all externalities are internalised and based on the maximisation of a global discounted welfare with weighted regional welfare (Negishi weights), or ii) a non-cooperative solution that is strategically optimal for each region (Nash equilibrium) (Leimbach et al. 2017b).

Models cover different **investment** flows according to model type. Partial equilibrium sectoral models compute energy system and/or sectoral (transport, building, industry, etc.) technology specific investment flows associated with productive capacities and equipment. Full economy models compute both energy system and macroeconomic investment, the second being used to increase macroeconomic capital stock. Full economy multi-sector models compute sector specific (energy and non-energy sectors) investment and capital flows with some details about the investments goods involved.

Financial constraints are usually not represented in partial equilibrium models and all investment needs are automatically satisfied. Full economy models differ in the representation of macro-**finance**. In most CGE and compact growth models' financial mechanisms are only implicit and total financial capacity and investment is constrained and driven by savings. Such models usually represent full crowding-out of investments. In other models such as macroeconometric models, macro-finance is sometimes explicit, and investments can be financed by credit on top of savings. They also usually include limited crowding-out of investments (Mercure et al. 2019). In both partial and full economy models the financial environment of investment decisions is usually based on a weighted average cost of capital (WACC) modelled as a discount rate which can be region, sector or technology specific.

Models compare economic flows and costs over time through discounting, which is standard practice in economics. Discounting first enables to compare costs and benefits of climate mitigation in the context of cost-benefit analysis (CBA). In this case the choice of discount rate is crucial for the balance of mitigation costs and avoided climate damages occurring over the very long run. In the context of cost-effectiveness and mitigation analysis, discounting allows to estimate the intertemporal policy costs to reach a given objective such as respecting a carbon budget. The choice of the appropriate discounted rate is highly debated and two general approaches are commonly used. Based on ethical principles, the first states that the discount rate should reflect how costs and benefits supported by different generations should be weighted, which usually leads to the lowest discount rates. The second approach identifies the discount rate to the rate of return to capital or the interest rate as observed in the real economy which yields higher values. The choice of discount rate influences the mitigation schedule and tempo in economic models, interplays with capital inertia and technical change, and determines the extent of negative emissions used in the modelled pathways.

I.3 Energy system modelling

I.3.1 Modelling electricity system operation with large scale penetration of renewables

Integration of high penetration of variable renewable energies (VRE) in the grid imposes a major challenge to electricity system operation. Unlike conventional fossil generation, VRE plants cannot provide firm capacity as the balance between demand and supply needs to be maintained in real time (e.g. seconds timescale), while output of renewable generation is variable and there may be long periods with very low output (Miranda et al. 2017; Buttler et al. 2016; Hoicka and Rowlands 2011). Furthermore, large penetration of VRE, which are inverter-based power generation, will significantly reduce system inertia requiring considerably greater amount of various ancillary services, including both operating reserve and frequency regulation services, in order to maintain system stability (as system inertia, reserve and frequency regulation services have been widely available by thermal generation as by-products of energy production). The key modelling challenge is related to the need to incorporate grid dynamic stability requirements (quantified by differential equations) in the system optimisation framework (expressed by algebraic equations), aimed at quantifying the operation cost of managing large scale penetration of renewable generation (Esteban et al. 2018; Lin and Chen 2013).

A number of advanced grid modelling approaches have been developed, such as robust optimisation (Jiang et al. 2012), interval optimisation (Dvorkin et al. 2015), and stochastic optimisation (Meibom et al. 2011; Monforti et al. 2014) to optimally schedule the operation of the future low carbon systems with high penetration of VRE. Advanced stochastic models demonstrated that this would not only lead to significantly higher cost of system management but may eventually limit the ability of the system to accommodate renewable generation (Badesa et al. 2020; Hansen et al. 2019; Perez et al. 2019; Bistline and Young 2019). Modelling tools such as European Model for EMPIRE[1] (Skar et al. 2016), REMix[2] (Scholz et al. 2017), EUCAD[3] (Després 2015) also investigated these issues. Furthermore, advanced modelling tools have been developed for the purpose of providing estimations of system wide inertial frequency response that would assist system operators in maintaining adequate system inertia (Sharma

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FOOTNOTE: [1] Power system Investment with Renewable Energy

FOOTNOTE: [2] Renewable Energy Mix for Sustainable Electricity Supply

FOOTNOTE: [3] European Unit Commitment And Dispatch model et al. 2011). Furthermore, advanced modelling analysis has been informing the development of security standards related to frequency stability, by using the concept of Value of Lost Load (VoLL) as the security measure, so that optimal balance between the cost associated with the provision of various ancillary services against the benefit related to reduced cost associated with demand curtailment, can be determined (Teng and Strbac 2017).

These innovative models also provided fundamental evidence regarding the role and value of advanced technologies and control systems in supporting cost effective operation of future electricity systems with very high penetration of renewable generation. In particular, the importance of enhancing the control capabilities of renewable generation and applying flexible technologies, such as energy storage (Hall and Bain 2008; Obi et al. 2017; Arbabzadeh et al. 2019), demand side response (DSR) interconnection (Aghajani et al. 2017) and transmission grid extensions (Schaber et al. 2012) for provide system stability control, is demonstrated through novel system integration models (Sinsel et al. 2020; Lund et al. 2015). A novel modelling framework is proposed to deliver inertia and support primary frequency control through variable-speed wind turbines (Morren et al. 2006), including quantification of the value of this technology in future renewable generation dominated power grids (Chu et al. 2020). Furthermore, innovative modelling of advanced control strategies for PVs that can provide frequency regulation (including DC link capacitors and storage) are proposed (Waffenschmidt and Hui 2016; Liu et al. 2017). Advanced models for controlling distributed energy storage systems to provide an effective virtual inertia have been developed, demonstrating the provision of virtual-synchronous-machine capabilities for storage devices with power electronic converters, which can support system frequency management following disturbances (Hammad et al. 2019; Markovic et al. 2019).

In the context of DSR, alternative methods for controlling residential loads to provide frequency support have been developed, while not compromising on service quality delivered to consumers (Weckx et al. 2013). Demand-based frequency support in grids with a high penetration of distributed generation, both from the technical and economic perspectives is investigated (Black and Ilic 2002). Furthermore, novel modelling approaches demonstrated that a critically important concept for the provision of frequency regulation in future renewable dominated systems, is the concept of Vehicle-to-grid (V2G) (Alhelou and Golshan 2016; Aunedi and Strbac 2020). Regarding the application of interconnection for exchange of balancing services between neighbouring power grids, alternative control schemes for High Voltage Direct Current (HVDC) converters have been proposed demonstrating that this would reduce the cost of balancing (Tosatto et al. 2020).

I.3.2 Modelling the interaction between different energy sectors

Several integrated models have been developed in order to study the interaction between different energy vectors and whole system approaches. This includes the Integrated Energy System Simulation model (IESM) (NREL 2020), the Integrated Whole-Energy System (IWES) model (Strbac et al. 2018), the UK TIMES (Daly and Fais 2014), Calliope (Pfenninger and Pickering 2018), the Open Energy Modelling Framework (Hilpert et al. 2017), among others.

IESM is an approach in which the multi-system energy challenge is investigated holistically rather than looking at each of the systems in isolation. NREL (2020) capabilities include co-optimisation across multiple energy systems, including electricity, natural gas, hydrogen and water systems. These provide the opportunity to perform hydro, thermal, and gas infrastructure investment and resource use coordination for time horizons ranging from sub-hourly (markets and operations) to multi-year (planning).

IWES model incorporates detail modelling of electricity system, modelling of heating technologies including district heating, heat network, heat pumps (air/ground source, hybrid) and a module that optimises the hydrogen infrastructure. Overall, IWES model includes electricity, gas, transport, hydrogen and heat systems and captures the complex interactions across those energy vectors. The IWES model also considers the short-term operation and long-term investment timescales (from seconds to years) simultaneously and covering both local district and national/international level energy infrastructure, including energy-flow interactions via interconnectors. This functionality is essential since those aspects are complexly intertwined and required to be analysed simultaneously in the whole-system concept. In order to provide sufficient spatial granularity to capture the regional characteristics; Each region has two (or more) distribution network models representing different distribution network characteristics (e.g. urban and rural systems). The distribution network modelling is also essential, e.g. for the district heating modelling, as it can capture the length of heat network which is the primary component of district heating costs. However, one of the challenges remained in the whole system modelling is to increase the spatial and temporal granularity. In the IWES model, the stochastic scheduling model presented in Teng and Strbac (2017), is used to approximate the inertia level and corresponding real time requirements for frequency regulation, also capturing changes in demand renewable generation outputs.

In the context of innovative energy vectors, such as hydrogen, the IWES model is used to optimise the required capacity of hydrogen production from different technologies, e.g. steam methane reforming (SMR) with CCUS, electrolysis, BECCS, and hydrogen storage. This considers the cost of production, transport and/or CCS facilities. This enables the optimisation and analysis of the cost of different locational distributions of hydrogen sources. In order to investigate the physics of hydrogen transport through the gas infrastructure, the stochastic model developed in Shabazbegian et al. (2020) based on the Combined Gas and Electricity Network model (Chaudry et al. 2008), is capable to analyse hydrogen transport in transmission and low, medium and high-pressure gas distribution networks. This model provides fundamental evidence regarding the ability of the existing gas transmission and distribution gas networks to deliver hydrogen in time by taking into account the operational uncertainties associated with renewables

The UK TIMES Model is an integrated MARKAL-EFOM model. It portrays the UK energy system, from fuel extraction and trading, to fuel processing and transport, electricity generation and all final energy demands (Taylor et al. 2014; Daly and Fais 2014). The model generates scenarios for the evolution of the energy system based on different assumptions around the evolution of demands, future technology costs, measuring energy system costs and all greenhouse gases (GHGs) associated with the scenario. UKTM is built using the TIMES model generator: as a partial equilibrium energy system and technologically detailed model, is well suited to investigate the economic, social, and technological trade-offs between long-term divergent energy scenarios. TIMES is generally used to generate vertically integrated models of whole energy systems, regional, national or global, but can also be used to study elements of an energy system in isolation. For the region being modelled, the user provides projections of baseline energy service demands (lighting, heating, car travel etc.) as well as a description of the existing stock of energy technologies (efficiencies, retirement profiles, inputs and output fuels, operational costs), the characteristics of future technologies available, and a projection of future energy supply and trade (Li et al. 2018; Fais et al. 2016; Pye et al. 2017; McGlade et al. 2018). TIMES uses a linear optimisation objective function to choose the level of investment and operation of energy system technologies and fuel supply/trade in order to minimise total system cost (or maximise the total discounted producer and consumer surplus) subject to technical, environmental and economic constraints (Hall and Buckley 2016). The participants of this system are assumed to have perfect foresight, in that decisions are made with the full inter-temporal knowledge of future policy, technological and economic developments. Hence, under a range of input assumptions, which are key to the model outputs, TIMES delivers an economy-wide solution of cost-optimal energy market development (see Section I.9 Integrated assessment modelling).

I.3.3 Modelling of energy systems in context of large-scale economy

To study the impact of low carbon energy systems on the economy, numerous integrated assessment modelling tools are applied, such as the World Energy Model (WEM) (IEA 2020a), the National Energy Modelling System (NEMS) (EIA 2009), and the General Equilibrium Model for Economy-Energy-Environment (GEM-E3) (Capros et al. 2013).

The WEM is a simulation model covering energy supply, energy transformation and energy demand. The majority of the end-use sectors use stock models to characterise the energy infrastructure. In addition, energy-related CO_2 emissions and investments related to energy developments are specified. The model is focused on determining the share of alternative technologies in satisfying energy service demand. This includes investment costs, operating and maintenance costs, fuel costs and in some cases costs for emitting CO_2. The main exogenous assumptions are related to the demographics, socioeconomic development pathways and technological developments. Consumption of the main oil products is modelled individually in each end-use sector (e.g., industry and agriculture) and the refinery model links it with the demand for individual products. Demand for primary energy serves as an input for the supply modules. Complete energy balances are compiled at a regional level and the CO_2 emissions of each region are then calculated using derived CO_2 factors. The time resolution of the model is in annual steps over the whole projection horizon. The model is each year recalibrated to the latest available data. Estimates are based on updates of the Global Energy Review reports which relies on a number of sources, including the latest monthly data submissions to the IEA's Energy Data Centre, other statistical releases from national administrations, and recent market data from the IEA Market Report Series that cover coal, oil, natural gas, renewables and power.

The NEMS is an energy-economy modelling system applied for the U.S.A. through 2030. NEMS projects the production, imports, conversion, consumption and prices of energy, subject to assumptions on macroeconomic and financial factors, world energy markets, resource availability and costs, behavioural and technological choice criteria, cost and performance characteristics of energy technologies, and demographics. NEMS was designed and implemented by the Energy Information Administration (EIA) of the U.S. Department of Energy. NEMS is used by EIA to project the energy, economic, environmental, and security impacts on the United States considering alternative energy policies and assumptions related to energy markets. The projection horizon is approximately 25 years in the future. This time period is one in which technology, demographics, and economic conditions are sufficiently understood in order to represent energy markets with a reasonable degree of confidence. NEMS provides a consistent framework for representing the complex interactions of the U.S. energy system and its response to a wide variety of alternative energy program assumptions and policy initiatives.

GEM-E3 is a recursive dynamic computable general equilibrium model that covers the interactions between the economy, the energy system and the environment. It is especially designed to evaluate energy, climate and environmental policies. GEM-E3 can evaluate consistently the distributional and macro-economic effects of policies for the various economic sectors and agents across the countries / regions.

I.4 Building sector models

The three modelling approaches used to assess mitigation pathways in the building sector include bottom-up, top-down and the hybrid approaches.

I.4.1. Modelling approaches of mitigation potentials in the building sector

Mitigation potentials in the building sector are modelled using either a top-down approach, a bottom-up one or a hybrid approach which combines both bottom-up and top-down (Figure I.1). The **top-down approach** is based on macroscopic regional/national historical aggregate of energy consumption of the overall sector, which are very general and have low granularity. Top-down models can be either econometric models using macro-economic indicators such as income or technological models relying on data such as ownership. Top-down models are used for assessing economic-wide responses of building policies.

The **bottom-up approach** is based on microscopic data of individual end-uses and the characteristics of each component of buildings. Geographical Information Systems (GIS) layers can be used to create datasets of building characteristics (Reinhart and Cerezo Davila 2016). Bottom-up models can be either physics-based, also known as engineering models; data-driven, also known as statistical models; or a combination of both, also known as hybrid bottom-up models. Bottom-up models are data intensive and as such require long computing time. Machine learning techniques allow optimising the computing time (Bourdeau et al. 2019). Bottom-up models are useful to assess the techno-economic potential of the overall building stock by extrapolating the estimated energy consumption of a representative set of individual buildings (Duerinck et al. 2008; Swan and Ugursal 2009; Hall and Buckley 2016; Bourdeau et al. 2019).

One way to overcome the drawbacks of the bottom-up and the top-down modelling approaches, is to combine the two into a **hybrid model** which bridges the gap between the detailed bottom-up end-use models and the aggregated top-down models. Hybrid models can be either optimisation models or simulation models (Duerinck et al. 2008; Hall and Buckley 2016; Bourdeau et al. 2019). The latter can also be agent-based models and could be combined with building performance models to allow for an assessment of occupants behaviour (Papadopoulos and Azar 2016). Hybrid models are used for exploring the impacts of resource constraints, investigating the role of specific technological choices as well as for analysing the impact of specific energy policies.

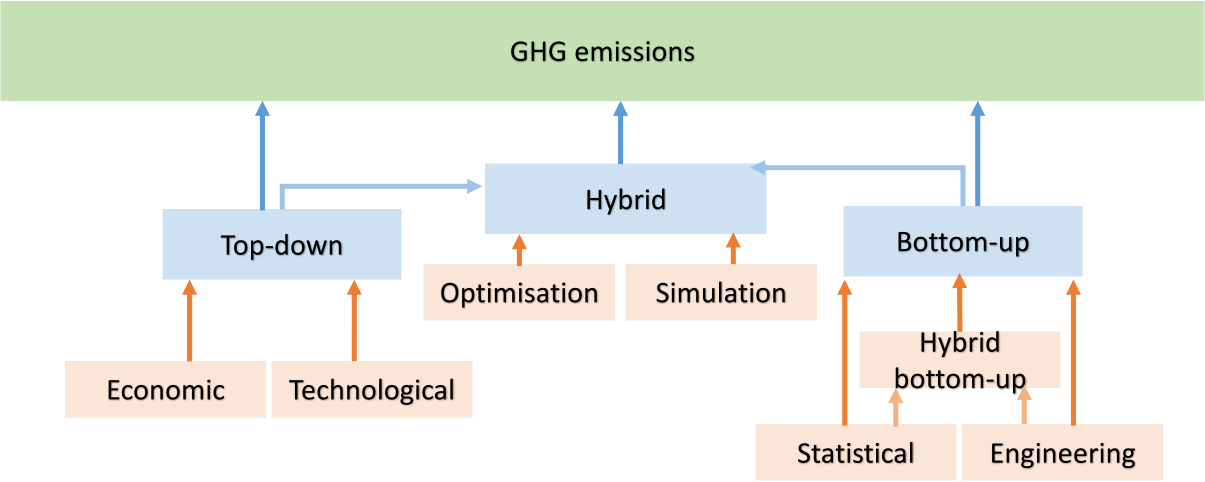

Figure I.1. Modelling approaches of GHG emissions used in the building sector

I.4.2. Assessment of mitigation potentials in illustrative pathways (IPs) (preliminary results)

Five, out of the 11, IPs proposed in Chapter 3 (see in Section II.2.2. Illustrative pathways) were considered to assess mitigation potentials in the building sector (Figure I.2). NGFS_Current policies from GCAM 5.2 Model serves as a baseline scenario, while the remaining four scenarios are related to different mitigation action(s) ranging from a moderate scenario (EN_INDCi2030_3000f from IMAGE 3.0) to a scenario aiming at 2°C target (CO_Bridge from WITCH 5.0), another aiming at 1.5°C target (DeepElec_SSP2_ HighRE_Budg900 from REMIND 2.1) and a scenario aiming at shifting development towards sustainability (SusDev_SDP-PkBudg1000 from REMIND-MAgPIE 2.1-4.2).

Due to lack of data, the proposed IPs from chapter 3 were not used for the analysis included in the building chapter. Instead, scenarios considered for the analysis in the chapter are those of the IEA 2019 World Energy Outlook (current policies scenario, stated policies scenario and sustainable development scenario) (see Chapter 9, Section 9.3). Similarly, bottom-up scenarios submitted to IIASA database were not used for the SOD analysis due to lack of baselines associated with these scenarios. Estimates from bottom-up models were derived as shares of baseline emissions at regional level aggregating estimates from existing national literature (see Chapter 9, Section 9.6).

Mitigation potentials of the selected IPs are calculated as a difference between CO_2 emissions in 2030 and 2050 of the current policies scenario and the scenario considered. Based on the data available, at the time of the drafting, under the moderate scenario, emissions are projected to increase in all regions except in the developed region of Asia-Pacific where they are projected to remain equivalent to those under the current policies scenario and in South-East Asia and developing Pacific where they are projected to decrease. Emissions are also projected to increase under the 2°C scenario in several regions including Eastern Asia, Europe, South Asia, Middle East, North America, Asia-Pacific developed and Eurasia. Further investigation is needed to understand the expected increase of CO_2 emissions under the 2°C scenario (Figure I.2).

Literature suggests that top-down models are pessimistic about the mitigation potentials while bottom-up models are optimistic (Hourcade and Robinson 1996). However, mitigation potentials from the selected IPs show high potentials, up to 99% in 2050, in Europe under SDGs scenario. Europe is also the region with the highest (89%) mitigation potential based on the IEA sustainable development scenario. On the other hand, estimates of mitigation potentials from bottom-up models range between 50% and 75%. The largest potential as a share of baseline is in Eastern Asia (75%) and Middle East (70%). In all developed countries, the potential is scaled on a declining baseline; in developing countries, the potential is against sharply growing baselines. The largest potential from bottom-up models in absolute amount is in Eastern Asia and Southern Asia (see Chapter 9, Section 9.6).

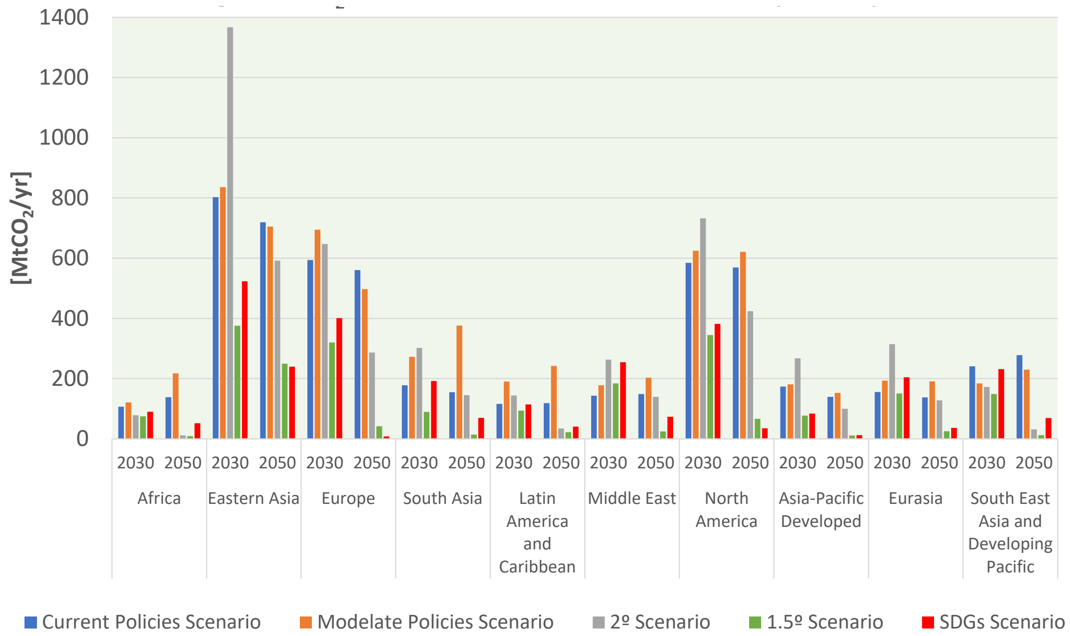

Figure I.2. Direct emissions for residential and non-residential buildings by region as reported in selected IPs.

I.5 Transport models

I.5.1 Purpose and Scope of Models

GHG emissions from transport are largely a function of **travel demand, transport mode,** and **transport technology and fuel**. The purpose of transportation system models is to describe how future **demand** for transport can be fulfilled through different **modes** and **technologies** under different climate change mitigation targets or policies. Within a given transport mode, technologies differ by efficiency and fuel use

Common components of transportation systems models mirror these main drivers of GHG. Models commonly quantify **transportation mode**, or **how movement occurs** (e.g. active transit, passenger vehicles, trucks, boats, planes, etc.). Higher fidelity models provide more nuanced breakdowns of modes, e.g. by **technologies**. Most models will also quantify **how much movement occurs**, or the **travel demand** associated with each mode. Higher fidelity models further decompose travel demand by time and region (e.g. miles or kilometres per hour or year per region). The scope of the model often determines how much information it provides on **where and when movement occurs**. While larger scale models typically provide aggregate travel demand, higher resolution travel demand models can be integrated into transportation system models and provide much more information on origin and destination of trips, when trips occur, and the route of travel taken. This level of detail is not often characterised in the output of system models but can be employed as a “base” model to determine how travel occurs before aggregation (Edelenbosch et al. 2017a; Yeh et al. 2017).

A key distinguishing feature between different model types is how they control the above components. Our review of the transport energy system models can be broadly divided into three main categories: i) optimisation models, ii) simulation models, and iii) accounting and exploratory models.

i) Optimisation models: Identify least cost pathways to meet policy targets (such as CO_2 emission targets of transport modes or economy-wide) given constraints (such as rate of adoption of vehicle technologies or vehicle efficiency standards). For example MessageIX-TransportV5 (Krey et al. 2016) and TIMES (Daly et al. 2014).

ii) Simulation models: Simulate behaviour of consumers and producers given prices, policies, and other factors by using parameters calibrated to historically observed behaviours such as demand price elasticity and consumer preferences. For example models by Barter et al. (2015), Brooker et al. (2015) and Schäfer (2017).

iii) Accounting and exploratory models: Track the outcomes (such as resources use and emissions) of key decisions (such as the adoption of advanced fuels or vehicle technologies) that are based on "what-if" scenarios. The major difference between accounting models versus optimisation and simulation models are that key decision variables such as new technologies adoptions typically follow modeler's assumptions as opposed to being determined by mathematical formulations as in optimisation and simulation models. See models in Fulton et al. (2009), IEA (2020a), Gota et al. (2019) and Khalili et al. (2019).

Due to the model types' relative strengths and weaknesses, they are commonly applied to certain problem types (Table I.1). Models can do **forecasting,** which makes projections of how futures may evolve, or **backcasting**, which makes projections of a future that meets a predefined goal such as a policy target of 80% reduction in GHG emissions from a historical level by a certain year. Models often are also used to explore what-if questions, to confirm the **feasibility** of certain assumptions/outcomes, and to quantify the **impacts** of a change such as a policy under different conditions. Enhancing fuel efficiency standards, banning internal combustion engines, setting fuel quality standards, and the impacts of new technologies are the typical examples of problem types analysed in energy system models.

Table I.1: Taxonomy of transport models.

Problem Type	**Optimisation model**	**Simulation model**	**Accounting model**	**Heuristic model**
Backcasting	x			x
Forecasting	x	x	x	
Exploring feasibility space		x	x	x
Impact analysis	x	x	x	

While these three model types drive the component dynamics in different ways, they commonly include modules that include: learning and diffusion (via exogenous, e.g. autonomous learning, or endogenous learning regarding costs and efficiency: i.e. cost decreases and/or efficiency increases as a function of penetration, and increased diffusion due to lower costs) (Jochem et al. 2018), stock turnover (the performance and characteristics of vehicle fleets including survival ages, mileages, fuel economies and loads/occupancy rates are tracked for each new sales/vehicle stocks), consumer choice (theories of how people decide to spend their money based on their individual preferences given the characteristics of mode or technology) (Daly et al. 2014; Schäfer 2017), or other feedback loops (Linton et al. 2015).

IAMs (Krey et al. 2016; Edelenbosch et al. 2017a) are typically global in scope and seek to solve for feasible pathways meeting a global temperature target (see Section I.9 Integrated assessment modelling). This implies solving for mitigation options within and across sectors. In contrast, global/national transport energy system models (GTEM/NTEMs) typically only solve for feasible pathways within the transport sector (Yeh et al. 2017). The range of feasible pathways can be determined through optimisation, simulation, accounting and exploratory methods as we explained in Table I.1. Some GTEMs are linked to IAMs model (Krey et al. 2016; Edelenbosch et al. 2017a; Roelfsema et al. 2020).

The key difference between IAMs and GTEM or NTEMs is whether the transportation systems is integrated with the rest of the energy systems specifically regarding energy and fuel productions and use, fuel prices, economic drivers such as GDP, and mitigation options given a policy goal. IAMs can endogenously determine these factors because the transport sector is just one of many sectors captured by the IAM. While this gives IAMs certain advantages, IAMs sacrifice resolution and complexity for this broader scope. For example, most IAMs lack a sophisticated travel demand model that reflects the heterogeneity of demands and consumer preferences, whereas GTEM/NTEMs can incorporate greater levels of details regarding travel demands, consumer choices, and the details of transport policies. Consequently, what GTEM/NTEMs lack in integration with other sectors they make up through more detailed analyses of travel patterns, policies, and impacts (Yeh et al. 2017).

I.5.2 Inventory of Models

GTEM/NTEMs models included in Chapter 10 are listed below (Table I.2). For IAMs see Chapter 3

[To be updated subject to final submission to the AR6 scenario database]

Table I.2: GTEM/NTEMs models evaluated in Chapter 10.

Model names	Organisation	Scope	Resolution	Period	Economy-wide	Method
Mobility model (MoMo)	International Energy Agency (IEA)	Global	Country groups	2040	Soft-link	Accounting model
Global Transportation Roadmap	International Council on Clean Transportation (ICCT)	Global	Country groups	2050	No	Accounting model
MESSAGE-Transport V.5	International Institute for Applied Systems Analysis (IIASA)	Global	Country groups	2100	Yes	Optimisation model

I.6 Industry sector models

I.6.1. Types of industry sector models

Industry sector modelling approaches can vary considerably from one another. Generally, a first-order differentiation can be made between ‘top-down’, ‘bottom-up’ and ‘hybrid’ modelling approaches.

Top-down models typically cover the total energy system, with industry as one of several subsystems. In these models, energy demand and supply and their changes over time depend on aggregate economic variables, such as economic output, energy prices and price elasticities. Individual technologies and processes are typically represented in a more aggregate form compared to bottom-up models. Studies using top-down models are more capable of representing economic structural change than adopting technology-explicit decarbonisation strategies (Kriegler et al. 2015a; van Vuuren et al. 2009).

Studies exploring the technological options for and the related infrastructural needs of strong emission reductions in the industry sector or specific industry sub-sectors typically resort to *bottom-up (or 'engineering') models*. Especially when these models focus exclusively on the industry sector and on specific countries, they tend to be associated with detailed representations of individual sub-sectors, technologies and processes, and are therefore more explicit than top-down models in depictions of technological change.

As bottom-up models generally do not assess the associated implications in a broader spatial or economy-wide context, they are sometimes coupled to integrated assessment models (IAMs) in a *'hybrid' modelling framework* to balance explicitness with broader trends (see Section I.9 Integrated assessment modelling) (e.g. Jochem and Schade (2009)).

The studies discussed in detail in Chapter 11 (Section 11.4.2.2 'In-depth discussion and "reality" check of pathways from specific sector scenarios') rely on bottom-up models of the industry sector as the aim of the section is to obtain sector- and technology-specific insights on how far-reaching GHG emission reductions can be realised in key industry sub-sectors.

In the following, the modelling approaches for the industry sector used by two of the key studies discussed are introduced, as discussed in Chapter 11. Both of these studies rely on technologically detailed bottom-up models for scenario development. This is followed by a discussion of how the industry sector is typically represented in IAMs.

I.6.2. Industry sector modelling in IEA (2020a)

In the IEA (2020b) study 'Energy Technology Perspectives 2020', the energy-intensive industry is modelled using bottom-up, technology-rich optimisation sub-models for five energy-intensive sectors (iron and steel, chemicals and petrochemicals, cement, pulp and paper, and aluminium). These five sub-models characterise the energy performance of process technologies from each of the energy-intensive sectors, covering 40 countries and regions. The remaining final energy consumption of other industrial sectors is accounted for in a simulation model that estimates energy consumption based on activity level. In each of the five energy-intensive sectors, demand for materials is projected through interaction between an activity model and a stock model. The activity model uses country-level historical data on material consumption to calculate demand per capita, then projects forward total demand using population projections and industry value-added projections.

Each industry sub-model is designed to account for sector-specific production routes for which relevant process technologies are represented in the model. Such technologies include hydrogen-based direct reduced iron for primary steel production or CCS technologies for cement production, as discussed in Chapter 11 (see Section 11.4.1). Industrial energy use and technology portfolios for each country or region are characterised in the base year using relevant energy use and material production statistics for each energy-intensive industrial sector. Demand for materials (as dictated by the activity model outputs) is met by technologies and fuels chosen for the production processes through a constrained optimisation framework, with the objective function set to minimise overall system cost. System cost comprises energy costs and investments.

I.6.3. Industry sector modelling in Material Economics (2019)

The modelling approach in the study ‘Industrial Transformation 2050’ starts from a characterisation of future activity levels. A baseline scenario for demand in 2050 is estimated using a range of bottom-up models. The next step defines a wide range of low-CO_2 production routes. The analysis characterises the technological maturity, investment requirements, energy and feedstock inputs, other operating costs, mass balance, and CO_2 emissions of each process.

Alongside primary production, the analysis uses a range of models to explore opportunities for advancing the circular economy, which are often underrepresented in IAMs. This analysis of the potential for improved materials efficiency and increased materials circulation leads to the study’s finding that CO_2 emissions of the steel, chemicals and cement sectors can be cut significantly through circular economy measures. Costs of the identified measures are estimated and compared to primary production.

The third component is a characterisation of end-of-life flows of materials and production routes that use these as inputs for new materials production. For steel, for example, a dynamic materials flow model is used to estimate future availability and use of steel scrap. Scrap generation is derived by analysing different steel use cases with their specific quality requirements and the lifetime of products like cars or buildings. Region-specific scrap availability is estimated by assuming future product-specific collection rates and future scrap trade. These three components are put together in a scenario analysis.

I.6.4. Industry sector modelling in Integrated Assessment Models (IAMs)

As is the case for other end-use sectors, the industry sector is typically modelled in less technological detail in IAMs than in bottom-up models such as those introduced above. However, individual IAMs differ from one another in how detailed their industry sector representation is. In IAMs, demand for basic materials and industry sector energy demand are often implicit functions of population and GDP. While some energy-intensive sectors such as iron and steel or cement are included separately in a generalised manner in most IAMs, typically few if any sector-specific technologies are explicitly represented. Instead, energy efficiency improvements in the industry sector and its subsectors are often either determined by exogenous assumptions or are a function of energy prices. Likewise, fuel switching occurs primarily as a result of changes in relative fuel prices, which in turn are influenced by CO_2 price developments. In IAMs that include specific technologies, fuel switching can be constrained based on the characteristics of those technologies, while in IAMs with no technological detail more generic constraints on fuel switching in the industry sector are embedded (Edelenbosch et al. 2017b).

I.7 Land use modelling

Land use related IAM modelling results as presented in Chapter 7 are based on comprehensive land-use models (LUMs) that are either integrated directly, or through emulators into the integrated assessment framework. Given the increasing awareness of the importance of the land use sector to achieve ambitious climate mitigation targets, LUMs and their integration into IAMs systems was one of the key innovations to the integrated assessment over the past decade to allow for an economy wide quantification of climate stabilisation pathways.

LUMs allow to project developments in the land use sector over time and assess impacts of mitigation policies on different economic (markets, trade, prices, demand, supply etc.) and environmental (land use, emissions, fertiliser, irrigation water use, etc.) indicators. LUMs can be broadly differentiated between bottom-up partial equilibrium (PE) and top-down computable general equilibrium (CGE) models. Bottom-up PE models are usually characterised by a detailed (spatially explicit) representation of different production activities and management systems considering both biophysical land characteristics and impacts due to their linkage with e.g. dynamic vegetation model such as EPIC or LPJmL. Top-down CGE models tend to have a comparative advantage in assessing economy wide implications and market dynamics including their feedback on the land use sector e.g. from the energy system. In addition, the representation and portfolio of land-based mitigation options varies across LUMs as does the representation of sustainability targets other than climate mitigation. The following models submitted scenarios to the AR6 database: AIM, EPPA, GCAM, IMAGE, MERGE, MESSAGE-GLOBIOM, POLES, REMIND-MAgPIE, WITCH.

I.7.1 Modelling of land use and land use change

LUMs represent different land use activities for managed land (agriculture including cropland and pastures, managed forests, and dedicated energy crops) while natural lands (primary forests, natural grasslands, shrubland, savannahs etc.) act as land reserve that can be converted to management depending on other constraints. Typically, the agricultural sector has the greatest level of detail across land use sectors. LUMs include different crop- and livestock production activities, some even at the spatially explicit level and differentiated by production system. Forestry is covered with varying degree of complexity across LUMs. While some models represent only afforestation/deforestation activities dynamically, others have detailed representation of forest management activities and/or forest industries. The models endogenously determine the land allocation of different land use activities as well as land use changes according to different economic principles (land rent, substitution elasticities etc.) and/or considering biophysical characteristics such as land suitability (Popp et al. 2017a; Schmitz et al. 2014).

I.7.2 Demand for food, feed, fibre and agricultural trade

LUMs project demand for food, feed, other industrial or energy uses for different agriculture and forestry commodities over time. While PE models typically use reduced-form demand functions with greater level of detail at the commodity level, however limited agriculture and forestry, CGE models represent demand starting from utility functions from which it is possible to derive demand functions, and functional forms for income and price elasticities however for a more limited set of agricultural and forestry commodities but with full coverage of all economic sectors (Valin et al. 2014). Over time, demand for food, feed, and other industrial uses is projected conditional on population and income growth while bioenergy demand is typically informed in PE models by linking with IAMs/energy systems models, and is usually endogenous in CGE/IAMs. Depending on the model, demand projections are sensitive to price changes. International trade is often represented in LUMs using either Armington or spatial equilibrium approaches.

I.7.3 Treatment of land-based mitigation options

Two broad categories of land-based mitigation options are represented in LUMs: i) reduction of GHG (CO_2, CH_4 and N_2O) emissions from land use, ii) carbon sink enhancement options including biomass supply for bioenergy. Each of these categories is underpinned by a portfolio of mitigation options with varying degree of complexity and parameterisation across LUMs. The representation of mitigation measures is influenced, on the one hand, by the availability of data for its techno-economic characteristics and future prospects as well as the computational challenge, e.g. in terms of spatial and process detail, to represent the measure, and on the other hand, by structural differences and general focus of the different LUMs, and prioritisation of different mitigation options by the modelling teams. While GHG emission reduction and CO_2 sequestration options such as afforestation, are typically covered directly in LUMs, carbon sequestration from biomass supplied for bioenergy coupled with carbon sequestration (BECCs) is usually not accounted for in LUMs but in the energy sector and hence is taken care of directly in the IAMs. Yet, LUMs provide estimates of available biomass for energy production and the impacts of its production.

I.7.3.1 Treatment of GHG emissions reduction

Agricultural non-CO_2 emissions covered in LUMs include CH_4 from enteric fermentation, manure management and cultivation of rice paddies, and N_2O emissions from soils (fertiliser and manure application, crop residues) and manure management and are based on IPCC accounting guidelines (IPCC 2019a). For each of those sources, LUMs typically represent a (sub)set of technical, structural and demand side mitigation options. Technical options refer to technologies such as anaerobic digesters, feed supplements or nitrogen inhibitors that are either explicitly represented (Frank et al. 2018) or implicitly via the use of MACCs (Beach et al. 2015; Harmsen et al. 2019; Lucas et al. 2007). Emission savings from structural changes refer to more fundamental changes in the agricultural sector for example through international trade, production system changes or reallocation and substitution effects (Havlík et al. 2014). Demand side options include dietary changes and reduction of food waste (Mbow et al. 2019; Rosenzweig et al. 2020; Springmann et al. 2016; Ivanova et al. 2020; Ritchie et al. 2018; Creutzig et al. 2018; Clark et al. 2020; Popp et al. 2010; Frank et al. 2019). For the forest sector, emission reduction options are mainly targeting CO_2 from deforestation (Rochedo et al. 2018; Eriksson 2020; Overmars et al. 2014; Bos et al. 2020; Hasegawa et al. 2017). Mitigation/restoration options for wetlands to reduce emissions from drained organic soils are typically not represented in LUMs (Humpenöder et al. 2020).

There are significant differences between UNFCCC nationally reported GHG inventories and analytical global land use models. According to Grassi et al. (2017), this discrepancy results in a 3GtCO_2e difference in estimates between country reports and global models. The difference relies on different methods to classify and assess managed forests and its forest management fluxes (Houghton et al. 2012; Pongratz et al. 2014; Tubiello et al. 2015; Smith et al. 2014; Grassi et al. 2017). While global models account for GHG emissions from indirect human induced effects and natural effects in unmanaged land, country only consider fluxes of land use and land use change in managed land. In order to produce policy relevant land use model exercises, reconciling these differences is needed by harmonising definitions and approaches of anthropogenic land and the treatment of indirect environmental change (Grassi et al. 2017).

I.7.3.2 Treatment of terrestrial carbon dioxide removal options including biomass supply for bioenergy

Terrestrial Carbon Dioxide Removal (tCDR) options are only partially included in LUMs and mostly rely on afforestation and bioenergy with CCS (BECCS) (Smith et al. 2019; Fuss et al. 2014, 2018; Minx et al. 2018; Butnar et al. 2020). Especially some nature-based solutions (Griscom et al. 2017) such as soil carbon management (Paustian et al. 2016) which have the potential to alter the contribution of land-based mitigation in terms of timing, potential and sustainability consequences are only recently becoming implemented in LUMs (Frank et al. 2017; Humpenöder et al. 2020). The representation of bioenergy feedstocks varies across models but typically LUMs have comprehensive representation of a series of crops (starch, sugar, oil, wood/lignocellulosic feedstocks) or residues/byproducts that can be used for liquid and solid bioenergy production (Hanssen et al. 2019).

I.7.4 Treatment of climate change impacts and CO_2 fertilisation

Although LUMs have, in general, the capacity to consider the average impact of climate change on crops, livestock-, forest productivities, and potential benefits of increasing CO_2 concentration in the atmosphere on vegetal growth, typically climate change impacts are not considered in climate mitigation scenarios to allow for a cleaner interpretation of the results and impact assessment of climate change mitigation efforts.

I.7.5 Treatment of environmental and socio-economic impacts of land use

Aside reporting the implications on AFOLU GHG emissions, LUMs can provide a set of environmental and socioeconomic impact indicators to assess the quantified climate stabilisation pathways in a broader sustainable development agenda. These indicators typically span from land use area developments (Popp et al. 2017a), fertiliser use, irrigation water use and environmental flows (Bonsch et al. 2015; Pastor et al. 2019), and on biodiversity (Leclère et al. 2020), to market impacts on commodity prices and food consumption, or impact on undernourishment (Fujimori et al. 2019a; Hasegawa et al. 2018).

I.8 Reduced complexity climate modelling

Climate model emulators (often referred to as reduced complexity or simple climate models) are used to integrate the WG I knowledge of physical climate science in WG III assessment. Hence, emulators are used to assess the climate implications of the GHG and other emissions trajectories that IAMs produce (Rogelj et al. 2018a; Clarke et al. 2014; Rogelj Joeri and Hare 2011; Schaeffer et al. 2015). The IAM literature typically uses one of two approaches: comprehensive emulators such as MAGICC (Meinshausen et al. 2011) or Hector (Hartin et al. 2015) or minimal complexity representations such as the representation used in DICE (Nordhaus 2018), PAGE (Yumashev Dmitry and Hope 2019) and Fund (Waldhoff et al. 2014). In physical science research, a wider range of different emulators are used (Nicholls et al. 2020b,c).

A key application of emulators within IPCC WG III is the classification of emission scenarios with respect to their global mean temperature outcomes (Clarke et al. 2014; Rogelj et al. 2018a). WG III relies on emulators to assess the full range of carbon-cycle, and climate response uncertainty of thousands of scenarios, as assessed by AR6 WG I. An exercise of such amplitude is currently infeasible with more computationally demanding state-of-the-art Earth system models. Cross-chapter Box 7.1 of WG I documents how emulators used in AR6 WG3 are consistent with the physical science assessment of WG I.

Previous IPCC Assessment Reports relied either on the climate output from each individual IAM (IPCC 2000) or a more streamlined approach, where one consistent emulator setup was used to assess all scenarios. For instance, in AR5 and SR1.5, MAGICC was used for scenario classification (Clarke et al. 2014; Rogelj et al. 2018a). In recent years, numerous other emulators have been developed and increased confidence and understanding can thus be gained by combining insights from more than one emulator. For example, although SR1.5 continued to use MAGICC for its classification of scenarios, additional insights from the FAIR model (Smith et al. 2018) were used to assess the robustness of this approach. The SR1.5 experience with multiple emulators highlighted that the veracity of emulators “is a substantial knowledge gap in the overall assessment of pathways and their temperature thresholds” (Rogelj et al. 2018a). Since SR1.5, international research efforts have demonstrated tractable ways to compare emulator performance (Nicholls et al. 2020b) as well as their ability to accurately represent a set of uncertainty ranges in physical parameters (Nicholls et al. 2020c), such as those reported by the AR6 WG I assessment.

Finally, dedicated efforts over the past year have reduced a key barrier for non-expert users to incorporate multiple emulators in their assessment of the climate outcome of emissions scenarios. The OpenSCM-Runner package (Nicholls et al. 2020a) provides users with the ability to run multiple emulators from a single interface. OpenSCM-Runner has been built in collaboration with the WG III research community and forms part of the WG III climate assessment (see Section II.2.4.1. Assessment of WG III scenarios building on WG I physical climate knowledge).

I.9 Integrated assessment modelling

Integrated assessment models (IAMs) describe the coupled energy-land-economy-climate system (Weyant 2009, 2017; Krey 2014). They typically capture all greenhouse gas (GHG) emissions induced by human activities and, in many cases, other emissions of climate forcers like sulphate aerosols. Process-based IAMs represent most GHG and climate pollutant emissions by modelling the underlying processes in energy and land use. Those models are able to endogenously describe the change in emissions due to changes in energy and land use activities, particularly in response to climate action. But IAMs differ in the extent to which all emissions and the corresponding sources, processes and activities are represented endogenously and, thus, can be subjected to policy analysis.[4] IAMs also differ regarding the scope of representing carbon removal options and their interlinkage with other vital systems such as the energy and the land-use sector.

Typically, IAMs are global models that span the time horizon until 2100 using time-steps of five to ten years. To obtain global coverage, countries are aggregated into a limited number of world regions, typically 10 to 60. IAMs consider multi-level systems of global, regional, national and local constraints and balance equations for different categories such as emissions, material and energy flows, financial flows, land availability that are solved simultaneously. Intertemporal IAMs can fully incorporate not only flow constraints that are satisfied in each period, but also stock constraints that are aggregated over time and require to balance activities over time. Changes of activities, e.g. induced by policies to reduce emissions are connected to a variety of balance equations and constraints and therefore such policies lead to system wide changes that can be analysed with IAMs. Many IAMs also contain gridded components to capture, e.g., land use and climate change processes where the spatial distribution matters greatly for the dynamics of the system. Processes that operate on smaller spatial and temporal scales than resolved by IAMs, such as temporal variability of renewables, are included by parameterisations and statistical modelling approaches that capture the impact of these subscale processes on the system dynamics at the macro level (Pietzcker et al. 2017).

Global IAMs are used to analyse global emissions scenarios extrapolating current trends under a variety of assumptions and climate change action pathways under a variety of global goals. In recent years, a class of national / regional IAMs have emerged that describe the coupled energy-land-economy system in a given geography. They typically have higher sectorial, policy and technology resolution than global models and make assumptions about boundary conditions set by global markets and international policy regimes. These IAMs are used to study trends and transformation pathways for a given region (Shukla and Chaturvedi 2011; Capros et al. 2014; Lucena et al. 2016).

I.9.1. Types of Integrated Assessment Models

IAMs include a variety of model types that can be distinguished into two broad classes (Weyant 2017). The first class comprises *cost-benefit IAMs* that fully integrate a stylized socioeconomic model with a

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FOOTNOTE: [4] See the common IAM documentation at www.iamcdocumentation.eu.

reduced form climate model to simultaneously account for the costs of mitigation and the damages of global warming using highly aggregate cost functions derived from more detailed models. In the model context these functions do not explicitly represent the underlying processes, but map mitigation efforts and temperature to costs. This closed-loop approach between climate and socioeconomic systems enables cost-benefit analysis by balancing the cost of mitigation and the benefits of avoided climate damages. This can be done in a globally cooperative setting to derive the globally optimal climate policy where no region can further improve its welfare without reducing the welfare of another region (Pareto optimum). Alternatively, it can be assumed that nations do not engage in emission mitigation at all or mitigate in a non-cooperative way only considering the marginal benefit of their own action (Nash equilibrium). Also, differing degrees of partial cooperation are possible.

The second class of IAMs, called *detailed process IAMs*, focuses on the analysis of transformation processes depending on a broad set of activities that induce emissions as side effects. They describe the interlinkages between economic activity, energy use, land use, and emissions with emission reductions and removals as well as broader sustainable development targets. GHGs and other climate pollutants are caused by a broad range of activities that are driven by socioeconomic developments (Riahi et al. 2017) and also induce broader environmental consequences such as land-use change (Popp et al. 2017a) and air pollution (Rao et al. 2017b). The process-based modelling approach replicates the IPCC method of GHG emission measuring by relating emission coefficients to activities and processes, which in turn are influenced by policies. With few exceptions, these models typically do not close the loop with climate change and damages that affect the economy, but focus on emission scenarios and climate change mitigation pathways. Due to the process based representations of emission sources and alternatives it is not only possible to investigate the implications of policies on GHG emissions, but also the trade-offs and synergies with social and environmental sustainability criteria (von Stechow et al. 2015) (Section I.8.3). The analysis of different cross-sectorial synergies and trade-offs is frequently termed a nexus analysis, such as the energy-water-land nexus. The analysis can also address socioeconomic sustainability criteria such as energy access and human health. Process-based IAMs are also used to explore the synergies and trade-offs of 'common, but differentiated responsibilities' by analysing issues of burden sharing, equity, international cooperation, policy differentiation and transfer measures (Tavoni et al. 2014; Leimbach and Giannousakis 2019; Bauer et al. 2020b; Fujimori et al. 2016).

There exists a broad range of detailed process IAMs that differ regarding the economic modelling approaches (see Section I.2 Economic modelling) as well as the methodology and detail of sector representation (Sections I.3 Energy system modelling-I.7 Land use modelling) and how they are interlinked with each other. This leads to differences in model results regarding global aggregates as well as sectorial and regional outputs. Several approaches have been used to evaluate the performance of IAMs and understand differences in IAM behaviour (Wilson et al. 2017; Schwanitz 2013), including sensitivity analysis (McJeon et al. 2011a; Luderer et al. 2013; Rogelj et al. 2013; Bosetti et al. 2015; Marangoni et al. 2017), model comparisons (Clarke et al. 2009; Kriegler et al. 2014a; Tavoni et al. 2014; Kriegler et al. 2015a; Riahi et al. 2015; Kriegler et al. 2016; Riahi et al. 2017; Luderer et al. 2018; McCollum et al. 2018a), model diagnostics (Kriegler et al. 2015a; Wilkerson et al. 2015), and comparison with historical patterns (Wilson et al. 2013; van Sluisveld et al. 2015).

I.9.2. Components of integrated assessment models

I.9.2.1. Energy-economy component

Typically, IAMs comprise a model of energy flows, emissions and the associated costs. The demand for exploring the Paris Agreement climate goals led to model developments to make the challenges and opportunities of the associated transformation pathways more transparent. Since AR5 much progress has been achieved to improve the representation of mitigation options in the energy supply sector (e.g. renewable energy integration (Pietzcker et al. 2017), energy trade (Bauer et al. 2017, 2016; Jewell et al. 2018; McCollum et al. 2016), capacity inertia, carbon removals, decarbonisation bottlenecks (Luderer et al. 2018)) and technological and behavioural change measures in energy demand sectors such as transport (Edelenbosch et al. 2017a; van Sluisveld et al. 2016; McCollum et al. 2017). An energy sector model can be run as a partial equilibrium model using exogenous demand drivers for final energy and energy services. These models derive mitigation policy costs in terms of additional energy sector costs and area under the MAC curve.

Energy models can be also embedded into a broader, long-term macroeconomic context in a general equilibrium model (Messner and Schrattenholzer 2000; Bauer et al. 2008). The demands for final energy and energy services are endogenously driven by an economic growth model that also endogenises the economic allocation problem of macroeconomic resources for the energy sector that crowd out with alternatives. This allows impact analysis of climate policies on economic growth and structural change, investment financing and crowding-out as well as income distribution and tax revenue recycling (Guivarch et al. 2011). Moreover, general equilibrium models also derive mitigation costs in terms of GDP losses and Consumption losses, which comprise the full macroeconomic impacts rather than only the narrow energy related costs (Paltsev and Capros 2013).

I.9.2.2. Land system component

In recent years substantial efforts have been devoted to improve and integrate land-use sector models in IAMs (Popp et al. 2017a, 2014; Weindl et al. 2017). This acknowledges the importance of land-use GHG emissions of the agricultural and forestry sectors as well as the role of bioenergy, afforestation and other land-based mitigation measures. The integration is particularly important in light of the long-term climate goals of the Paris Agreement for four reasons (IPCC 2019b). First, the GHG emissions from the land use sector accounts for LUC emissions account for more than 10% of global GHG emissions (Kuramochi et al. 2020) and some sources of CH_4 and N_2O constitute serious mitigation bottlenecks. Second, bioenergy is identified as crucial primary energy source for low-emission energy supply and carbon removal (Bauer et al. 2020a). Third, land use-based mitigation measures such as afforestation and reduced deforestation have substantial mitigation potentials. Finally, land-cover changes alter the earth surface albedo, which has implications for regional and global climate. Pursuing the Paris Agreement climate goals requires the inclusion of a broad set of options regarding GHG emissions and removals, which will intensify the interaction between the energy, the economy and the land use sector. Consequently, intersectoral policy coordination becomes more important and the land-related synergies and trade-offs with sustainable development targets will intensify (Calvin et al. 2014b; Humpenöder et al. 2018; Frank et al. 2017; Kreidenweis et al. 2016; van Vuuren et al. 2017; Bauer et al. 2020c). IAMs used by the IPCC in the AR6 have continuously improved the integration of land-use models with energy models to explore climate mitigation scenarios under varying policy and technology conditions (Rogelj et al. 2018a; Smith et al. 2019). However, feedbacks from changes in climate variables are not or only to a limited degree included in the land use sector models.

I.9.2.3. Climate system component

Reduced complexity climate models (often called simple climate models or emulators) are used for communicating WG I physical climate science knowledge to the research communities associated with other IPCC working groups (Section I.8). They are used by IAMs to model the climate outcome of the multi-gas emissions trajectories that IAMs produce (van Vuuren et al. 2011a). A main application of such models is related to scenario classifications in WG III of the IPCC (Clarke et al. 2014; Rogelj et al. 2018a). Since WG III assesses a large number of scenarios, it must rely on the use of these simple climate models; more computationally demanding models (as used by WG I) will not be feasible to apply. Analysing various features of the broad scenario database, like the timing of peak warming and carbon neutrality, or 2030 emission levels in line with a certain global temperature goal, requires a large amount of multi-gas scenarios to be analysed. For consistency across the AR6 reports, it is important that these reduced-complexity models are up to date with the latest assessments from IPCC Working Group I. This relies on calibrating these models so that they match, as closely as possible, the assessments made by WG I (see Section **II.2.4. Scenario approaches to connect WG III with the WG I and WG II assessments**). The calibrated models can then be used by WG III in various parts of its assessment.

I.9.3. Representation of nexus issues and sustainable development impacts in IAMs

An energy-water-land nexus approach integrates the analysis of linked resources and infrastructure systems to provide a consistent platform for multi-sector decision-making (Howells et al. 2013). Many of the IAMs that contributed to the assessment incorporate a nexus approach that considers simultaneous constraints on land, water and energy, as well as important mutual dependencies (Calvin et al. 2019; Fricko et al. 2017; Dietrich et al. 2019; Fujimori et al. 2017; Van Vuuren et al. 2019). Recently IAMs have also been integrated with life cycle assessment tools in assessing climate mitigation policies to better understand the relevance of life cycle GHG emissions in cost-optimal mitigation scenarios (Tokimatsu et al. 2020; Portugal-Pereira et al. 2016; Pehl et al. 2017; Arvesen et al. 2018). This holistic perspective ensures mitigation pathways do not exacerbate challenges for other sectors or environmental indicators. At the same time, pathways are leveraging potential synergies along the way towards achieving multiple goals.

IAMs rely on biophysical models with a relatively high-degree of spatial and temporal resolution to inform coarser scale economic models of the potentials and costs for land, water and energy systems (Johnson et al. 2019). IAMs leverage population, GDP and urbanisation projections to generate consistent water, energy and crop demand projections across multiple sectors (e.g., agriculture, livestock, domestic, manufacturing and electricity generation) (Mouratiadou et al., 2016). The highly-distributed nature of decisions and impacts across sectors, particularly for land and water, has been addressed using multi-scale frameworks that embed regional and sub-regional models within global IAMs (Mosnier et al. 2014; Hejazi et al. 2015; Bijl et al. 2018; Portugal-Pereira et al. 2018). These analyses have demonstrated how local constraints and policies interact with national and international strategies aimed at reducing emissions.

Sustainable development impacts extending beyond climate outcomes have been assessed by the IAMs that contributed to the assessment, particularly in the context of the targets and indicators consistent with the Sustainable Development Goals (SDGs). The representation of individual SDGs is diverse (Figure I.3), and recent model development has focused mainly on improving capabilities to assess climate change mitigation policy combined with indicators for economic growth, resource access, air pollution and land use (van Soest et al. 2019). Synergies and trade-offs across sustainable development objectives can be quantified by analysing multi-sector impacts across ensembles of IAM scenarios generated from single or multiple models (McCollum et al. 2013; Mouratiadou et al. 2016). Modules have also been developed for IAMs with the specific purpose of incorporating policies that address non-climatic sustainability outcomes (Fujimori et al. 2018; Parkinson et al. 2019; Cameron et al. 2016). Similar features have been utilised to incorporate explicit adaptation measures and targeted policies that balance mitigation goals with other sustainability criteria (Bertram et al. 2018; McCollum et al. 2018a).

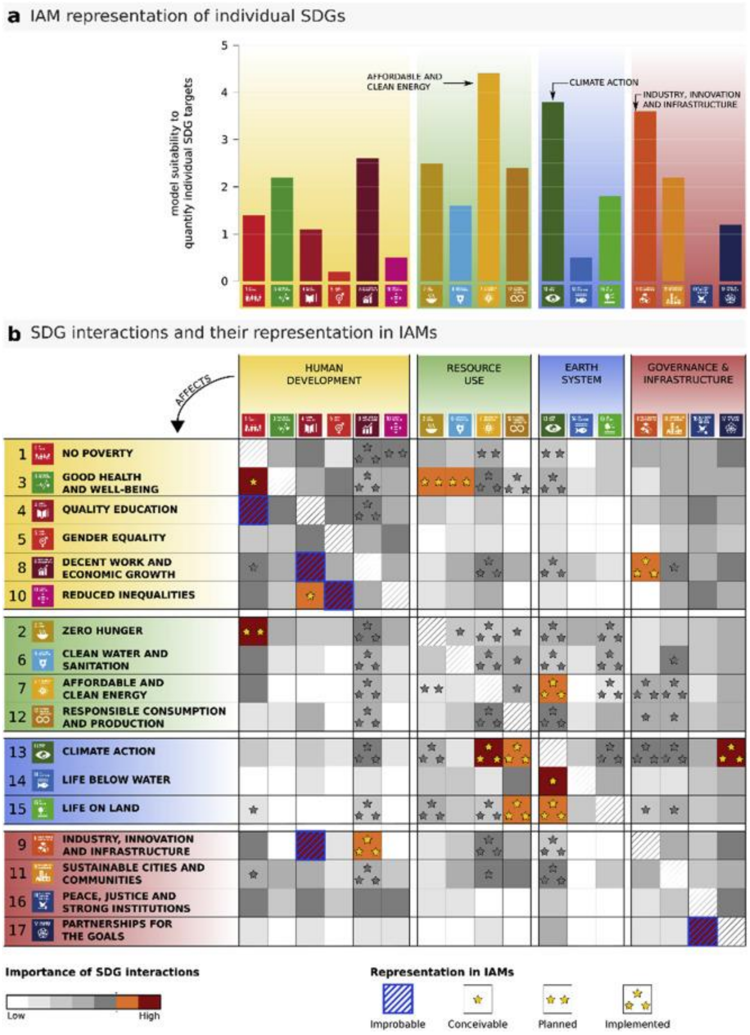

Figure I.3. The representation of SDGs by IAMs. a) Individual target coverage from a multi-model survey; and b) SDG interactions and coverage by IAM models according to a combination of expert and model surveys. The strength dimension of SDG interactions is indicated by grey shading: darker shades represent strong interactions while white represents no interactions. Orange cells indicate where there is the highest agreement between the importance of interactions and model representation, while blue coloured cells show the most important interactions without model representation. Source: van Soest et al. (2019).

I.9.4 Policy analysis with IAMs

A key purpose of IAMs is to provide orientation knowledge for the deliberation of future climate action strategies by policy makers, civil society and the private sector. This is done by presenting different courses of actions (climate change and climate action pathways) towards a variety of long-term climate outcomes under a broad range of assumptions about future socio-economic, institutional and technological developments. The resulting climate change and climate action pathways can be analysed in terms of their outcomes towards a set of societal goals (such as the SDGs) and the resulting trade-offs between different pathways. Key trade-offs that have been investigated in the IAM literature are between (1) no, moderate, and ambitious mitigation pathways (Riahi et al. 2017), (2) early vs. delayed mitigation action (Riahi et al. 2015; Luderer et al. 2018), (3) global action with a focus on economic efficiency equalising marginal abatement costs across countries and sectors vs. regionally and sectorially fragmented action (Kriegler et al. 2015b; Bertram et al. 2015; Kriegler et al. 2018b), (4) pathways with different emphasis on supply side vs. demand side mitigation measures (van Vuuren et al. 2018a; Grubler et al. 2018) or more broadly different sustainable development strategies (van Vuuren et al. 2015), and (5) pathways with different preferences about technology deployment, in particular with regard to CCS and carbon dioxide removals (Kriegler et al. 2014a; van Vliet et al. 2014; Strefler et al. 2018). Key uncertainties that were explored in the IAM literature are between (1) different socio-economic futures as, e.g., represented by the Shared Socioeconomic Pathways (SSPs) (Riahi et al. 2017; Bauer et al. 2017; Popp et al. 2017a), (2) different technological developments (Bosetti et al. 2015) and (3) different resource potentials (Kriegler et al. 2016).

Policy analysis with IAMs follows the approach that a baseline scenario is augmented by some kind of policy intervention. To address the uncertainties in baseline projections, the scientific community has developed the Shared Socioeconomic Pathways (SSPs) that provide a set of vastly different future developments as reference cases (see Section II.1.2.2. Scenario framework for climate change research and SSP-based mitigation scenarios). Most scenarios used in AR6 are based on the middle-of-the-road reference system (SSP2). Depending on the research interest the baseline can be defined as a no-policy baseline or it can include policies that either address GHG emissions like the NDCs or other pre-existing policies such as energy subsidies and taxes. There is no standard definition for baseline scenarios regarding the inclusion of policies. The baseline scenario is augmented by additional policies like a carbon tax aiming towards a long-term climate goal. Hence, the IAM based policy analysis assumes a reference system like SSP2 within which policy scenarios are compared with a baseline scenario.

Most policy analysis with process-based IAMs apply a mix of short-term policy evaluation and long-term policy optimisation. Policy evaluation applies an exogenous set of policies such as the stated NDCs and evaluates the emission outcomes. Policy optimisation is mostly implemented as a cost-effectiveness analysis: a long-term climate stabilisation target is set to derive the optimal mitigation strategy that equalises marginal abatement cost across sectors, GHGs and countries. This optimal mitigation strategy can be implemented by a broad set of well-coordinated sector specific policies or by comprehensive carbon pricing policies.

Most commonly the baseline scenario is either a no-policy baseline or based on the NDCs applying an extrapolation beyond 2030. The climate policy regimes most commonly applied include a long-term target to be reached. The optimal climate strategy can be phased in gradually or applied immediately after 2020. It can focus on a global carbon price equalising marginal abatement costs across countries or policy intensities can vary across countries and sectors in the near- to medium-term. The climate policy regime can or cannot include effort sharing mechanisms and transfers between regions. Also, it can be extended to include additional sector policies such as improved forest protection or fossil fuel subsidy removal. If certain technologies or activities are related to spill-overs such as technology learning carbon-pricing might be complemented by technology support (Schultes et al. 2018). If carbon pricing policies are fragmented or delayed additional and early sector policies can help reduce distortions and carbon leakage effects (Bauer et al. 2020b). All these variations to the policy regime can lead to very different transformation pathways and policy costs, which is a core result of the IAM analysis.

By applying sensitivity analysis IAMs can be used to assess the importance to strategically develop new technologies and options for mitigation and identify sticking points in climate policy frameworks. The sensitivity analysis evaluates differences in outcomes subject to changes in assumptions. For instance, the assumption about the timing and costs of CCS and CDR availability can be varied (Bauer et al. 2020a). The differences in mitigation costs and the transformation pathway support the assessment of policy prioritisation by identifying and quantifying crucial levers for achieving long-term climate mitigation targets such as R&D efforts and timing of policies.

I.9.5 Limitations of IAMs

The application of IAMs and the use of IAM results for providing orientation knowledge on climate change response strategies has been criticised for mainly four reasons. First, there are concerns that IAMs are missing important dynamics, e.g. with regard to climate damages and economic co-benefits of mitigation (Stern 2016), demand side responses (Wilson et al. 2012), bioenergy, land degradation and management (Creutzig et al. 2014; IPCC 2019b), carbon dioxide removal (Smith et al. 2016), rapid technological progress in the renewable energy sector (Creutzig et al. 2017), actor heterogeneity, and distributional impacts of climate change and climate policy. This has given rise to criticism that IAMs lack credibility in set of crucial assumptions, among which stands out the critique on the availability of carbon dioxide removal technologies (Bednar et al. 2019; Anderson and Peters 2016).

These concerns spur continuous model development and improvements in scenario design, particularly with regard to improved representations of energy demand, renewable energy, carbon dioxide removal technologies, and land management. IAMs are aiming to keep pace with the development of sector-specific models, including latest advances in estimating climate damages (Piontek et al. 2018). In places, where dynamic modelling approaches are lacking, scenarios are being used to explore relevant futures (Grubler et al. 2018). Although most models are still relying on the concept of a single representative household representing entire regions, efforts are under way to better represent agent heterogeneity and distributional impacts of climate change and climate mitigation policies (Rao et al. 2017a).

Second, concerns have been raised that IAMs are non-transparent and thus make it difficult to grasp context and meaning of their results. These concerns are partly addressed by a substantially increase in model documentation (see the common IAM documentation at www.iamcdocumentation.eu as entry point) and open-source models, but more communication tools and co-production of knowledge formats will be needed to contextualise IAM results for users. When projecting over a century, uncertainties are large and cannot be ignored. Efforts have been undertaken (Marangoni et al. 2017; Gillingham et al. 2018) to better gauge what are robust findings from these models and how much they depend on key assumptions (as for example long term growth of the economy, the monetary implication of climate damages or the diffusion and cost of key mitigation technologies).

Third, there are concerns that IAMs are describing transformative change on the level of energy and land use, but are largely silent about the underlying socio-technical transitions that could imply restructuring of society and institutions. Weyant (2017) notes the inability of IAMs to mimic extreme and discontinuous outcomes as one of their major limitations. This is relevant when modelling extreme climate damages as well as when modelling disruptive changes. Dialogues and collaborative work between IAM researchers and social scientists have explored ways to bridge insights from the various communities to provide a more complete picture of high impact climate change scenarios and, on the other end, deep transformation pathways (Turnheim et al. 2015; Geels et al. 2016). The extension of IAM research to sustainable development pathways is giving rise to further inter-disciplinary research on underlying transformations towards the Paris climate goals and other sustainable development goals (Kriegler et al. 2018c; Sachs et al. 2019).

Finally, there are concerns that IAM analysis could focus on only a subset of relevant futures and thus push society in certain direction without sufficient scrutiny (Beck and Mahony 2017). These concerns can be effectively addressed by adopting an iterative approach between researchers and societal actors in shaping research questions and IAM applications (Edenhofer and Kowarsch 2015). IAM research is constantly taking up concerns about research gaps and fills it with new pathway research, as e.g. occurred for low energy demand and limited bioenergy with CCS scenarios (Grubler et al. 2018; van Vuuren et al. 2018a).

I.10 Comparative table of key characteristics of models that contributed scenarios to the assessment

[Table to be included in FGD]

I.11. Comparative table of mitigation measures represented by models that contributed scenarios to the assessment

[Table to be included in FGD]

Part II Scenarios

II.1. Overview on climate change scenarios

Scenarios are coherent and internally consistent descriptions of alternative futures. They are used to explore possible developments in a situation of deep uncertainty about the future. Such deep uncertainty usually precludes predictions of the probability of future events. While scenarios are not predictions or forecasts, they can still be used to explore possible outcomes under a variety of assumptions.

Future climate change is a prime example for the application of scenarios. It is driven by human activities across the world and thus can be altered by human agency. It affects all regions over many centuries to come. Humankind's response to climate change touches not only on the way we use energy and land, but also on socio-economic and institutional layers of societal development. Climate change scenarios provide a central approach to analyse this wicked problem.

II.1.1. Purposes of climate change scenarios

Climate change scenarios are developed for a number of purposes (O'Neill et al. 2020). First they are constructed to explore possible climate change futures covering the causal chain from (i) socio-economic developments to (ii) energy and land use to (iii) greenhouse gas emissions to (iv) changes in the atmospheric composition of greenhouse gases and associated radiative forcing to (v) changes in temperature and precipitation patterns to (vi) bio-physical impacts of climate change and finally to (vii) impacts on socio-economic developments, thus closing the loop. Quantitative scenarios exploring possible climate change futures are often called climate change (impact) projections.

Second, climate change scenarios are developed to explore pathways towards long-term climate goals. Goal-oriented scenarios often carry the word pathway in their name, such as climate change mitigation pathway, climate change adaptation pathway, or more generally climate change transition / transformation pathway. They are sometimes called backcasting scenarios, or short backcasts, in the literature, particularly when contrasted with forecasts (Robinson 1982). Goal-oriented / backcasting scenarios are inherently normative and intricately linked to human intervention. They can be used to compare and contrast different course of actions. For example, they are often applied in the framework of policy impact analysis by comparing a reference (baseline) scenario without or with only moderate climate policy intervention with a mitigation and/or adaptation pathway (Grant et al. 2020). A set of transformation pathways to climate goals of varied ambition can be used to learn about the multi-dimensional trade-offs between raising or lowering ambition (Clarke et al. 2014). Likewise, different transformation pathways to the same goal are often used to analyse trade-offs between different routes towards this goal (Rogelj et al. 2018a). Since these scenarios have very limited predictive power, they need to be looked at as a set to understand attainable outcomes and the trade-offs between them. With scenarios, context matters!

Third, climate change scenarios are used to integrate knowledge and analysis between the three different climate change research communities working on the climate system and its response to human interference (linked to WG I of the IPCC), climate change impacts, adaptation and vulnerability (linked to WG II) and climate change mitigation (linked to WG III) (IPCC 2000; van Vuuren et al. 2011b; O'Neill et al. 2016). This involves the adoption of common scenario frameworks that allow the consistent use of, e.g., shared emissions scenarios, socio-economic development scenarios and climate change projections (Moss et al. 2010; Kriegler et al. 2012; van Vuuren et al. 2012, 2014; O'Neill et al. 2014). The integrative power of climate change scenarios extends beyond the climate change research community into neighbouring fields such as the social sciences and ecology (Rosa et al. 2020). To foster such integration, underlying scenario narratives have proven extremely useful as they allow to develop and link quantitative scenario expressions in very different domains of knowledge (O'Neill et al. 2020).

Fourth, climate change scenarios and their assessment aim to inform society (Weber et al. 2018; Auer et al. 2020). Scenarios can help to coordinate perception about possible and desirable futures. It will therefore be important to relate climate change scenarios to societal developments and goals (Kriegler et al. 2018c). To this end, scenarios can be seen as tools for societal discourse and decision making which are used in an iterative process between scenario researchers and societal actors (Edenhofer and Kowarsch 2015; Beck and Mahony 2017).

II.1.2. Types of climate change mitigation scenarios

There are a number of different types of climate change scenarios, given the different purposes and knowledge domains covered by them. The different types are linked to different models used to construct them (see Part I Modelling methods). Global reference and mitigation scenarios and their associated emissions projections (often called emission scenarios), and national, sector and service transformation / transition scenarios are key types of scenarios that are assessed in the 6th Assessment Report of Working Group III of the IPCC (see Section **II.2.4. Scenario approaches to connect WG III with the WG I and WG II assessments** for a discussion how the WG I and WG II assessments relate to the WG III scenario assessment). Since mitigation and transformation scenarios are goal-oriented, the terms mitigation / transformation scenario and mitigation / transformation pathway can be used interchangeably.

II.1.2.1. Global mitigation scenarios

Since the IPCC Fifth Assessment Report (AR5), many new global mitigation pathways and associated emissions projections have been developed and published. These include scenarios extrapolating currently implemented policies and the NDCs until the end of the century, moderate near-term action scenarios that run through the mitigation ambition of current NDCs until 2030 and then aim towards the Paris climate targets (Luderer et al. 2018; Roelfsema et al. 2020; Riahi et al. 2021), accelerated action scenarios that gradually phase in regulatory policies and carbon pricing to strengthen ambition beyond current NDCs before 2030 (Kriegler et al. 2018b; van Soest et al. 2020), demand-side driven deep mitigation pathways towards 1.5°C with sustainable development co-benefits (van Vuuren et al. 2018a; Grubler et al. 2018; Bertram et al. 2018), and deep mitigation pathways without the use of net negative CO_2 emissions (Riahi et al. 2021). There is also a push to extend mitigation pathways to cover a broader range of sustainable development goals, with the ultimate goal to develop more and more holistic Sustainable Development Pathways (SDPs) (van Vuuren et al. 2018b; Fujimori et al. 2020a; Soergel et al. 2021). The scenarios described above are primarily assessed in Chapter 3 of the Report from a climate mitigation perspective, however sectoral chapters have also used the scenarios, including their climate mitigation categorisations to ensure consistent cross-chapter treatment. In addition to these policy-oriented scenarios, a variety of mitigation scenarios were explored to diagnose system (Bauer et al. 2020a; Smith et al. 2020) and model behaviour (Harmsen et al. 2020a). Purely diagnostic scenarios were typically not collected in the AR6 scenario database.

II.1.2.2. Scenario framework for climate change research and SSP-based mitigation scenarios

The current scenario framework for climate change research (van Vuuren et al. 2014; O'Neill et al. 2014; Kriegler et al. 2014b) is based on the concept of Shared Socio-Economic Pathways (SSPs) (Kriegler et al. 2012; O'Neill et al. 2014). Unlike their predecessor scenarios in the IPCC Special Report on Emissions Scenarios (SRES) (IPCC 2000), their underlying narratives are motivated by the purpose of using the framework for mitigation and adaptation policy analysis. Hence the narratives are structured to cover the space socio-economic challenges to adaptation and socio-economic challenges to mitigation. They tell five stories of sustainability (SSP1), middle of the road development (SSP2), regional rivalry (SSP3), inequality (SSP4) and fossil-fuelled development (SSP5) (O'Neill et al. 2017). Those have been translated into population and education (Kc and Lutz 2017), economic growth (Dellink et al. 2017; Crespo Cuaresma 2017; Leimbach et al. 2017a), and urbanisation projections (Jiang and O'Neill 2017) for each of the SSPs. The SSP narratives and associated projections of socio-economic drivers provide the core components for building SSP-based scenario families. They have been extended in various ways, including the addition of quantitative projections on further key socio-economic dimensions like inequality (Rao et al. 2019) and governance (Andrijevic et al. 2019), or spatially downscaled projections of, e.g., population (Jones and O'Neill 2016). By now, the SSPs have been widely used in climate change research ranging from projections of future climate change to mitigation, impact, adaptation and vulnerability analysis (O'Neill et al. 2020).

The integrated assessment modelling community has used the SSPs to provide a set of global integrated energy-land use-emissions scenarios (Riahi et al. 2017; Rogelj et al. 2018b) in line with the matrix architecture of the scenario framework (van Vuuren et al. 2014). It is structured along two dimensions: socio-economic assumptions varied along the SSPs, and climate (forcing) outcomes varied along the Representative Concentration Pathways (RCPs) (van Vuuren et al. 2011b). The resulting scenarios are typically named SSPx-y with x = 1,…,5 the SSP label and y = {1.9, **2.6**, 3.4, **4.5**, **6.0**, 7.0, **8.5**} W/m^2 the forcing level obtained by the end of the century. The four forcing levels that were already covered by the original RCPs are bolded. The original RCPs were used as an input to the Climate Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al. 2011) and the new SSP-based emissions and concentrations pathway are providing the input (Gidden et al. 2019a) for CMIP6 (Eyring et al. 2015; O'Neill et al. 2016) assessed in AR6 of WG I.

SSP-based emissions scenarios (Riahi et al. 2017; Bauer et al. 2017; Popp et al. 2017b) could not identify scenarios for all combinations of SSPs and RCPs (Figure II.1). The highest forcing level, RCP8.5, is only obtained in a no policy baseline in SSP5 (SSP5-8.5). Since there are already moderate climate policies implemented in many countries around the world, it is highly unlikely that a forcing level as high as RCP8.5 will actually be obtained. Baselines for SSP1 and SSP4 reach only up to 6.0 W/m^2, with baselines for SSP2 and SSP3 coming in above this level. On the lower end, no 1.5°C (RCP1.9) and likely 2°C scenarios (RCP2.6) could be identified for SSP3 due to the lack of cooperative action in this world of regional rivalry. 1.5°C scenarios (RCP1.9) could only be reached by all models under SSP1 assumptions with SSP4 struggling to stay below 1.5°C due to limited ability to sustainably manage land and SSP5 struggling due to its high dependence on ample fossil fuel resources in the baseline (Rogelj et al. 2018b).

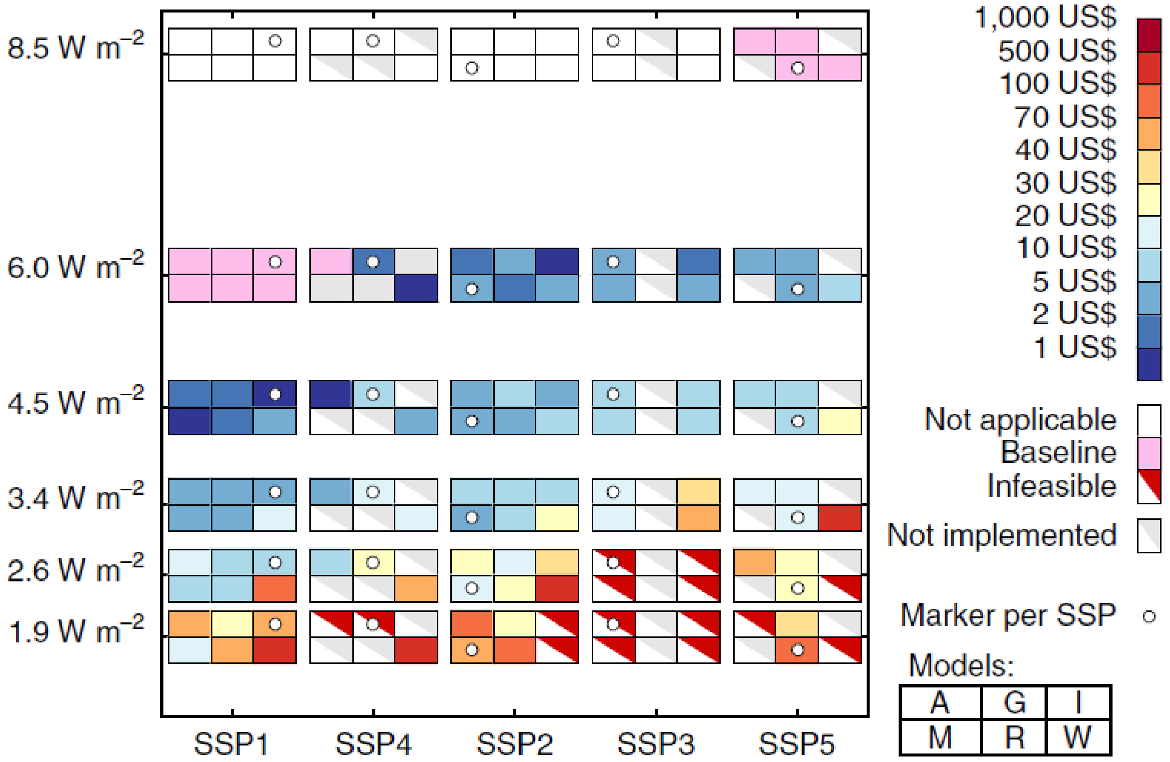

Figure II.1: SSP/RCP matrix. The SSP/RCP matrix shows the SSPs on the horizontal axis and the forcing levels on the vertical axis. Not all SSP/RCP combinations are possible (red triangles), not all combinations were tried (grey triangles), and not all combinations are applicable (white boxes). The colours in each box are successful model runs, with the colours indicating the carbon price (log scale), with the higher prices indicating feasibility constraints are approached. Source: Rogelj et al. (2018b).

II.1.2.3. National transition scenarios

A large number of transition scenarios is developed on a national/regional level by national integrated assessment, energy-economy or computable general equilibrium models, among others. These aim to analyse the implications of current climate plans of countries and regions, as well as long-term strategies until 2050 investigating different degrees of low carbon development. National/regional transition scenarios are assessed in Chapter 4 of the Report.

Recent research has focused on several different types of national transition scenarios that focus on accelerated climate mitigation pathways in the near-term to 2050. These include scenarios considered by the authors as tied to meeting specific global climate targets[5] and scenarios tied to specific policy targets (e.g., carbon neutrality or 80-95% reduction from a certain baseline year). A majority of the accelerated national transition modelling studies up to 2050 evaluate pathways that the authors consider compatible with a 2˚C global warming limit, with fewer scenarios defined as compatible with 1.5˚C global pathways. Regionally, national transition scenarios have centred on countries in Asia

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FOOTNOTE: [5] National emission pathways in the near- or mid-term cannot be linked to long-term mitigation goals without making additional assumptions about emissions by other countries up to the mid-term, and assumptions by all countries up to 2100 (see Chapter 4, Box 4.1).

(particularly in China, India, Japan), in the European Union, and in North America, with fewer and more narrowly focused scenario studies in Latin America and Africa (Lepault and Lecocq 2020).

II.1.2.4. Sector transition scenarios

There are also a range of sector transition scenarios, both on the global and the country level. These include scenarios for the transition of the electricity, buildings, industry, transport and AFOLU sectors until 2050. Due to the accelerated electrification in mitigation pathways, sector coupling plays an increasingly important role to overcome decarbonisation bottlenecks, complicating a separate sector-by-sector scenario assessment. Likewise, the energy-water-land nexus limits the scope a separate assessment of the energy and agricultural sectors. Nevertheless, sector transition scenarios play an important role for this assessment as they can usually offer much more technology, policy and behaviour detail than integrated assessment models. They are primarily assessed in the sector chapters of the report. Their projections of emissions reductions in the sectors in the near- to medium-term is used to check the sector dynamics of global models in Chapter 3 of the Report.

Recent transition scenarios considered overarching accelerated climate mitigation strategies across multiple sectors, including demand reduction, energy efficiency improvement, electrification and switching to low carbon fuels. The sectoral strategies considered are often specific to national resource availability, political, economic, climate, and technological conditions. Many sectoral transition strategies have focused on the energy supply sectors, particularly the power sector, and the role for renewable and bio-based fuels in decarbonising energy supply and carbon capture and sequestration (CCS). Some studies present comprehensive scenarios for both supply-side and demand-side sectors, including sector-specific technologies, strategies, and policies. Nearly all demand sector scenarios have emphasised the need for energy efficiency, conservation and reduction through technological changes, with a limited number of models also exploring possible behavioural changes enabled by new technological and societal innovations.

II.1.2.5. Service transition scenarios

A central feature of service transition pathways is a focus on the provision of adequate energy services to provide decent standards of living for all as the main scenario objective. Energy services are proxies for well-being, with common examples being provision of shelter (expressed as m^2/capita), mobility (expressed as passenger-kilometres), nutrition (expressed as kCal/capita), and thermal comfort (expressed as degree-days) (Creutzig et al. 2018). Service transition pathways seek to meet adequate levels of such energy services with minimal carbon emissions, using combinations demand- and supply-side options. Ideally this is done by improving the efficiency of service provision systems to minimise overall final energy and resource demand, thereby reducing pressure on supply-side and carbon dioxide removal technologies (Grubler et al. 2018). Service transition pathways provide a compelling scenario narrative focused on wellbeing, resulting in technology and policy pathways that give explicit priority to decent living standards. Furthermore, more efficient service provision often involves combinations of behavioural and technological change, expanding the options available to policymakers for achieving mitigation goals (van Sluisveld et al. 2016, 2018). Service transition scenarios are primarily assessed in Chapter 5 of the Report.

II.1.3. Key design choices and assumptions in mitigation scenarios

The development of a scenario involves design choices, in addition to the selection of the model. This section will focus on key choices related to design of the scenario, and the respective socioeconomic, technical, and policy assumptions. Model selection cannot be separated from these choices, but the various advantages and disadvantages of models are described in Part I Modelling methods (Modelling Methods).

Target setting: Goal-oriented scenarios in the climate scenario literature initially focussed on concentration stabilisation but have now shifted more towards radiative forcing and temperature limits. In early model intercomparisons, climate targets were often specified as a CO_2 equivalent concentration level that could not be crossed, for example, 450ppm CO_2-eq or 550ppm CO_2-eq (Clarke et al. 2009). These targets were either applied as not-to-exceed or overshoot targets. In the latter case, concentration levels could be returned to the target level by 2100. Overshoot targets were particularly applied for low concentration and temperature targets as many models could not find a solution otherwise (Clarke et al. 2009; Kriegler et al. 2014a; Blanford et al. 2014; Rogelj et al. 2018b). Bioenergy with Carbon Capture and Storage (BECCS) was an important technology that facilitated aggressive targets to be met in 2100, by allowing overshoot of the target leading to a distinctive peak-and-decline behaviour in concentration, radiative forcing, and temperature (Clarke et al. 2014; Fuss et al. 2014). The mitigation scenarios based on the SSP-RCP framework also applied radiative forcing levels in 2100 (Riahi et al. 2017). Temperature targets were often implemented by imposing end-of-century carbon budgets, i.e. cumulative emissions up until 2100. In the case of 2°C pathways, those budgets were usually chosen such that the 2°C limit was not overshoot with some pre-defined probability (Luderer et al. 2018). Nevertheless, due to the availability of net negative CO_2 emissions and assumptions of exponentially increasing policy stringency (with carbon pricing used as proxy), peak and decline emissions and temperature profiles could still occur below the target (Strefler et al. 2020). Arguably, the availability of net negative CO_2 emissions has led to high levels of carbon dioxide removal (CDR) in the second half of the century, although CDR deployment is often already substantial to compensate residual emissions (Rogelj et al. 2018a). Recent literature has begun to explore the implications of using alternative approaches such as peak warming or peak CO_2 budget constraints to implement targets (Rogelj et al. 2019b; Johansson et al. 2020; Riahi et al. 2021).

Efficiency considerations: Process-based IAMs typically calculate cost-effective mitigation pathways towards a given target as benchmark case (Clarke et al. 2014). In these pathways, global mitigation costs are minimised by exploiting the abatement options with the least marginal costs across all sectors and regions at any time, implicitly assuming a globally integrated and harmonised mitigation regime. This idealised benchmark is typically compared across different climate targets or with reference scenarios extrapolating current emissions trends (UNEP 2019).

The notion of cost-effectiveness is sensitive to economic assumptions in the underlying models, particularly concerning the assumptions on pre-existing market distortions (Clarke et al. 2014; Krey et al. 2014) and the discount rate on future values. Those assumptions are often not clearly expressed. Most models have a discount rate of 3-5%, though the range of alternatives is larger. Cost-benefit IAMs have had a tradition of exploring the importance of discount rates, but process-based IAMs have generally not. A lower discount rate brings mitigation forward in time and uses less carbon dioxide removal, but also increases modelled mitigation costs (Emmerling et al. 2019; Realmonte et al. 2019). While most models report discount rates in documentation, there is arguably too little sensitivity analysis of how the discount rate effects modelled outcomes.

Cost-effective pathways typically do not account for climate impacts below the target. They also do not include equity considerations as long as compensation schemes to equalise the mitigation burden between countries are not explicitly considered (Tavoni et al. 2014; Leimbach and Giannousakis 2019; van den Berg et al. 2020).

Policy assumptions: Cost-effective mitigation scenarios assume that climate policies are globally uniform. There is a substantial literature contrasting these benchmark cases with pathways derived under the assumption of regionally fragmented and heterogeneous mitigation policy regimes (Blanford et al. 2014; Kriegler et al. 2015b, 2018b; Roelfsema et al. 2020; van Soest et al. 2020; Bauer et al. 2020b). For example, the Shared Policy Assumptions (Kriegler et al. 2014b) used in the SSP-RCP framework allows for some fragmentation of policy implementation, and many scenarios follow current policies or emission pledges to a certain time period (2030) before implementing stringent policies (Vrontisi et al. 2018; Roelfsema et al. 2020; Riahi et al. 2015). Other studies assume a gradual strengthening of emissions pledges and regulatory measures converging to a globally harmonised mitigation regime slowly over time (Kriegler et al. 2018b; van Soest et al. 2020). Scenarios limiting warming to below 2°C phase in climate policies in all regions and sectors. Almost all converge to a harmonised global mitigation regime before the end of century (with the exception of Bauer et al. (2020b)). In practice, policies are often a mix of regulations, standards, or subsidies. Implementing these real-world policies can give different outcomes to optimal uniform carbon pricing. Modelled carbon prices will generally be lower when other policies are implemented (Calvin et al. 2014a; Bertram et al. 2015). As countries become to implement more policies, the need to further develop the policy assumptions in models is becoming apparent (O’Neill et al. 2020).

Socio-economic drivers: Key socio-economic drivers of emission scenarios are assumptions on population and economic activity. There are other socio-economic assumptions, often included in underlying narratives (O’Neill et al. 2017), that strongly affect energy demand per capita / unit of GDP and dietary choices (Popp et al. 2017b; Bauer et al. 2017; Grubler et al. 2018; van Vuuren et al. 2018a). The SSPs are often used to help harmonise socio-economic assumptions, and further explore the scenario space. Many studies focus on the middle-of-the-road SSP2 as their default assumption, and many use SSP variations to explore the sensitivity of their results to socio-economic drivers (Riahi et al. 2017; Rogelj et al. 2017; Marangoni et al. 2017). While the SSPs help harmonisation, they are not unique and do not fully explore the scenario space (O’Neill et al. 2020). The population in the five SSPs does not span the full UN range (Kc and Lutz 2017), and arguably is biased low relative to the UN estimates (Figure II.2). A wider range of narratives describing alternative worlds is also conceivable. The sustainability world (SSP1), for example, is a world with strong economic growth, but sustainability worlds with low growth or even elements of degrowth in developed countries could also be explored. Thus, standardisation of scenario narratives and drivers has advantages, but can also risk narrowing the scenario space that is explored by the literature. Consequently, many studies in the literature have adopted other socio-economic assumptions, for example with regard to population and GDP (Kriegler et al. 2016; Gillingham et al. 2018) and sustainable development trends (Soergel et al. 2021).

Technology availability and costs: Technology assumptions are a key component of IAMs, with some models representing hundreds or thousands of technologies. Despite the importance of technology costs (Creutzig et al. 2017), there has been limited comparison of technology assumptions across models (Krey et al. 2019; Kriegler et al. 2015a). There is, however, a substantial literature on the sensitivity of mitigation scenarios to technology assumptions, including model comparisons (Kriegler et al. 2014a; Riahi et al. 2015), single model sensitivity studies (McJeon et al. 2011b; Krey and Riahi 2013; Giannousakis et al. 2021) and multi-model sensitivity studies (Bosetti et al. 2015). Not only are the initial technology costs important, but also how these costs evolve over time either exogenously or endogenously. Since IAMs have so many interacting technologies, assumptions on one technology can affect the deployment of another. For example, limits on solar energy expansion rates, or integration, may lead to higher levels of deployment for alternative technologies. Because of these interactions, it can be difficult to determine what factors affect deployment across a range of models.

Within these key scenario design choices, model choice cannot be ignored. Not all models can implement aspects of a scenario or implement in the same way. Alternative target implementations are difficult for some model frameworks, and implementation issues also arise around technological change and policy implementation. Certain scenario designs may lock out certain modelling frameworks. These issues indicate the need for a diversity of scenario designs (Johansson et al. 2020) to ensure that model diversity can be fully exploited.

It is possible for many assumptions to be harmonised, depending on the research question. The SSPs were one project aimed at increasing harmonisation and comparability. It is also possible to harmonise emission data, technology assumptions, and policies (Giarola et al. 2020). While harmonisation facilitates greater comparability between studies, it also limits scenario and model diversity. The advantages and disadvantages of harmonisation need to be discussed for each model study.

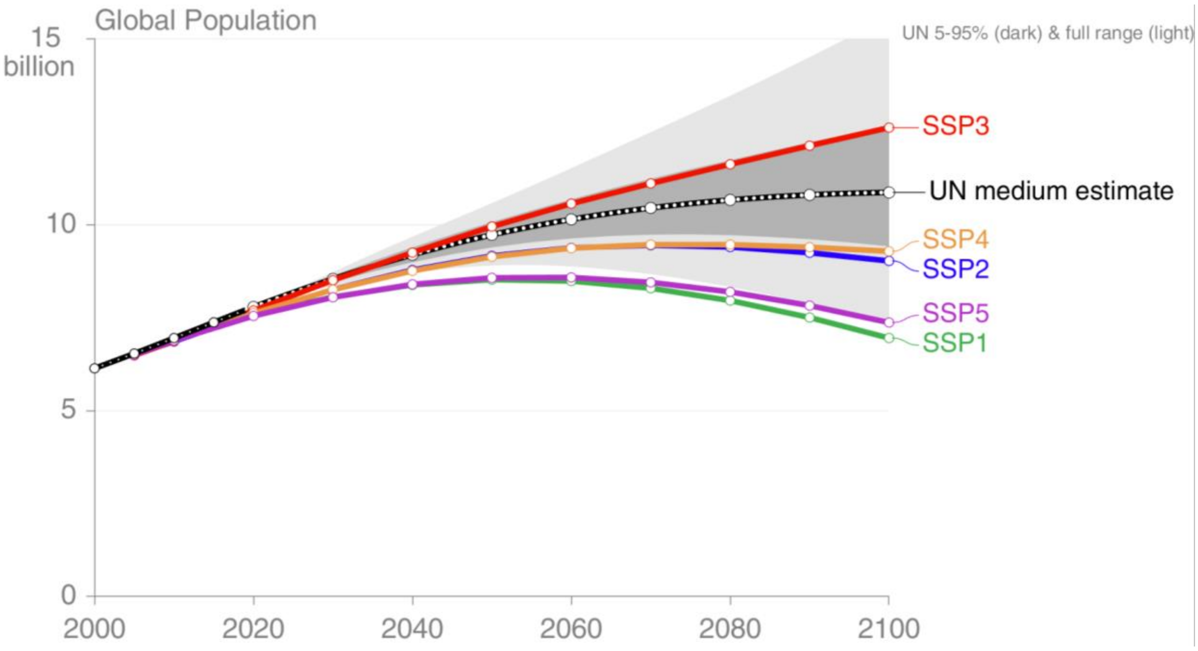

Figure II.2: Population projections from the SSPs compared to the UN estimates. Source: Riahi et al. (2017), Rogelj et al. (2018a) and SSP Database (version 2).

II.2. Use of scenarios in the assessment

II.2.1. Use of scenario literature and database

The WGIII assessment draws on the full literature on mitigation scenarios. To support the assessment, as many as possible mitigation scenarios in the literature were collected in a scenario database with harmonised output reporting (see Section II.3. WG III AR6 scenario database). The collection of mitigation pathways in a common database is motivated by a number of reasons: First, to establish comparability of quantitative scenario information in the literature which is often only sporadically available from tables and figures in peer-reviewed publications, reports and electronic supplementary information. Moreover, this information is often reported using different output variables and definitions requiring harmonisation. Second, to increase latitude of the assessment by establishing direct access to quantitative information underlying the scenario literature. Third, to improve transparency and reproducibility of the assessment by making the quantitative information underlying the scenario figures and tables shown in the report available to the readers of AR6. The use of such scenario databases in AR5 of WG III (Krey et al. 2014) and SR1.5 (Huppmann et al. 2018) proved its value for the assessment as well as for broad use of the scenario information by researchers and stakeholders. This is now being continued for AR6.

II.2.2. Illustrative pathways

In the IPCC Special Report on 1.5°C Warming, illustrative pathways (IPs) were used in addition to scenario ranges to assess and communicate the results from the scenario literature. While ranges express the spread in scenario outcomes highlighting uncertain vs. robust outcomes, IPs can be used to contrast different stories of mitigating climate change (Rogelj et al. 2018a). IPs have also been selected for the assessment in WG3, AR6.

The IPs were selected by representatives from each chapter in AR6. They focus on changes in scenario characteristics as a function of 1) the level of ambitious of climate policy, 2) the different mitigation strategies, 3) timing of mitigation actions and 4) the combination of climate policy with sustainable development policies. The IPs consists of a narrative – as well as possible quantifications. The selection of the IPs is preliminary and for use in the SOD and may thus change in the future. The IPs are illustrative and denote implications of different societal choices for the development of future emissions and associated transformations of main GHG emitting sectors. For Chapter 3, for each of the IPs a quantitative scenario was selected from the AR6 scenario database to have particular characteristics and from diverse modelling frameworks.

One IP follows current policies as formulated around 2018 (Current Policies, CurPol) through to 2030 and follows a similar mitigation effort to 2100. This IP leads to about 3-4 degree C warming at the end of the century, A second follows emission pledges to 2030 (NDCs) and then continues with moderate climate action over time (Moderate Action, ModAct). The remaining IPs are deep mitigation pathways consistent with a 66% chance of limiting warming to 2°C (<2) or a 50% change of limiting warming to 1.5°C by 2100 (1.5). These scenarios respectively focus on supply side measures (<2-SUP, 1.5-SUP), no net negative CO_2 emissions (Never Below Zero, <2-NBZ, 1.5NBZ), renewable electricity (<2-Ren, 1.5-Ren), low energy demand (1.5-LD), and gradual strengthening beyond NDC ambition levels until 2030 (<2C-GS). All these scenarios follow the SSP2 socioeconomic assumptions. There is one additional scenario, following SSP1 socio-economic assumptions and strengthened sustainable development trends, called Shifting Pathways (1.5-SP). The IPs are discussed further in Chapter 1.3, Chapter 3.2 and the respective sector chapters.

Table II.1: The storylines for the eleven Illustrative Pathways (IPs) considered in IPCC WG3.

		General characteristics	Policy	Innovation	Energy	Land use, food biodiversity	Lifestyle
CurPol		Continuation of current policies and trends;	- Implementation of current climate policies and neglect of stated goals and objectives; - Grey Covid recovery (focus on economic stimulus to incumbent industries).	Business-as-usual; slow progress in low-carbon technologies	Fossil fuels remain important; lock-in	Further expansion of western diets; further slow expansion of agriculture area	Demand will continue to grow; no significant changes in current habits
ModAct		NDCs in 2030; fragmentated policy landscape; post-2030 action consistent with modest action until 2030	- Strengthening of policies to implement NDCs and some further strengthening after 2030; - Mixed grey-green recovery.	Modest change compared to CurPol	Mostly moving away from coal; growth of renewables; some lock-in in fossil investments	Afforestation/reforestation policies as in NDcs	Modest change compared to CurPol
1.5/<2	**Sup**	Mitigation in all sectors, includes also heavy reliance on net negative emissions (supply-side)	Successful international climate policy regime with focus on long-term climate target	Further development of CDR options;	CDR forms part of energy mix.	Afforestation/reforestation, BECCS, increased competition for land	Not critical – some induced via price increases
	NBZ	Still some CDR– but no net negative emissions at the global scale (never below zero)	Successful international climate policy regime – globally not allowing net negative emissions to offset earlier emissions		CDR still forms part of the energy mix – but only to offset residual emissions.	Still some CDR	Not critical – some induced via price increases

	Ren	Rapid deployment and technology development of renewables; electrification;	Successful international climate policy regime; policies and financial incentives favouring renewable energy	Rapid further development of innovative electricity technologies and policy regimes	Renewable energy, electrification – also in transport; sector coupling; storage or power-to-X technologies; better interconnections		Service provisioning and demand changes to better adapt to high RE supply
	LD	Reduced demand leads to early emission reductions		Social innovation; efficiency; across all sectors	Demand reduction; modal shifts in transport; rapid diffusion of BAT in buildings and industry	Lower food and agricultural waste; less meat-intensive lifestyles	Service provisioning and demand changes; behavioural changes
	GS	Mitigation action is gradually strengthened until 2030 compared to NDCs, but a gap remains to immediate action	Until 2030, mostly current NDCs are implemented – but move towards strong, universal regime > 2030		Similar as Sup, but with some delay.	Similar as Sup, but with some delay.	
	SP	***Shifting pathways.*** Major transformations shift development towards sustainability, including deep GHG emissions reduction	SDG policies in addition to Paris consistent climate action (international transfers; poverty reduction; healthy diets, environmental protection)		Demand reduction; renewable energy	Lower food and agricultural waste; less meat-intensive lifestyles; afforestation.	Service provisioning and demand changes

II.2.3. Treatment of scenario uncertainty

The calls for scenarios issued in preparation of this assessment report allowed to collect a large ensemble of scenarios, coming from many modelling teams using various modelling frameworks in many different studies. Although large ensembles of scenarios were gathered, it should be acknowledged that only a portion of the full uncertainty space is investigated, and that scenarios ensembles distribution of results are an “artefact” of the context of the studies the scenarios were developed in. This introduces “biases” in the ensemble: (i) the topics of the scenario studies collected in the database determine coverage of the scenario space, with large model-comparison studies putting large weight on selected topics over lesser explored topics explored by individual models, (ii) low-emissions scenarios are over-represented in scenarios databases, compared to overlooked intermediate emissions levels (van Ruijven 2016), (iii) some models are more represented than others, (iv) only “optimistic” models (i.e. models finding lower mitigation costs) reach the lowest mitigation targets (Tavoni and Tol 2010), (v) more scenarios explore uncertainty associated with energy-supply technologies than with demand and behaviours. This list would have to be adapted to the ensembles collected. Where appropriate, sampling bias was recognised in the assessment, but formal methods to reduce bias were not employed due to conceptual limitations.

Furthermore, although it has been attempted to elicit scenario likelihoods from expert knowledge (Christensen et al. 2018), scenarios are difficult to associate with probabilities as they typically describe a situation of deep uncertainty (Grübler and Nakicenovic 2001). This and the non-statistical nature of the scenario ensemble collected in the database does not allow a probabilistic interpretation of the distribution of output variables in the scenario database. Throughout the report, descriptive statistics are used to describe the spread of scenario outcomes across the scenarios ensemble. The ranges of results and the position of scenarios outcomes relative to some thresholds of interest are analysed. In some figures, the median of the distribution of results is plotted together with the interquartile range and possibly other percentiles (5th-10th-90th-95th) to facilitate the assessment of results. This needs to be done with caution to avoid a statistical interpretation of these ranges.

II.2.4. Scenario approaches to connect WG III with the WG I and WG II assessments

II.2.4.1. Assessment of WG III scenarios building on WG I physical climate knowledge

A transparent emission scenario climate assessment pipeline has been set up across WG I and WG II to ensure integration of assessment results across the two working groups This pipeline consists of a step where emissions scenarios are harmonised with the historical record, a step in which missing species are transparently filled in, and a step in which the emission evolutions are assessed with a suit of climate model emulators (see Section I.8 Reduced complexity climate modelling) calibrated to the WG1 assessment. These three steps ensure a consistent and comparable assessment of the climate response to emission scenarios in the literature

Harmonisation: Given that IAMs may use slightly different historical datasets, emission scenarios submitted to the AR6 WG3 scenario database (see Section II.3. WG III AR6 scenario database) are harmonised against a common source of historical emissions with the aneris scientific software package (Gidden et al. 2018). The harmonisation is performed so that different climate futures resulting from two different scenarios are a result of different future emission evolutions within the scenarios, not due to slightly different historical definitions and starting points. Emissions are harmonised to 2015 values based on (Hoesly et al. 2018; van Marle et al. 2017; Velders et al. 2015; Quéré et al. 2016; Gütschow et al. 2016) and inverse emissions from (Meinshausen et al. 2020), using aneris’ default settings. CO_2 from energy and industrial processes and CO_2 from agriculture, forestry, and land use change were harmonised separately. All other emissions species are harmonised based on the total reported emissions per species. In the case that emissions input is not reported in 2015, the emissions offset between historical and modelled emissions in 2010 is used to determine the harmonisation method.

Infilling missing species: Infilling ensures that scenarios include all relevant anthropogenic emissions for an accurate climate assessment given that not all IAMs report all emission species. Infilling is performed using the silicone software package (Lamboll et al. 2020). Missing species that are not reported for a specific scenario, are infilled based on the relationships between species as found in the harmonised set of all scenarios reported to the WG III scenario database. As a minimum, submitted scenarios required either total CO_2 emissions or CO_2 from energy and industrial processes (E&IP). By applying silicone's default Quantile Rolling Window method described in (Lamboll et al. 2020), up to 21 species can be infilled, including aerosol precursor emissions, greenhouse gases and volatile organic compounds, plus CO_2 emissions from agriculture, forestry and other land use. Total CO_2 is applied as the lead gas, and E&IP CO_2 is used if the former is not available.

WG I-calibrated emulators: The WG I emulators' probabilistic parameter ensembles are derived such that they match a range of key climate metrics assessed by WG1 and the extent to which agreement is achieved is evaluated (WG I cross-chapter Box 7.1). Of particular importance to this evaluation is the verification against the WG I temperature assessment of the five scenarios assessed in Chapter 4 of WG1 (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5). The inclusion of the temperature assessment as a benchmark for the emulators provides the strongest verification that WG3's scenario classification reflects the WG I assessment.

The evaluation of the emulators against the WG I assessment ensures that emulator differences are clearly explained. The comprehensive nature of the evaluation is a clear improvement on previous reports and ensures that multiple components of the emulators, from their climate response to effective radiative forcing through to their carbon cycles, have been examined before they are deemed fit for use by WG3.

Using expert judgement, emulators that reproduce the best estimates and uncertainties of the majority of WG I assessed metrics are recommended for scenario classification use by WG3. MAGICC7 and FaIR1.6 are currently recommended (see WG1 cross-chapter Box 7.1). Due to technical limitations, the SOD deadlines and the requirement for emulators to be in line with the latest available WG I assessment, only MAGICC7 is presently used for scenario classification in the SOD. When FaIR1.6 and Cicero-SCM results will become available they will be used alongside MAGICC7 to improve the understanding of the uncertainties involved in the scenario classification process, particularly those due to climate model uncertainty.

Scenario climate assessment: For the WG III scenario climate assessment, emulators are run hundreds of times per scenario, sampling from an emulator-specific probabilistic parameter set, which incorporates carbon cycle and climate system uncertainty in line with the WG I assessment. The emulator output is reported as percentiles from the full set of ensemble member runs in the AR6 scenario database. Percentiles for different output variables provide information about the spread in individual variables for a given scenario, but as a set do not form a consistent climate change projection. These are represented by individual ensemble member runs which however are not separately reported in the AR6 scenario database. The emulators provide an assessment of GSAT, peak warming, year of peak warming, ocean heat uptake, atmospheric CO_2, CH_4 and N_2O concentrations and effective radiative forcings from a range of species including CO_2, CH_4, N_2O and aerosols for each emissions scenario. The climate emulator's GSAT projections are in line with the WG1 climate assessment and normalised to match the WG1 Ch.2 assessed total warming between 1850-1900 and 1995-2014 of 0.84°C. These projections are used for classifying the WG III scenarios based on their temperature implications (see Section II.3.2. Global pathways).

An estimate of CO_2 and non-CO_2 induced warming is also provided. The estimate is calculated by performing two extra experiments for each scenario for each of the climate emulator ensemble members, one in which only anthropogenic climate forcers are considered and one in which only CO2 forcing is considered. The CO_2 forcing experiment quantifies the CO_2-induced warming and the difference between the anthropogenic experiment and the CO_2 experiment quantifies the anthropogenic non-CO_2 induced warming. Due to feedbacks and non-linearities within the climate system, the sum of the diagnosed CO_2 and non-CO_2 induced warming does not exactly add up to the total warming in each scenario. For completeness, we also report the residual (which approximately quantifies the impact of these non-linearities and feedbacks as well as the impact of natural climate forcers). The residual is on the order of 0.05°C.

II.2.4.2. Relating the WG II and WG III assessments by use of warming levels

WG II is adopting common climate dimensions to facilitate consistent communication of impacts and synthesis, as well as to integrate with WG I and WG III (AR6 WGII Cross-Chapter Box 1.1). The common climate dimensions will be used to analyse, present and communicate observed and projected climate change impacts across WGII. They include (1) adoption of a common range of global warming levels (GWLs) from WGI, (2) assessment of how impacts at given GWLs depend on level of exposure/vulnerability, level of adaptation, and time period, (3) adoption of common ranges for other climate variables as needed (e.g., sea-level rise), (4) adoption of common regional climates as needed, and (5) a climate information translation resource for WG II use that maps climate variable levels to climate projections (e.g., RCPs, SSPx-y, SRES) and vice versa. Common socioeconomic dimensions are not being adopted in WG II due to a desire to draw on the full literature, inform the broad ranges of relevant possibilities (climate, development, adaptation, mitigation), and be flexible. The impacts literature is wide-ranging and diverse, with a fraction based on global socioeconomic scenarios. WGII's approach allows chapters and cross-chapter boxes to assess how impacts and ranges depend on socioeconomic factors affecting exposure, vulnerability, and adaptation independently as appropriate for their literature. For example, WG II Chapter 16 assesses how Representative Key Risks vary under low vs. high exposure/vulnerability conditions by drawing on SSP-based impact literature.

WG II's common GWL range is based on AR6 WGI's "Tier 1" dimensions of integration range – 1.5, 2.0, 3.0, and 4.0˚C (relative to the 1850 to 1900 period) – and will be used as a key WGII dimension of integration for impacts studies. However, GWL bands are needed in WG II to map to the diverse temperature levels and projections found across WG II's literature. Within WG II, use of GWLs facilitates comparison of climate states across climate change projections, assessment of the full impacts literature, and cross-chapter comparison. Across AR6, use of GWLs facilitates integration across WGs of climate change projections, climate change risks, adaptation opportunities, and mitigation.

For facilitating integration with WG III, GWLs need to be related to WG III's classification of mitigation efforts by temperature outcome. WG III's Chapter 3 groups full century emissions projections resulting from a large set of assessed mitigation scenarios into temperature classes (see Sections II.2.4.1. Assessment of WG III scenarios building on WG I physical climate knowledge, II.3.2.1. Temperature classification of global pathways, Chapter 3.3). Scenarios are classified by median peak global average temperature increase in the bands <2°C, 2-2.5°C, 2.5-3°C, and >3°C, with the range below 2°C broken out in greater detail. Estimates of the temperature response to emissions projections are attached with uncertainty. WG3 uses estimates of the median (50th percentile) and 67th percentile warming to classify mitigation scenarios, but actual warming outcomes can be lower or higher within the range of the estimated uncertainty. WG II's GWL bands and WG III's peak warming bands thus differ in terms of definition (transient GWL vs. median peak warming through 2100). The WG III scenario assessment is using additional classifications relating to, inter alia, near term policy developments, technology availability, energy demand, population and economic growth (see Section

II. 3.2.2. Additional classifications of global pathways, Chapter 3.3), and a set of illustrative pathways with varying socio-techno-economic assumptions (see Section II.2.2. Illustrative pathways, Chapter 3.2). Synthesising WG II assessments of climate change impacts and WG III assessments of climate change mitigation efforts for similar GWLs / peak warming levels will have to address how socio-techno-economic conditions affect impacts, adaptation, and mitigation outcomes. Furthermore, a synthesis of mitigation efforts and mitigation benefits in terms of avoided climate change impacts would require the use of similar reference scenarios and socioeconomic development assumptions, for consistency (O'Neill et al. 2020) (Cross WG-box "Economic benefits from avoided climate impacts along long-term mitigation pathways").

II.3. WG III AR6 scenario database

As for previous IPCC reports of Working Group III, including the Special Report on 1.5 degrees (SR1.5) (Huppmann et al. 2018; Rogelj et al. 2018a) and the Fifth Assessment Report (AR5) (Clarke et al. 2014; Krey et al. 2014), quantitative information on mitigation pathways is collected in a dedicated AR6 scenario database[f] to underpin the assessment.

By the time of the SOD (December 2020) the AR6 scenario database comprises 140 modelling frameworks – 61 globally comprehensive, 60 national/regional s, and 19 sectoral models – with in total 2,266 scenarios, summarised in Table II.3 and Table II.4 (global mitigation pathways), Table II.5 (national and regional mitigation pathways) and Table II.6 (sector transition pathways) below. The studies submitting these scenarios are summarised in factsheets in the Supplementary Material to this Annex.

[The AR6 scenario database will be open for submission of new scenarios until January 2021. Section II.3 will be updated in FGD to reflect the final status of the database.]

II.3.1. Process of scenario collection and vetting

To facilitate the AR6 assessment, modelling teams were invited to submit their available emissions scenarios to a web-based database hosted by the International Institute for Applied Systems Analysis (IIASA)[g]. The co-chairs of Working Group III as well as a range of scientific institutions, including the Integrated Assessment Modelling Consortium (IAMC), University of Cape Town (UCT) and the Centre International de Recherche sur l'Environnement (CIRED), support the open call for scenarios which is subdivided into four dedicated calls,

1. a call for global long-term scenarios to underpin the assessment in chapter 3 as well as facilitating integration with sectoral chapters 6, 7, 8, 9, 10 and 11,
2. a call for short- to medium-term scenarios at the national and regional scale underpinning the assessment in chapter 4, and
3. a call for building-focused scenarios to inform the assessment in chapter 9, and
4. a call for transport-focused scenarios to inform the assessment in chapter 10.

A common data reporting template with a defined variable structure was used and all teams were required to register and submit detailed model and scenario metadata. Scenarios were required to come from a formal quantitative model and the scenarios must be published in accordance with IPCC literature requirements. The calls for scenarios were open for a period of 16 months (Sept 2019-Jan 2021), with updates possible until July 2021 in line with the literature acceptance deadline. The data

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FOOTNOTE: [f] https://data.ene.iiasa.ac.at/ar6-scenario-submission/
FOOTNOTE: [g] https://data.ene.iiasa.ac.at/ar6-scenario-submission/#/about

submission process included various quality control procedures to increase accuracy and consistency in reporting. Additional categorisation and processing of metadata over the full database provided a wide range of indicators and categories that were made centrally available to Lead Authors of the Report to enhance consistency of the assessment, such as: climate, policy and technology categories; characteristics about emissions, energy, socioeconomics and carbon sequestration; metadata such as literature references, model documentation and related projects.

For all scenarios reporting global data, a vetting process is undertaken to ensure that key indicators are within reasonable ranges for the baseline period – primarily for indicators relating to emissions and the energy sector (Table II.2). As part of the submission process, model teams were contacted individually with information on the vetting outcome with regard to their submitted scenarios giving them the opportunity to verify the reporting of their data. Checks on technology-specific variables for nuclear, solar & wind and CCS screen not only for accuracy with respect to recent developments, but also indicate reporting errors relating to different Primary Energy accounting methods. Whilst the criteria ranges appear to be large, the focus of these scenarios is the medium-long term and there is also uncertainty in the historical values. For vetting of illustrative pathways, the same criteria were used, albeit with narrower ranges (Table II.2). Future values were also assessed and reported to Lead Authors, but not used as exclusion criteria. Where possible we used latest values available, generally 2018, and if necessary extrapolated to 2020 as most models report only at 5-10 year intervals. 2020 as reported in the scenarios does not include the impact of the COVID-19 pandemic.

Around two thirds of submitted scenarios passed the vetting. The remaining third comprised a fraction of scenarios that were rolled over from the SR1.5 database, and were no longer up-to-date with recent developments (excluding the COVID shock). This included scenarios that started stringent mitigation action already in 2015. Other scenarios were expected to deviate from historical trends due to their diagnostic design.

Table II.2. Summary of the vetting criteria and ranges applied to the global scenarios for the climate assessment and preliminary screening for Illustrative Pathways. N.B. rows do not sum to the same total of scenarios as not all scenarios reported all variables. *[Final # of models and scenarios will be updated for the FGD].*

	Reference value	Range (IP range)	Pass	Fail
Historical Emissions (sources: EDGAR vIPCC and CEDS, 2018 value)				
CO_2 total (EIP + AFOLU)	43792-43897 MtCO_2/yr	±40% (±20%)	1439	29
CO_2 EIP	37037-37525 MtCO_2/yr	±20% (±10%)	1456	22
CH_4 emissions	350.0-399.1 MtCH_4/yr	±40% (±20%)	1396	8
CO_2 EIP 2010-2020 % change	-	+0 to |+50%	1398	59
CCS from Energy 2020	-	0-250 Mt CO_2/yr	1242	87
Historical Energy production (sources: IEA 2019; IRENA; BP; EMBERS; trends extrapolated to 2020)				
Primary Energy (2020, IEA)	578 EJ	±20% (±10%)	1394	0
Electricity Nuclear (2020, IEA)	9.77 EJ	±30% (±15%)	1299	230
Electricity Solar & Wind (2020. IEA, IRENA, BP, EMBERS).	8.51 EJ	±50% (±25%)	1171	358
Overall			**1065**	**450**
Future criteria (not used for exclusion in climate assessment but flagged to authors as potentially problematic)				
No net negative CO_2 emissions before 2030	CO_2 total in 2030 >0		1474	4
CCS from Energy in 2030	< 2000 Mt CO_2/yr		1186	143
Electricity from Nuclear in 2030	< 20 EJ/yr		1235	205

II.3.2. Global pathways

Almost 1600 global scenarios were submitted to the scenario database, 1065 passed the vetting criteria. Scenarios were submitted by both individual studies and model inter-comparisons (see factsheets in the Supplementary Material to this Annex). The main model inter-comparisons submitting scenarios are shown in Table II.3. Model inter-comparisons have a shared experimental design and assess research questions across different modelling platforms to enable more structured and systematic assessments. The model comparison projects thus help to understand the robustness of the insights.

The number of submitted scenarios varies considerably by study, e.g. from 90 to over 300 scenarios for the model inter-comparison studies (Table II.3). The numbers of scenarios also varies substantially by model (Table II.4), reinforcing the discussion of sampling bias in Section II.2.3. Treatment of scenario uncertainty

Table II.3. Model inter-comparisons providing emission scenarios that are assessed in Chapter 3.

[Scenario numbers to be confirmed in FGD]

Project/model comparison	Description	Duration	Key references	Website	Number of scenarios in the database
SSPs	The SSPs are part of a new framework that the climate change research community has adopted to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation.	2013-2016	(Riahi et al. 2017; Rogelj et al. 2018b; Gidden et al. 2019a)	https://tntcat.iiasa.ac.at/SspDb	121
ADVANCE	ADVANCE developed a new generation of advanced IAMs and applied the improved models to explore different climate mitigation policy options in the post-Paris framework.	2013-2016	(Luderer et al. 2018; Vrontisi et al. 2018)	http://www.fp7-advance.eu/	93
CD-LINKS	Exploring the complex interplay between climate action and development, while simultaneously taking both global and national perspectives and thereby informing the design of complementary climate-development policies.	2015-2019	(McCollum et al. 2018b; Roelfsema et al. 2020)	https://www.cd-links.org/	127
COMMIT	Exploring new climate policy scenarios in different parts of the world based on team modelling groups worldwide	2017-2020	(van Soest et al. 2020)	https://themasites.pbl.nl/commit/	116
ENGAGE	Exploring new climate policy scenarios in different parts of the world	ongoing	(Riahi et al. 2021)	http://www.engage-climate.org/	323
EMF30	Energy Modelling Forum study into the role of non-CO_2 climate forcers	2015-2019	(Smith et al. 2020; Harmsen et al. 2020b)	https://emf.stanford.edu/projects/emf-30-short-lived-climate-forcers-air-quality	149
EMF33	Energy Modelling Forum study into the role of bioenergy	2015-2019	(Rose et al. 2020; Bauer et al. 2020a)	https://emf.stanford.edu/projects/emf-33-bio-energy-and-land-use	181

II.3.2.1. Temperature classification of global pathways

The global long-term pathways underpinning the assessment in Chapter 3, to the degree possible, have been classified by the temperature goal that they correspond to, i.e. “1.5°C with no or low OS”, “1.5°C with high OS”, “likely 2°C”, “median 2°C”, “below 2.5°C”, “below 3.0°C”, and “above 3.0°C”. The first four of these categories correspond to the ones used in the IPCC SR1.5 (Rogelj et al. 2018a) while the latter three have been added as part of the AR6 to capture a broader set of temperature goals. Finally, a number of pathways could not be evaluated in terms of their temperature outcomes, either because of missing information or due to an insufficient time horizon. Table II.4 shows the climate outcomes of the full scenario set (without vetting). For numbers relating to vetted scenarios refer to the main text of Chapter 3, Section 3.2.

Table II.4. Global mitigation pathways by modelling framework and climate category. *[Final # of models and scenarios will be updated for the FGD]*.

Model group	**C1: 1.5°C with no or low OS**	**C2: 1.5°C with high OS**	**C3: likely 2°C**	**C4: median 2°C**	**C5: below 2.5°C**	**C6: below 3.0°C**	**C7: above 3.0°C**	**No climate assessment**	**Grand Total**
AIM/CGE	20	7	52	15	28	11	47	12	192
BET		3	4	4	2	2	1		16
C3IAM						2	7		9
COFFEE			1						1
COPPE-COFFEE	1	5	19	13	26	6	6		76
C-ROADS-5.005	3	2					1		6
DNE21+	6		8	6	4	3	9	13	49
EDGE-Buildings								16	16
En-ROADS-96	2						1		3
ENV-Linkages								15	15
EPPA			3	4		1	2		10
FARM							13		13
GAINS-dw4								2	2
GCAM	6	2	15	4	16	8	23		74
GEM-E3	7	4	4				2	11	28
GENeSYS-MOD								2	2
GMM-17								4	4

GRAPE-15			1		7	9	1		18
HEB								2	2
IEA ETP								1	1
IEA WEM			1					1	2
IMACLIM			3	1	6	1		48	59
IMAGE	9	2	28	12	17	12	31	7	118
LUT-ESTM								1	1
MAgPIE								3	3
McKinsey								3	3
MERGE-ETL			1		1		1		3
MESSAGE		1	4	3			1	1	10
MESSAGE-GLOBIOM	2	4	15	7	10	2	18		58
MESSAGEix-GLOBIOM	1	9	19	14	29	11	12	2	97
MESSAGE-Transport								3	3
MIGRATION	2					4	4	25	35
POLES	18	15	32	11	20	8	19		123
PROMETHEUS								9	9
REmap								2	2
REMIND	9	16	35	2	3	9	34	15	123
REMIND-Buildings								4	4
REMIND-EDGET			8		1	1			10
REMIND-MAgPIE	18	23	57	10	20	11	22		161
REMIND-Transport			20			2	6		28
Shell								1	1
TIAM-ECN	6	2	18	2	5	4	3	13	53
TIAM-Grantham			10				1		11
TIAM-UCL			2				1		3
TIAM-WORLD			1		4	4	2		11
WITCH	5	1	24	10	14	5	5		64

WITCH-GLOBIOM	4	2	9	4	8	7	25	3	62
Grand Total	**119**	**98**	**394**	**122**	**221**	**123**	**298**	**219**	**1594**

II. 3.2.2. Additional classifications of global pathways

[Discussion to be extended in FGD]

In addition to their temperature outcome, global pathways have a large number of other characteristics that are important for the WG3 assessment. Therefore, metadata on a number of key characteristics has been added to the database and has been used for analysis. These characteristics include:

- Socio-economic characteristics. Scenarios were classified as high, medium and low for population and economic growth based on a comparison with the assumed growth rates in the SSPs.
- Energy system characteristics. Scenarios have also been classified regarding a number of key energy system characteristics including energy demand (very low, low, medium, high and very high), the contribution of renewables, bio-energy, nuclear power, and CCS.
- Climate policy characteristics. A critical characteristic is the use of net negative emissions. Therefore scenarios were also classified on the basis of low, medium and high cumulative net negative emissions.
- The scenarios were also classified on the basis of assumptions regarding climate policy. Some scenarios are mostly meant for diagnostic purposes and classified as such. A second set of scenarios represents the situation in absence of climate policy. These scenarios (which are mostly used as counterfactual) have been classified as baseline scenarios. A third set of scenarios represent current policies. These are classified in various subclasses representing current policies, stated objectives (pledges) as well as scenarios that are particularly designed to explore specific assumed policies. For each of these categories, additional assumption for post- 2030 can be made. Finally, the largest set of scenarios represents immediate action (= as of 2020) scenarios that explore various climate targets. Many of these scenarios describe cost-effective pathways to achieve the targets.

II. 3.3. National and regional pathways

National and regional pathways have been collected in the AR6 scenario database to support the Chapter 4 assessment. To date, more than 500 pathways for 27 countries/regions have been submitted to the AR6 scenario database by integrated assessment, energy-economic and computable general equilibrium modelling research teams. This represents a limited sample of the overall literature on mitigation pathways at the national level. The majority of these pathways originate from a set of larger model intercomparison projects, JMIP/EMF35 (Sugiyama et al. 2020) focusing on Japan, CD-LINKS (Schaeffer et al. 2020; Roelfsema et al. 2020), COMMIT (van Soest et al. 2020), ENGAGE (Fujimori et al. 2020b), each covering several countries/regions from the following set of countries: Australia, Brazil, Canada, China, EU-28, India, Indonesia, Japan, Korea, Russia, Thailand, USA, Vietnam. The remaining pathways stem from individual modelling studies that were submitted/collected (Table II.5).

Table II.5. National and regional mitigation pathways by modelling framework, region and scenario type.

[*Note to Reviewers: The final set of models and scenarios contributing to the assessment may still change as not all underlying studies have been accepted for publication. Also, scenarios that were submitted close to submission deadline for the SOD for technical reasons may not have been included in the SOD.]*

Region	Model	Current Policies	NDCs	Other	Total
ARG	IMACLIM-ARG		2	2	4
AUS	TIMES-Australia	1		7	8
BRA	BLUES-Brazil	2	2	16	20
BRA	COPPE_MSB-Brazil			8	8
BRA	IMACLIM-BRA			5	5
CAN	GCAM-Canada	1	1	4	6
CHE	STEM-Switzerland	1		10	11
CHN	AIM/Hub-China	2	2	14	18
CHN	GENeSYS-MOD-CHN			3	3
CHN	IPAC-AIM/technology-China	1	1	11	13
CHN	PECE-China			1	1
CHN	TIMES-China	1	1	4	6
ECU	ELENA-Ecuador			2	2
ETH	TIAM-ECN ETH	1		1	2
EU	JRC-EU-TIMES			8	8
EU	PRIMES	2	1	8	11
EU	REMIND_EU			12	12
FRA	TIMES-France			8	8
GBR	7see			11	11
IDN	AIM/Hub-Indonesia			1	1
IDN	DDPP Energy			4	4
IND	AIM/Enduse India	1	1	5	7
IND	AIM/Hub-India	1	1	7	9
IND	MARKAL-INDIA	2	3	13	18
JPN	AIM/CGE-Enduse-Japan			6	6
JPN	AIM/Enduse-Japan	3	3	55	61
JPN	AIM/Hub-Japan	2	3	50	55
JPN	DNE21-Japan		1	30	31
JPN	DNE21+ V.14 (national)	1	1	4	6
JPN	IEEJ-Japan		1	34	35
KEN	TIAM-ECN KEN	1	1	2	4
KOR	AIM/CGE-Korea	1	1	6	8
KOR	AIM/Hub-Korea	2	2	14	18
MDG	TIAM-ECN MDG		2	1	3
MEX	GENeSYS-MOD-MEX			4	4
PRT	TIMES-Portugal			8	8
RUS	RU-TIMES	2	2	9	13
SAU	KLEM-SAU			2	2
SWE	TIMES-Sweden			4	4
THA	AIM/Hub-Thailand	1	2	18	21
USA	GCAM-USA	2	1	10	13
USA	RIO-USA			12	12
VNM	AIM/Hub-Vietnam	1	2	20	23
ZAF	TIAM-ECN AFR			4	4
	Total	32	35	456	523

II. 3.4. Sector transition pathways

[Discussion to be extended in FGD]

Sectoral transition pathways based on the AR6 Scenario database are addressed in a number of Chapters, primarily Chapter 6 (energy systems), 7 (AFOLU), 9 (buildings) and 10 (transport). These analyses cover both contributions from global IAMs and from sector-specific models with regional or global coverage. The assessments cover a variety of perspectives, including long-term global and macro-region trends for the sectors, sectoral analysis of the Illustrative Pathways, and comparison of the scenarios between full-economy IAMs and sector-specific models on shorter time horizons. These perspectives have a bi-directional utility – to understand how well IAMs are representing sectoral trends from more granular models, and position sectoral models in the context of full economy transitions to verify consistency with different climate targets.

Table II.6. Overview of how models and scenarios were used in sectoral chapters. *[Final # of models and scenarios will be updated for the FGD]*

Sector	# models	# scenarios	Key sections	Key perspectives
Energy systems (Ch6)	58	393	6.6, 6.7	Energy and electricity system at net-zero; carbon intensity of electricity; investments; Final energy electrification; hydrogen
AFOLU (Ch7)	59	523	7.4, 7.5	Regional and global GHG emissions and land use dynamics; economic mitigation potential for different GHGs; integrated mitigation pathways
Buildings (Ch9)	51	53	9.3, 9.6	Regional and global GHG emissions with a breakdown per end use and energy carrier
Transport (Ch10)	5	18	10.7	Global transport system, modes, vehicles, fuels.

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Annex C: Scenarios and modelling methods

Supplementary Material

Coordinating Lead Authors: Celine Guivarch (France), Elmar Kriegler (Germany), Joana Portugal Pereira (Brazil)

Lead Authors: Valentina Bosetti (Italy), James Edmonds (the United States of America), Manfred Fischedick (Germany), Petr Havlik (Austria), Paulina Jaramillo (the United States of America), Volker Krey (Austria), Franck Lecocq (France), André Lucena (Brazil), Malte Meinshausen (Australia/Germany), Sebastian Mirasgedis (Greece), Brian O'Neill (the United States of America), Glen Peters (Norway/Australia), Joeri Rogelj (Belgium/UK), Steve Rose (the United States of America), Yamina Saheb (France/Algeria), Goran Strbac (United Kingdom), Anders Hammer Strømman (Norway), Detlef van Vuuren (the Netherlands), Nan Zhou (the United States of America).

Contributing Authors: Novikova Aleksandra (Germany), Cornelia Auer (Germany), Nico Bauer (Germany), Edward Byers (Austria/Ireland), Bruno Cunha (Brazil), Stefan Frank (Austria), Jan Fuglestvedt (Norway), Mathijs Harmsen (the Netherlands), Alan Jenn (the United States of America), Jarmo Kikstra (Austria/Finland), Paul Kishimoto (Canada), Robin Lamboll (United Kingdom), Julien Lefèvre (France), Eric Masanet (the United States of America), Craig Michael (the United States of America), Zebedee Nicholls (Australia), Simon Parkinson (Canada), Pedro Rochedo (Brazil), Sasha Samadi (Germany), Yeh Sonia (Sweden/the United States of America), David Vérez (Spain/Cuba).

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Supplementary Material to the Annex C

Part I: Scenario Study Factsheets

[The fact sheets collected for the SOD are preliminary and still contain placeholders. Those will be filled and the collection of factsheets updated in FGD to cover all studies that submitted scenarios to the AR6 scenario database]

The Sixth Assessment Report (AR6) of Working Group 3 assesses global and national climate change mitigation pathways in the literature. Global mitigation pathways are primarily assessed in Chapter 3 and national climate change mitigation pathways are primarily assessed in Chapter 4 of the report. The supplementary material presented here documents the scenarios that were submitted to the AR6 scenario database (see Chapter 3.2 and Annex C Part II.3) for the assessment. The submitting entities were scenario studies published in the literature. The presentation of scenarios in this supplement is organized study by study in terms of *Scenario study factsheets*.

The scenario studies are steered by a set of specific scientific questions and produce insights, accordingly. The factsheets provided in this document summarize the essential information about the individual studies. Hereby, great emphasis is applied that readers can transparently connect scenario and model information to publications summarizing the most important facts for alleviated access. A factsheet briefly summarizes by publication

- the associated publication(s),
- the guiding scientific questions,
- the results,
- the scenarios,
- the models.

The guiding scientific questions give an understanding which aspects were investigated in the study. The results summarize the central insights developed by the study. The list of scenarios used in the study helps to get an orientation in naming and specification of decisive parameters for individual scenarios. Finally, the list of participating models allows to understand which models contributed to the insights of the study.

The factsheets are structured as described below:

1) Global scenario studies with participation of multiple models;
2) Hybrid multi-model scenario studies with participation of global and national models;
3) Global scenario studies from a single model;
4) Sectoral scenario studies, including global and national scale;
5) National scenario studies;
6) Other studies that cannot be assigned to the categories above.

The benefit of this approach is as follows:

- The essential information of a scenario study outcome becomes easier digestible for users. Further, describing each study in the same format supports orientation and comprehension in this diverse spectrum of multiple studies.
- The essential research questions and outcomes can be quickly grasped. They are summed up in a very high-level, abstract manner, no details like technical approaches or similar are allowed; only the questions to be answered and the results through the eyes of an external person, i.e. a stakeholder.

- The factsheets are stand-alone and can be used in a modular way also allowing to utilize them in different contexts outside this document.

1. Global scenario studies with participation of multiple models

Those studies are usually model comparison studies with harmonized scenario assumptions across models and aim to explore robust features of mitigation pathways. They typically produce a larger set of scenarios than single model studies.

1.1 Shared Socio-economic Pathways (SSP)

1.1.1 Publications

- Van Vuuren, D. P., Riahi, K., Calvin, K., Dellink, R., Emmerling, J., Fujimori, S., Kc, S., Kriegler, E. & O'Neill, B. 2017. The Shared Socio-economic Pathways: Trajectories for human development and global environmental change. Global Environmental Change, 42, 148-152.
- Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L. A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J. C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A. & Tavoni, M. 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change, 42, 153-168.
- Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., Van Vuuren, D. P., Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M., Havlík, P., Humpenöder, F., Stehfest, E. & Tavoni, M. 2018. Scenarios towards limiting global mean temperature increase below 1.5 °c. Nature Climate Change, 8, 325-332.
- O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., Van Ruijven, B. J., Van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M. & Solecki, W. 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change, 42, 169-180.
- Kc, S. & Lutz, W. 2017. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Global Environmental Change, 42, 181-192.
- Dellink, R., Chateau, J., Lanzi, E. & Magné, B. 2017. Long-term economic growth projections in the Shared Socioeconomic Pathways. Global Environmental Change, 42, 200-214.
- Leimbach, M., Kriegler, E., Roming, N. & Schwanitz, J. 2017. Future growth patterns of world regions – A GDP scenario approach. Global Environmental Change, 42, 215-225.
- Crespo Cuaresma, J. 2017. Income projections for climate change research: A framework based on human capital dynamics. Global Environmental Change, 42, 226-236.
- Jiang, L. & O'Neill, B. C. 2017. Global urbanization projections for the Shared Socioeconomic Pathways. Global Environmental Change, 42, 193-199.
- Bauer, N., Calvin, K., Emmerling, J., Fricko, O., Fujimori, S., Hilaire, J., Eom, J., Krey, V., Kriegler, E., Mouratiadou, I., Sytze De Boer, H., Van Den Berg, M., Carrara, S., Daioglou, V., Drouet, L., Edmonds, J. E., Gernaat, D., Havlik, P., Johnson, N., Klein, D., Kyle, P., Marangoni, G., Masui, T., Pietzcker, R. C., Strubegger, M., Wise, M., Riahi, K. & Van Vuuren, D. P. 2017. Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives. Global Environmental Change, 42, 316-330.

- Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., Bodirsky, B. L., Dietrich, J. P., Doelmann, J. C., Gusti, M., Hasegawa, T., Kyle, P., Obersteiner, M., Tabeau, A., Takahashi, K., Valin, H., Waldhoff, S., Weindl, I., Wise, M., Kriegler, E., Lotze-Campen, H., Fricko, O., Riahi, K. & Vuuren, D. P. V. 2017. Land-use futures in the shared socio-economic pathways. Global Environmental Change, 42, 331-345.
- Rao, S., Klimont, Z., Smith, S. J., Van Dingenen, R., Dentener, F., Bouwman, L., Riahi, K., Amann, M., Bodirsky, B. L., Van Vuuren, D. P., Aleluia Reis, L., Calvin, K., Drouet, L., Fricko, O., Fujimori, S., Gernaat, D., Havlik, P., Harmsen, M., Hasegawa, T., Heyes, C., Hilaire, J., Luderer, G., Masui, T., Stehfest, E., Strefler, J., Van Der Sluis, S. & Tavoni, M. 2017. Future air pollution in the Shared Socio-economic Pathways. Global Environmental Change, 42, 346-358.
- Van Vuuren, D. P., Stehfest, E., Gernaat, D. E. H. J., Doelman, J. C., Van Den Berg, M., Harmsen, M., De Boer, H. S., Bouwman, L. F., Daioglou, V., Edelenbosch, O. Y., Girod, B., Kram, T., Lassaletta, L., Lucas, P. L., Van Meijl, H., Müller, C., Van Ruijven, B. J., Van Der Sluis, S. & Tabeau, A. 2017. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Global Environmental Change, 42, 237-250.
- Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., Ermolieva, T., Forsell, N., Herrero, M., Heyes, C., Kindermann, G., Krey, V., Mccollum, D. L., Obersteiner, M., Pachauri, S., Rao, S., Schmid, E., Schoepp, W. & Riahi, K. 2017. The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. Global Environmental Change, 42, 251-267.
- Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., Herran, D. S., Dai, H., Hijioka, Y. & Kainuma, M. 2017. SSP3: AIM implementation of Shared Socioeconomic Pathways. Global Environmental Change, 42, 268-283.
- Calvin, K., Bond-Lamberty, B., Clarke, L., Edmonds, J., Eom, J., Hartin, C., Kim, S., Kyle, P., Link, R., Moss, R., Mcjeon, H., Patel, P., Smith, S., Waldhoff, S. & Wise, M. 2017. The SSP4: A world of deepening inequality. Global Environmental Change, 42, 284-296.
- Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Bodirsky, B. L., Hilaire, J., Klein, D., Mouratiadou, I., Weindl, I., Bertram, C., Dietrich, J. P., Luderer, G., Pehl, M., Pietzcker, R., Piontek, F., Lotze-Campen, H., Biewald, A., Bonsch, M., Giannousakis, A., Kreidenweis, U., Müller, C., Rolinski, S., Schultes, A., Schwanitz, J., Stevanovic, M., Calvin, K., Emmerling, J., Fujimori, S. & Edenhofer, O. 2017. Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. Global Environmental Change, 42, 297-315.

1.1.2 Guiding questions

The SSPs are part of a scenario framework, established by the climate change research community in order to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation. The framework is built around a matrix that combines climate forcing on one axis (as represented by the Representative Concentration Pathways (RCPs)) and socio-economic conditions on the other. Together, these two axes describe situations in which mitigation, adaptation and residual climate damage can be evaluated.

1. In the absence of climate policy, how do scenarios based on the five different SSP narratives unfold in the future?
2. Across the different narratives, how does the challenge to climate mitigation compare when trying to limit global forcing levels consistent with those of the RCPs, going as low as 2.6W/m2?

1.1.3 Results

The SSPs are based on five narratives describing alternative socio-economic developments, including sustainable development, regional rivalry, inequality, fossil-fuelled development, and middle-of-the-road development. The long-term demographic and economic projections of the SSPs depict a wide uncertainty range consistent with the scenario literature. A multi-model approach was used for the elaboration.

1. The baseline scenarios lead to global energy consumption of 400–1200 EJ in 2100. The associated annual CO_2 emissions of the baseline scenarios range from about 25 $GtCO_2$ to more than 120 $GtCO_2$ per year by 2100.
2. With respect to mitigation, the scenarios show that associated costs strongly depend on three factors: (1) the policy assumptions, (2) the socio-economic narrative, and (3) the stringency of the target. The carbon price for reaching the target of 2.6 W/m2 that is consistent with a temperature change limit of 2 °C, differs in the analysis thus by about a factor of three across the SSP marker scenarios. Consistent with the narratives, mitigation costs and thus the challenge for mitigation is found lower in SSP1 & SSP4 relative to SSP3 & SSP5. Perhaps most importantly, we find that not all targets are necessarily attainable from all SSPs.

1.1.4 Scenarios

- SSP1-19
- SSP1-26
- SSP1-34
- SSP1-45
- SSP1-Baseline
- SSP2-19
- SSP2-26
- SSP2-34
- SSP2-45
- SSP2-60
- SSP2-Baseline
- SSP3-34
- SSP3-45
- SSP3-60
- SSP3-Baseline
- SSP4-26
- SSP4-34
- SSP4-45
- SSP4-Baseline
- SSP5-26
- SSP5-34
- SSP5-45
- SSP5-60
- SSP5-Baseline

1.1.5 Models

- AIM/CGE 2.0
- GCAM 4.2
- IMAGE 3.0.1
- IMAGE 3.2
- MESSAGE-GLOBIOM 1.0
- REMIND-MAgPIE 1.5
- WITCH-GLOBIOM 3.1

1.2 ADVANCE

1.2.1 Publications

- Luderer, G. et al. Residual fossil CO_2 emissions in 1.5–2 °C pathways. 2018. Nature Climate Change 8, 626–633.
- Vrontisi, Z. et al. Enhancing global climate policy ambition towards a 1.5 °C stabilization: a short-term multi-model assessment. 2018. Environ. Res. Lett. 13, 044039.

1.2.2 Guiding questions

The study aims to contribute the first multi-model assessment of Paris Agreement scenarios, exploring both the emission impacts of NDC until 2030 and strengthening scenarios that achieve the long-term targets of 2 or 1.5°C, with strengthening either after 2020 or 2030.

1. What energy system transformations are implied by nationally determined contributions (NDCs) for 2030, and how do they differ from transformations in cost-optimal pathways reaching the Paris Agreements (PA) long-term targets of well-below 2°C and 1.5°C?
2. How much residual emissions occur in different sectors in 2°C and 1.5°C scenarios, and what are the determinants for those?
3. What implications does failure to strengthen ambition before 2030 have for individual energy sectors and for achievability of the long-term targets?

1.2.3 Results

Aggregate NDC ambition level is not in line with long-term Paris Agreement targets. These targets require full decarbonization of energy system, for which electrification, decarbonization of power supply and increase in low-carbon fuels are required.

1. Aggregate NDC ambition level is not in line with long-term Paris Agreement (PA) targets, emissions gap to cost-optimal 2°C and 1.5°C pathways in 2030 already between 9-29 Gt CO_2eq;
2. Higher ambition would only lead to modest increases of mitigation cost (not accounting for avoided damages and co-benefits);
3. If countries fail to strengthen ambition before 2030, they lock-in more residual fossil emissions, which leads to a higher overshot of the net emissions budgets implied by the long-term targets, so that more carbon dioxide removal (CDR) is then needed to still meet the targets. On the other hand, failure to strengthen before 2030 also compromises the ability to scale-up negative emission options at tolerable costs.

1.2.4 Scenarios

- ADVANCE_2020_1.5C-2100
- ADVANCE_2020_Med2C
- ADVANCE_2020_WB2C
- ADVANCE_2030_Med2C
- ADVANCE_2030_Price1.5C
- ADVANCE_2030_WB2C
- ADVANCE_INDC
- ADVANCE_NoPolicy

- ADVANCE_Reference
- ADVANCE_WP2_IND-450-FullTech
- ADVANCE_WP2_IND-Base-FullTech
- ADVANCE_WP2_TRA-450-FullTech
- ADVANCE_WP2_TRA-Base-FullTech
- ADVANCE_WP2_TRA-Ctax-FullTech
- ADVANCE_2030_1.5C-2100
- ADVANCE_2020_1.5C-2100_WP6
- ADVANCE_2020_Med2C_WP6
- ADVANCE_2020_WB2C_WP6
- ADVANCE_2030_Med2C_WP6
- ADVANCE_2030_Price1.5C_WP6
- ADVANCE_2030_WB2C_WP6
- ADVANCE_INDC_WP6
- ADVANCE_NoPolicy_WP6
- ADVANCE_Reference_WP6

1.2.5 Models

- AIM/CGE 2.0
- AIM/CGE 2.2
- DNE21+ V.ADVANCE
- GCAM 4.2
- IMACLIM 1.1
- IMAGE 3.0
- IMAGE 3.0.1
- MESSAGE-GLOBIOM 1.0
- MESSAGE-Transport V.5
- POLES ADVANCE
- REMIND 1.7
- WITCH-GLOBIOM 4.2

1.3 Energy Modelling Forum 30 (EMF30)

1.3.1 Publications

- Smith, S. J., Klimont, Z., Drouet, L., Harmsen, M., Luderer, G., Riahi, K., … Weyant, J. P. 2020. The Energy Modeling Forum (EMF)-30 study on short-lived climate forcers: introduction and overview. *Climatic Change*, Vol. 163, pp. 1399–1408. https://doi.org/10.1007/s10584-020-02938-5
- Harmsen, M., van Vuuren, D. P., Bodirsky, B. L., Chateau, J., Durand-Lasserve, O., Drouet, L., … Wada, K. 2019. The role of methane in future climate strategies: mitigation potentials and climate impacts. *Climatic Change*, *163*(3), 1409–1425. https://doi.org/10.1007/s10584-019-02437-2

1.3.2 Guiding questions

The EMF30 project is designed to assess the impact of policies aiming at reducing short-lived climate forcers, namely CH_4 and BC/OC.

1. What is the impact of policies aiming at reducing short-lived climate forcers on emission reductions?

1.3.3 Results

We find that the health benefits of reduced air pollution of a coal exit by far exceed mitigation costs on a global level. Taking the same coal exit path and additionally introducing a 2°C consistent GHG budget shows that aggregated co-benefits almost compensate the additional cost.

1. Air pollution benefits and mitigation cost are regionally very heterogeneous with India and China yielding most of the resulting synergies.
2. Synergies are robust under different air pollution legislation scenarios, hence climate policy is a no-regret option for especially Asian countries.

1.3.4 Scenarios

- EMF30_BCOC-EndU
- EMF30_Baseline
- EMF30_CH4-Only
- EMF30_ClimPolicy
- EMF30_ClimPolicy+SLCF
- EMF30_D_BCOC-Red
- EMF30_D_CH4-ClimPolicy
- EMF30_D_CO2-Only
- EMF30_D_Frozen-CH4
- EMF30_D_Frozen-EF
- EMF30_D_Frozen-EF-EndU
- EMF30_D_Frozen-EF-SLCF
- EMF30_SLCF
- EMF30_Slower-Action

- EMF30_Slower-Action+SLCF
- EMF30_Slower-to-faster
- EMF30_Slower-to-faster+SLCF
- EMF30_Slower-to-faster+SLCF+HFC

1.3.5 Models

- AIM/CGE 2.0
- DNE21+ V.14E1
- ENV-Linkages 3.0
- GCAM 4.2
- IMAGE 3.0.1
- MESSAGE-GLOBIOM 1.0
- POLES EMF30
- REMIND 1.6
- WITCH-GLOBIOM 4.2

1.4 Energy Modelling Forum 33 (EMF33)

1.4.1 Publications

- Rose, S. K., Bauer, N., Popp, A., Weyant, J., Fujimori, S., Havlik, P., … van Vuuren, D. P. 2020. An overview of the Energy Modeling Forum 33rd study: assessing large-scale global bioenergy deployment for managing climate change. *Climatic Change*, Vol. 163, pp. 1539–1551. https://doi.org/10.1007/s10584-020-02945-6
- Bauer, N., Rose, S. K., Fujimori, S., Van Vuuren, D. P., Weyant, J., Wise, M., ... & Kitous, A. 2018. Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. Climatic Change, 1-16.

1.4.2 Guiding questions

Objective: Assessing large-scale global bioenergy deployment for managing climate change.

1. How is bioenergy used across different IAMs under harmonized variations of climate policies, availability of bioenergy technologies and constraints on biomass supply?

1.4.3 Results

1. Imposing a range of increasingly stringent carbon budgets mostly increases bioenergy use. Sector and regional bioenergy allocation varies dramatically mainly due to bioenergy technology options, final energy patterns and availability of alternative options of energy sector de-carbonization;
2. Although much bioenergy is used in combination with CCS (BECCS), it is not necessarily the driver of bioenergy use;
3. The flexibility to use biomass feedstocks in the energy sector makes large-scale bioenergy deployment a robust strategy in mitigation scenarios that is surprisingly insensitive with respect to reduced technology availability;
4. However, the impact on achievability of stringent carbon budgets and associated carbon prices is sensitive, if the availably of e.g. BECCS is reduced.

1.4.4 Scenarios

- EMF33_Baseline
- EMF33_Med2C_cost100
- EMF33_Med2C_full
- EMF33_Med2C_nobeccs
- EMF33_Med2C_nofuel
- EMF33_Med2C_none
- EMF33_WB2C_cost100
- EMF33_WB2C_full
- EMF33_tax_hi_full
- EMF33_tax_hi_none
- EMF33_tax_lo_full
- EMF33_tax_lo_none
- EMF33_1.5C_cost100

- EMF33_1.5C_full
- EMF33_1.5C_nofuel
- EMF33_Med2C_limbio
- EMF33_WB2C_limbio
- EMF33_WB2C_nofuel
- EMF33_1.5C_limbio
- EMF33_WB2C_nobeccs
- EMF33_WB2C_none

1.4.5 Models

- AIM/CGE 2.1
- BET EMF33
- DNE21+ V.14E2
- FARM 3.2
- GCAM 4.2
- GRAPE-15 1.0
- IMACLIM-NLU 1.0
- IMAGE 3.0.2
- MESSAGE-GLOBIOM 1.0
- POLES EMF33

1.5 Network for Greening the Financial System (NGFS)

1.5.1 Publications

- NGFS. 2019. A call for action: Climate change as a source of financial risk. First Comprehensive Report, Network for Greening the Financial System, Paris, France 42 pp. https://www.ngfs.net/sites/default/files/medias/documents/ngfs_first_comprehensive_report_-_17042019_0.pdf
- NGFS. 2019. Macroeconomic and financial stability: Implications of climate change. Technical supplement to the First NGFS Comprehensive Report, Network for Greening the Financial System, Paris, France, 51 pp. https://www.ngfs.net/sites/default/files/medias/documents/ ngfs-report-technical-supplement_final_v2.pdf
- NGFS. 2020. Guide for Supervisors – Integrating climate-related and environmental risks in prudential supervision. Network for Greening the Financial System, Paris, France, 62 pp. https://www.ngfs.net/sites/default/files/medias/documents/ ngfs_guide_for_supervisors.pdf
- NGFS. 2020. Guide for Supervisors Guide to climate scenario analysis for central banks and supervisors. Network for Greening the Financial System, Paris, France, 38 pp. https://www.ngfs.net/sites/default/files/medias/documents/ngfs_guide_scenario_analysis_final.pdf

1.5.2 Guiding questions

1. What scenarios can inform transition risk assessment for the financial sector?
2. What macroeconomic implications arise for the financial sector for the aspects of delayed vs. immediate action?
3. What macroeconomic implications arise for insufficient climate policies leading to a hot house world, i.e. following the NPis or NDCs?
4. What effect does reduced CDR availability have to the risk structure?

1.5.3 Results

Scenarios are used by actors in the finance sector to assess climate-related transition risk.

1.5.4 Scenarios | Models

In the NGFS report, IAM scenarios from other studies are re-named according to categories and pursued policies. Below we link the NGFS names to the original scenario names and their respective models.

- NGFS Category: Hothouse world – Current policies
    - NGFS_Current policies (Hot house world Rep)|GCAM 5.2
    - ENGAGE_NPi | MESSAGEix-GLOBIOM
    - PEP_NPi | REMIND-MAgPIE 1.7-3.0
- NGFS Category: Hothouse world – Nationally determined contributions (NDCs)
    - CD-LINKS_INDCi | MESSAGEix-GLOBIOM
    - PEP_NDC | REMIND-MAgPIE 1.7-3.0
- NGFS Category: Orderly – Immediate 2C scenario with CDR
    - NGFS_Immediate 2C with CDR (Orderly Rep)|GCAM 5.2
    - CD-LINKS_NPi2020_1000 | MESSAGEix-GLOBIOM
    - PEP_2C_full_eff | REMIND-MAgPIE 1.7-3.0

- NGFS Category: Orderly – Immediate 2C scenario with limited CDR
    - Zero2060_4_0 | MESSAGEix-GLOBIOM
    - PEP_2C_red_eff | REMIND-MAgPIE 1.7-3.0
- NGFS Category: Orderly – Immediate 1.5C scenario with CDR
    - CD-LINKS_NPi2020_400 | MESSAGEix-GLOBIOM
    - PEP_1p5_full_eff | REMIND-MAgPIE 1.7-3.0
- NGFS Category: Disorderly – Delayed 2C scenario with limited CDR
    - PEP_2C_red_NDC | REMIND-MAgPIE 1.7-3.0
- NGFS Category: Disorderly – Delayed 2C scenario with CDR
    - CD-LINKS_INDCi2030_1000 | MESSAGEix-GLOBIOM
    - PEP_2C_full_NDC | REMIND-MAgPIE 1.7-3.0
- NGFS Category: Disorderly – Immediate 1.5C scenario with limited CDR
    - Zero2050_4_2 | MESSAGEix-GLOBIOM
    - PEP_1p5C_red_eff | REMIND-MAgPIE 1.7-3.0

2. Hybrid scenario studies with participation of global and national models

2.1 Latin American Modelling Project (LAMP)

2.1.1 Publications

- van der Zwaan, B. C. C., Calvin, K. V., & Clarke, L. E. 2016. Climate Mitigation in Latin America: Implications for Energy and Land Use: Preface to the Special Section on the findings of the CLIMACAP-LAMP project. Energy Economics, Vol. 56, pp. 495–498. https://doi.org/10.1016/j.eneco.2016.05.005
- Lucena, A. F., Clarke, L., Schaeffer, R., Szklo, A., Rochedo, P. R., Nogueira, L. P., ... & Kober, T. 2016. Climate policy scenarios in Brazil: A multi-model comparison for energy. Energy Economics, 56, 564-574.

2.1.2 Guiding questions

This study is a multi-model assessment of climate change mitigation in Latin America.

1. How does the energy system evolve in Latin America under both baseline and mitigation scenarios?
2. What is the policy and low-carbon development context for individual Latin American countries?
3. How does climate change mitigation affect agriculture and land use and macro-economic activity in Latin America?

2.1.3 Results

Baseline and mitigation scenarios for Latin America differ across country and model.

1. The economic potential for mitigation of fossil fuel emissions in Latin America is lower than the world as a whole.
2. Mitigation potential and the cost of mitigation varies across individual Latin American countries.
3. There is significant uncertainty in future GHG emissions from AFOLU across models due to differences in underlying assumptions across models.

2.1.4 Scenarios

- 20% abatement (FF&I)
- 20% abatement (GHG)
- 450 concentration
- 50% abatement (FF&I)
- 50% abatement (GHG)
- 550 concentration
- 650 concentration
- Core baseline
- High CO2 price

- Low CO2 price
- Policy baseline

2.1.5 Models

- COPPE_MSB-Brazil 2.0
- TIAM-WORLD 1.0
- GCAM 4.0

2.2 CD-LINKS

2.2.1 Publications

- McCollum DL, Zhou W, Bertram C, de Boer H-S, Bosetti V, Busch S, Després J, Drouet L, Emmerling J, Fay M, Fricko O, Fujimori S, Gidden M, Harmsen M, Huppmann D, Iyer G, Krey V, Kriegler E, Nicolas C, Pachauri S, Parkinson S, Poblete-Cazenave M, Rafaj P, Rao N, Rozenberg J, Schmitz A, Schoepp W, van Vuuren D, Riahi K. 2018. Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. Nature Energy 3:589-599.
- Schaeffer R et al. 2020. Comparing transformation pathways across major economies, Climatic Change 162, 1787-1803. https://doi.org/10.1007/s10584-020-02837-10
- Vrontisi Z, Fragkiadakis K, Kannavou M, Capros P. 2019. Energy system transition and macroeconomic impacts of a European decarbonization action towards a below 2°C climate stabilization. Climatic Change. https://doi.org/10.1007/s10584-019-02440-7
- Roelfsema, M., van Soest, H. L., Harmsen, M., van Vuuren, D. P., Bertram, C., den Elzen, M., … Vishwanathan, S. S. 2020. Taking stock of national climate policies to evaluate implementation of the Paris Agreement. Nature Communications, 11(1), 2096. https://doi.org/10.1038/s41467-020-15414-6

2.2.2 Guiding questions

The CD-LINKS project is exploring the complex interplay between climate action and development, while simultaneously taking both global and national perspectives and thereby informing the design of complementary climate-development policies.

1. How do national decarbonisation pathways that are collectively consistent with global well-below-2°C pathways look like?
2. How do these low-carbon development pathways for the seven largest greenhouse gas emitters (China, the USA, the EU, India, Russia, Japan and Brazil) compare to each other and which sectoral mitigation measures are deployed?
3. How much achieve currently implemented national policies and submitted NDCs on the way to limit temperature change to 1.5 and 2°C and how large is the emissions gap to cost-effective emissions pathways?
4. What are implications of climate policy to achieve the 1.5 and 2°C targets for Sustainable Development Goals (SDGs)?
5. How can adverse effects of climate policies on non-climate SDGs, e.g. on food security, be avoided?
6. What are investment needs to limit temperature rise to 1.5 and 2°C and how do these compare to investment needs to achieve a subset of SDGs?

2.2.3 Results

The CD-LINKS scenarios are analysed from a set of different angles, including consistency of national action with global climate targets, investment needs and sustainable development implications of climate policy consistent with the Paris Agreement. These analyses have been (and are being) published in a series of journal articles, part of which are listed below in relation to the high-level insights. In addition, a full Special Issue with national level analysis in selected G20 countries is currently in preparation.

1. Roelfsema et al.: Seven G20 countries were assessed. Some seem on track to meet NDC targets with current policies, others display an ambition gap. Their NDCs are not on track with cost-efficient emission pathways which limit warming to well below 2°C. Current policies bring a reduction of 2 to 5.5 GtCO2eq. Additional policies and measures are required to fully implement the NDCs, which would reduce emissions by 7 to 17 GtCO2eq.The emissions gap in 2030 between planned national policies and a well below 2°C trajectory are 9 to 37 Gt. For a 1.5°C trajectory there is a gap of 17 to 43 Gt.
2. Kriegler et al.: Although countries differ considerably in the sectoral composition of emission reductions, a robust pattern emerges, with an almost complete decarbonisation of the electricity sector by 2050 that is accompanied by accelerated electrification and a limited reduction of carbon intensity of fuel consumption in the industry, buildings and transport sectors.
3. Krey et al.: Climate policies to achieve 1.5 and 2C potentially create both synergies and trade-offs with other SDGs, highlighting that integrated policy approaches are needed to ensure multiple SDGs are achieved simultaneously. In particular, dealing with undesirable distributional consequences of climate policies is key to avoid negative impacts on the poor, like ensuring food security and access to modern energy services.
4. McCollum et al.: The Nationally Determined Contributions lack the pronounced reallocation of the investment portfolio needed for transforming the energy system. Charting a course toward ‘well below 2 °C’ instead requires that low-carbon investments overtake fossil investments globally before 2025 and then continue to grow from there. Pursuing the 1.5 °C target demands a marked up-scaling in low-carbon capital beyond that demanded by 2 °C. The investment needs for making progress on certain other SDG targets are small relative to those for energy.

2.2.4 Scenarios

- CD-LINKS_INDC2030i_1600
- CD-LINKS_INDCi
- CD-LINKS_NDC2030i_1000
- CD-LINKS_NPi
- CD-LINKS_NPi2020_1000
- CD-LINKS_NPi2020_1600
- CD-LINKS_NPi2020_400
- CD-LINKS_NoPolicy
- CD-LINKS_INDC2030_high
- CD-LINKS_INDC2030_low
- CD-LINKS_NPi2020_high
- CD-LINKS_NPi2020_low
- CD-LINKS_NPi2020_verylow
- CD-LINKS_INDC2030_high_V3
- CD-LINKS_INDC2030_low_V3
- CD-LINKS_NPi2020_high_V3
- CD-LINKS_NPi2020_low_V3
- CD-LINKS_NPi_V3
- CD-LINKS_NoPOL_V3
- CD-LINKS_NoPOL
- CD-LINKS_INDCi_recGenTaxation
- CD-LINKS_INDCi_recSocialSecurity

- CD-LINKS_NPi2020_1000_recGenTaxation
- CD-LINKS_NPi2020_1000_recSocialSecurity
- CD-LINKS_NPi2020_400_recGenTaxation
- CD-LINKS_NPi2020_400_recSocialSecurity
- CD-LINKS_INDC2030i_400
- CD-LINKS_INDC2030i_1000

2.2.5 Models

- AIM/CGE 2.1
- AIM/Enduse India 3.1
- BLUES-Brazil 1.0
- COPPE-COFFEE 1.0
- DNE21+ V.14 (national)
- DNE21+ V.14C
- GCAM-USA_CDLINKS
- GEM-E3 V1
- IMAGE 3.0.1
- IPAC-AIM/technology V1.0
- India MARKAL
- MESSAGEix-GLOBIOM 1.0
- POLES CD-LINKS
- PRIMES_V1
- REMIND-MAgPIE 1.7-3.0
- RU-TIMES 3.2
- WITCH-GLOBIOM 4.4

2.2.6 Part of CD-LINKS special issue

Publications

- Oshiro, K., Gi, K., Fujimori, S., van Soest, H. L., Bertram, C., Després, J., … Vrontisi, Z. 2020. Mid-century emission pathways in Japan associated with the global 2 °C goal: national and global models' assessments based on carbon budgets. Climatic Change, 162(4), 1913–1927. https://doi.org/10.1007/s10584-019-02490-x

Guiding questions

Exploring national development pathways which are consistent with the global climate goals implied by the carbon budgets based on global model's analyses.

1. What are the level of carbon budgets and low-emission pathways in Japan given the Paris Agreement climate goals?
2. Energy system transformations required for meeting the national low emission pathways;
3. Is the national mid-century strategy consitent with the global climate goal stated in the Paris Agreement?

Results

1. CO_2 emissions in Japan in 2050 were estimated -66% and -75% below the 2010 level in the global 1600Gt and 1000Gt budget scenarios, respectively.
2. Large scale deployment of low-carbon energy (nuclear, renewable, and carbon capture and storage) is essential in both the 1600 and 1000Gt budget scenarios.
3. The 1000Gt budget scenarios, which require a 75% reduction of CO_2 emissions by 2050 for Japan, is nearly the same as Japan's governmental 2050 goal of reducing greenhouse gas emissions by 80%.

Scenarios

- CDLINKS-NDC
- CDLINKS-NDC1000
- CDLINKS-NDC1600
- CDLINKS-NPi
- CDLINKS-NPi1000
- CDLINKS-NPi1600

Models

- AIM/Enduse-Japan 2.1

2.3 COMMIT

2.3.1 Publications

- van Soest HL et al. 2020. A global roll-out of nationally relevant policies to bridge the emissions gap. *In Review*.

2.3.2 Guiding questions

Closing the remaining emissions gap between Nationally Determined Contributions (NDCs) and the global emissions levels needed to achieve the Paris Agreement's climate goals will likely require a comprehensive package of policy measures. National and sectoral policies can help fill the gap, but success stories in one country cannot be automatically replicated in other countries, but need to be adapted to the local context. In COMMIT, we developed a new bridging scenario based on nationally relevant measures informed by interaction with country experts.

1. To what extent can the emissions gap between NDCs and well-below 2C pathways be closed by the Bridge scenario?
2. What do the transformations in energy and land-use systems look like, and which sectors contribute most to the emisisons reductions in the Bridge scenario?
3. What are the costs of 'building the bridge'?

2.3.3 Results

The Bridge scenario was implemented with an ensemble of global and national Integrated Assessment Models. A global roll-out of the good practice policies until 2030 and transitioning to a cost-optimal 2C pathway thereafter closes the emissions gap by two-thirds by 2030 and more than fully by 2050. In the absence of immediate, all-encompassing and ambitious climate policy measures, therefore, a global roll-out and successful implementation of good practice policies can put the world on track to a 2 °C -compatible pathway without posing large additional challenges.

1. The Bridge scenario closes the global emissions gap between NDCs and a cost-optimal 2C pathway by 71% (median, range 26%–275%) by 2030, and compensates the slower start by a slightly deeper emission reduction in 2050, 106% (85%–112%). The 2030 emissions gap is closed by 17% in the USA, 49% in India, 56% in the EU and 75% in China.
2. The Bridge scenario leads to a scale-up of renewable energy (reaching 50%-85% of global electricity supply by 2050), electrification of end-uses, efficiency improvements in energy demand sectors, and enhanced afforestation and reforestation. The energy sector (through higher renewable energy share, electrification, energy efficiency improvement) is the largest contributor to emissions reductions between the NDCplus and Bridge scenarios, both in 2030 and in 2050. In most models, also mitigation of non-CO_2 emissions, the transport sector (zero-carbon vehicles and efficiency improvements), and AFOLU (notably in 2030) play an important role.
3. Although the Bridge scenario raises policy costs (as expressed by GDP cost per tonne CO_2e abated relative to the Current Policy scenario) in 2050 by more than 20% (1%–38%) compared to an immediate implementation of a cost-optimal 2 °C scenario with globally uniform carbon prices (2Deg2020), it has lower policy costs and carbon prices in the near term (2030). The Bridge scenario also outperforms a delayed 2 °C scenario (2Deg2030) with costs being more than 10% (-6%–33%) lower in 2050. As such, our analysis suggests that early but non cost optimal action is preferred over climate policy delay.

2.3.4 Scenarios

- CO_2Deg2020
- CO_2Deg2030
- CO_BAU
- CO_Bridge
- CO_Bridge_notax
- CO_CurPol
- CO_GPP
- CO_GPP_notax
- CO_NDC_2050convergence
- CO_NDCMCS
- CO_NDCplus

2.3.5 Models

- RU-TIMES 3.2
- GCAM-USA 4.2
- IMAGE 3.0
- COFFEE 1.1
- GCAM-Canada 4.2
- IPAC-AIM/technology-China 1.0
- MESSAGEix-GLOBIOM_1.0
- AIM/CGE 2.1
- MARKAL-India 1.0
- WITCH 5.0
- AIM/CGE-Korea 2.1
- COFFEE 1.0
- PROMETHEUS 1.0
- TIMES-Australia 20.73
- AIM/Enduse-Japan 2.1
- DDPP Energy 1.0
- PRIMES 1.0
- POLES GECO2019
- BLUES-Brazil 1.0

2.4 ENGAGE

2.4.1 Publications

- Riahi, K., Bertram, C., Huppmann, D., Rogelj, J., Bosetti, V., Cabardos, A.-M., … Zakeri, B. 2021. Long-term economic benefits of stabilizing warming without overshoot – the ENGAGE model intercomparison. *In Review*.
- Bertram, C., Riahi, K., Hilaire, J., Bossetti, V., & Drouet, L. (n.d.). Energy system developments and investments in the decisive decade for Paris Agreement targets. *In Review*, 1–30.
- Hasegawa, T. (n.d.). Agriculture and land use implications of early climate change mitigation efforts without reliance on net-negative emissions. *In Review*, 1–18.
- Drouet, L., Bosetti, V., Padoan, S., Aleluia Reis, L., Bertram, C., Dalla Longa, F., … Tavoni, M. 2020. Net zero emission pathways reduce the physical and economic risks of climate change. *Nature Climate Change, Submitted*.
- Fujimori S, Krey V, van Vuuren D, Oshiro K, Sugiyama M, Chunark P, Limmeechokchai B, Mittal S, Nishiura O, Park C, Rajbhandari S, Herran Silva D, Tu T T, Zhao S, Ochi1 Y, Shukla P R, Masui T, Nguyen, Phuong V.H. Cabardos A-M and Riahi K. 2020. A new national scenario framework: National Long-term Pathways (NLPs) Nature Climate Change. *In Review*.

2.4.2 Guiding questions

1. How do future generations benefit of rapid transformations avoiding net negative CO_2 emissions (NNCE), regarding long term economic benefits or losses?
2. How does a stabilization of warming without overshoot impact long-term economic benefits?
3. What insights can be taken from alternative configurations of net-zero CO_2 emissions systems?

2.4.3 Results

Scenarios that avoid temperature overshoot and NNCE are thus not only economically more attractive over the long term, they also involve lower climate risks.

1. Scenarios without a reliance on net negative CO_2 emissions avoid a systematic bias in favour of temperature overshoot, but at the same time require a much more pronounced near-term transition;
2. The long-term savings in mitigation costs are by far larger than the upfront near-term investments to avoid reliance on NNCE. Especially peak carbon prices over the course of the century are significantly lower in most scenarios without reliance on NNCE;
3. The study shows the importance of the underlying discount rate: rates of less than 2% would make the corresponding IAM scenarios without NNCE cheaper and thus cost-optimal overall;
4. Front-runner sectors (AFOLU, energy sector) and regions (e.g. Latin America or Reforming Economies including Russia) may provide an entry point for rapid and deep cuts towards zero CO_2 emissions. OECD economies could set their timing earlier to reach net zero if acknowledging a leadership position or historic responsibility;
5. The study shows a broad range in the portfolio of CDR measures and allows policy flexibility with respect to technology choices and sustainability aspects, like water availability, food security and biodiversity.

2.4.4 Scenarios

- EN_INDCi2030_1000
- EN_INDCi2030_1000f
- EN_INDCi2030_1200
- EN_INDCi2030_1200f
- EN_INDCi2030_1400
- EN_INDCi2030_1400f
- EN_INDCi2030_1600
- EN_INDCi2030_1600f
- EN_INDCi2030_1800
- EN_INDCi2030_1800f
- EN_INDCi2030_2000
- EN_INDCi2030_2000f
- EN_INDCi2030_2500
- EN_INDCi2030_2500f
- EN_INDCi2030_3000
- EN_INDCi2030_3000f
- EN_INDCi2030_300f
- EN_INDCi2030_400f
- EN_INDCi2030_500f
- EN_INDCi2030_600f
- EN_INDCi2030_700
- EN_INDCi2030_700f
- EN_INDCi2030_800f
- EN_INDCi2030_900
- EN_INDCi2030_900f
- EN_INDCi2030_900r
- EN_INDCi2100
- EN_NoPolicy
- EN_NPi2020_1000
- EN_NPi2020_1000f
- EN_NPi2020_1200
- EN_NPi2020_1200f
- EN_NPi2020_1400
- EN_NPi2020_1400f
- EN_NPi2020_1600
- EN_NPi2020_1600f
- EN_NPi2020_1800
- EN_NPi2020_1800f
- EN_NPi2020_2000
- EN_NPi2020_2000f
- EN_NPi2020_200f
- EN_NPi2020_2500
- EN_NPi2020_2500f
- EN_NPi2020_300
- EN_NPi2020_3000
- EN_NPi2020_3000f

- EN_NPi2020_300f
- EN_NPi2020_400
- EN_NPi2020_400f
- EN_NPi2020_500
- EN_NPi2020_500f
- EN_NPi2020_500r
- EN_NPi2020_600
- EN_NPi2020_600f
- EN_NPi2020_700
- EN_NPi2020_700f
- EN_NPi2020_700r
- EN_NPi2020_800
- EN_NPi2020_800f
- EN_NPi2020_900
- EN_NPi2020_900f
- EN_NPi2020_900r
- EN_NPi2100
- NDCCon2030_-100pc2050
- NDCCon2030_-30pc2050
- NDCCon2030_-40pc2050
- NDCCon2030_-50pc2050
- NDCCon2030_-60pc2050
- NDCCon2030_-70pc2050
- NDCCon2030_-80pc2050
- NDCCon2030_-90pc2050
- NDCUnc2030_-100pc2050
- NDCUnc2030_-30pc2050
- NDCUnc2030_-40pc2050
- NDCUnc2030_-50pc2050
- NDCUnc2030_-60pc2050
- NDCUnc2030_-70pc2050
- NDCUnc2030_-80pc2050
- NDCUnc2030_-90pc2050

2.4.5 Models

- AIM/CGE 2.2
- COFFEE 1.1
- GEM-E3_092019
- IMAGE 3.0
- MESSAGEix-GLOBIOM_1.0
- POLES ENGAGE
- REMIND-MAgPIE 2.0-4.1
- TIAM-ECN 1.1
- WITCH 5.0

3. Global scenario studies based on a single model

3.1 CEMICS study on the role of CDR for delayed action

3.1.1 Publications

- Strefler et al. 2018. Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. Enivronmental Research Letters 13, 4.

3.1.2 Guiding questions

CEMICS is driven by the hypothesis that society will not take decisions on climate engineering (CE) in isolation, but in consideration of the whole portfolio of existing climate policy options. The work within that project puts CE in the context of mitigation by exploring synergies, trade-offs, and side-effects of different CDR methods.

Please note: The project itself investigated the options of CE in a broader context also towards potential synergies or ethical aspects. This research however is not based on scenarios and thus not treated here.

1. How much CDR is at least necessary to achieve the Paris climate targets?
2. How does this minimum CDR requirement depend on short-term climate policy and medium-term emission reductions?

3.1.3 Results

There are major concerns about the sustainability of large-scale deployment of carbon dioxide removal (CDR) technologies. It is therefore an urgent question to what extent CDR will be needed to implement the long-term ambition of the Paris Agreement, and how this depends on short-term climate policy. In this paper we show that ambitious near-term mitigation significantly decreases CDR requirements to keep the Paris climate targets within reach.

1. Following the NDCs until 2030 requires then both fast CO_2 emission reductions until 2050 and high amounts of CDR to achieve the 2°C-target. Reducing 2030 emissions by 20% below NDC levels already alleviates the trade-off between high transitional challenges and high CDR deployment.
2. In order to achieve 2°C entirely without CDR, emissions have to be roughly halved until 2030 and again every decade until 2050.
3. Transitional challenges can only be kept in check if at least 5 Gt CO_2/yr CDR are available in any year. At least 8 Gt CO_2/yr CDR are necessary in the long term to achieve 1.5°C and more than 15 Gt CO_2/yr to keep transitional challenges in bounds.

3.1.4 Scenarios

- CEMICS-1.5-CDR12
- CEMICS-1.5-CDR20
- CEMICS-1.5-CDR8
- CEMICS-2.0-CDR12
- CEMICS-2.0-CDR20
- CEMICS-2.0-CDR8

- CEMICS-Ref

3.1.5 Models

- REMIND 1.7

3.2 Pathways and Entry Points to Limit Global Warming to 1.5°C (Pep1p5)

3.2.1 Publications

- Kriegler, E. et al. 2018. Short term policies to keep the door open for Paris climate goals. Environ. Res. Lett. 13, 074022.

3.2.2 Guiding questions

The Pep1p5 project aims to answer crucial questions about the feasibility of 1.5°C scenarios, related to the feasibility of policies - contrasting immediate pricing only and scenarios with gradual ratcheting up of ambition. Further it assesses the implications of carbon dioxide removal (CDR) availability.

1. To what extent can plausible bottom-up policy packages (sectoral policies like renewable support or efficiency targets as already observed in a number of countries) that are more ambitous than the NDCs close the emissions gap towards least-cost pathways?
2. Which implementability challenges (grouped into scale, speed, disruption, price impacts and efficiency)are major hurdles for different policy scenarios?
3. How do they differ between scenarios based on a range of regionally differentiated bottom-up policies and scenarios with a comprehensive and harmonized carbon price only (so called "first-best" or "cost-effective" scenarios)?
4. What implications follow from the assumption of more strongly limited availability of carbon dioxide removal (CDR)?

3.2.3 Results

The comparison across 3 different dimensions offer a rich exploration of implementability challenges.

1. A global roll-out of strengthened bottom-up policies could reduce global CO_2 emissions by an additional 10 $GtCO_2eq$ in 2030 compared to NDCs.

It would lead to emissions pathways close to the levels of cost-effective well below 2°C and 1.5°C scenarios until 2030, thereby reducing implementation challenges post 2030.

2. Comparing a gradual phase-in of a portfolio of regulatory policies with immediate cost-effective carbon pricing shows that the bottom-up policies might be less disruptive. However, they would perform worse in other dimensions. In particular, they lead to higher economic costs. Hence, such policy packages should not be viewed as alternatives to carbon pricing, but rather as complements that provide entry points to achieve the Paris climate goals.
3. Assuming lower availability of CDR implies faster and more disruptive near-term decarbonization.

3.2.4 Scenarios

- PEP_1p5C_full_NDC
- PEP_1p5C_full_eff
- PEP_1p5C_full_goodpractice
- PEP_1p5C_full_netzero
- PEP_1p5C_red_eff
- PEP_2C_full_NDC

- PEP_2C_full_eff
- PEP_2C_full_goodpractice
- PEP_2C_full_netzero
- PEP_2C_red_NDC
- PEP_2C_red_eff
- PEP_2C_red_goodpractice
- PEP_2C_red_netzero
- PEP_NDC
- PEP_NPi
- PEP_NoPolicy
- PEP_goodpractice
- PEP_netzero

3.2.5 Models

- REMIND-MAgPIE 1.7-3.0

3.3 UBA SMP

3.3.1 Publications

- Bertram, C. et al. 2018. Targeted policies can compensate most of the increased sustainability risks in 1.5 °C mitigation scenarios. Environ. Res. Lett. 13, 064038.

3.3.2 Guiding questions

The study aims to contribute to the understanding of key sustainability impacts of mitigation pathways, and how they can be managed by policy choice in order to maximize benefits and minimize risks.

1. What sustainability effects (benefits and risks) does mitigation targets of 2 and 1.5°C imply?
2. How does the choice of mitigation policy paradigm impact the sustainability effects (benefits and risks) of mitigation?
3. How do different measures interact?

3.3.3 Results

The study analyses a range of crucial sustainability indicators for 2 different temperature targets achieved by 5 different policy approaches respectively.

1. Mitigation leads to a number of sustainability benefits (air pollution, cooling water requirements), but under default policies also leads to severe risks (uranium use, food and energy price increases, land requirements for bioenergy, etc.). Both benefits and risks increase if ambition is raised from 2 to 1.5°C.
2. A combination of additional policies (direct sector-level regulation, early mitigation action, and lifestyle changes) can alleviate air pollution, water extraction, uranium extraction, food and energy price hikes, and dependence on negative emissions technologies, thus resulting in substantially reduced sustainability risks associated with mitigating climate change.
3. Importantly, we find that these targeted policies more than compensate for most increased sustainability risks of increasing climate ambition from 2°C to 1.5°C.

3.3.4 Scenarios

- SMP_1p5C_Def
- SMP_1p5C_Sust
- SMP_1p5C_early
- SMP_1p5C_lifesty
- SMP_1p5C_regul
- SMP_2C_Def
- SMP_2C_Sust
- SMP_2C_early
- SMP_2C_lifesty
- SMP_2C_regul
- SMP_REF_Def
- SMP_REF_Sust

3.3.5 Models

- REMIND-MAgPIE 1.7-3.0

3.4 REMIND2.1

3.4.1 Publications

- Baumstark, L., Bauer, N., Benke, F., Bertram, C., Bi, S., Gong, C. C., … Luderer, G. 2020. REMIND2.1: Transformation and innovation dynamics of the energy-economic system within climate and sustainability limits.

3.4.2 Guiding questions

The scenarios are the update of the SSP1, SSP2 and SSP5 scenarios (baseline, NDC, NPi, peak Budget 1300/1100/900) for our new version REMIND2.1.

1. What are the transformation pathways in the energy-economy sytem for a SSP1, SSP2 and SSP5 world?
2. What is REMIND?
3. How are different sectors represented in REMIND and what are possible models REMIND can belinket to?

3.4.3 Results

REMIND is a multi-regional model of the energy-economic system, it can fully capture the interactions between the energy transformation in response to climate policies and economic development.

1. Different socio-economic developments feature different strategies to achieve the 1.5°C target and the timing of emission reduction can vary strongly across regions.
2. The evolution of the global energy system fundamentally depends on socio-economic assumptions, and policy scenario. Fossil fuels dominance would continue for SSP5 socio-economic assumptions, but would be gradually reduced in SSP2 futures, and would be replaced by a rather diverse energy system with similar contributions from wind, solar, bioenergy and fossils in 2100 in SSP1.
3. The modular structure of REMIND enables detailed analysis of specific parts of the model tailored to the research question without increasing the numerical burden of the default model. The feasibility to link REMIND with other models (e.g. EDGE, MAgPIE, MAGICC) guarantees consistent detailed results with small increase of model complexity.

3.4.4 Scenarios

- R2p1_SSP1-Base
- R2p1_SSP1-NDC
- R2p1_SSP1-NPi
- R2p1_SSP1-PkBudg1100
- R2p1_SSP1-PkBudg1300
- R2p1_SSP1-PkBudg900
- R2p1_SSP2-Base
- R2p1_SSP2-NDC
- R2p1_SSP2-NPi
- R2p1_SSP2-PkBudg1100
- R2p1_SSP2-PkBudg1300

- R2p1_SSP2-PkBudg900
- R2p1_SSP5-Base
- R2p1_SSP5-NDC
- R2p1_SSP5-NPi
- R2p1_SSP5-PkBudg1100
- R2p1_SSP5-PkBudg1300
- R2p1_SSP5-PkBudg900
- SSP1-Base
- SSP1-NDC
- SSP1-NPi
- SSP1-PkBudg1100
- SSP1-PkBudg1300
- SSP1-PkBudg900
- SSP2-Base
- SSP2-NDC
- SSP2-NPi
- SSP2-PkBudg1100
- SSP2-PkBudg1300
- SSP2-PkBudg900
- SSP5-Base
- SSP5-NDC
- SSP5-NPi
- SSP5-PkBudg1100
- SSP5-PkBudg1300
- SSP5-PkBudg900

3.4.5 Models

- REMIND 2.1

3.5 Uncertainty in technology costs and CDR availability

3.5.1 Publications

- Giannousakis, A., Hilaire, J., Nemet, G. F., Luderer, G., Pietzcker, R. C., Rodrigues, R., … Kriegler, E. 2020. How uncertainty in technology costs and carbon dioxide removal availability affect climate mitigation pathways. Energy, 119253. https://doi.org/10.1016/j.energy.2020.119253

3.5.2 Guiding questions

We measure the sensitivities of mitigation indicators to the costs and potential of energy technologies (the costs of wind, solar, biomass, gas, coal, oil, nuclear, and electric/hydrogen vehicles, as well as the injection rate of Carbon Capture and Storage (CCS)) across economic sectors.

1. How are CDRdemands and individual sectors affected?
2. What is the relative importance of the costs of technologies when compared with each other?
3. How is the year of carbon neutrality affected by the uncertainty in technology costs?

3.5.3 Results

This sensitivity analysis of technology costs shows that the uncertainty in biomass&CCS followed by the transport-related options (ELH2 and oil) have the largest effects on both physical and economic mitigation indicators.

1. The use of CDR is a more sensitive economy-wide physical mitigation indicator, mainly affected by the CCS injection limit and the dipole oil/ELH2. The sector affected the most by energy technology cost variations is the transport sector;
2. The high overall influence of biomass&CCS (with uncertain potential) and transport-related technologies (difficult to decarbonize) on the indicators, highlights the need for robust and broad policy support for achieving the goals of the Paris Agreement;
3. The year of carbon neutrality remains largely unaffected by the variation in costs. This indicates the importance of early climate action, as even in “favorable” price scenarios, optimal emissions need to reach zero by 2065.

3.5.4 Scenarios

- TechCost-SSP2-B1100-bioH
- TechCost-SSP2-B1100-ccsH
- TechCost-SSP2-B1100-coalH
- TechCost-SSP2-B1100-elh2H
- TechCost-SSP2-B1100-gasH
- TechCost-SSP2-B1100-nucH
- TechCost-SSP2-B1100-oilH
- TechCost-SSP2-B1100-spvH
- TechCost-SSP2-B1100-windH

3.5.5 Models

- REMIND 2.1

3.6 Accelerated electrification based on cheap renewables

3.6.1 Publications

- Luderer, G., Madeddu, S., Ueckerdt, F., Pehl, M., Pietzcker, R., Rottoli, M., … Kriegler, E. (n.d.). Accelerated electrification based on cheap renewables facilitates reaching Paris Climate targets. Nature Energy. Submitted.

3.6.2 Guiding questions

Technological progress in photovoltaics, wind power and battery storage make reliable renewable electricity increasingly cheap. At the same time, any international effort to increase ambition towards keeping the targets of the Paris Agreement will make carbon-based fuels scarce and expensive. Our study shows that a continuation of rapid innovation in solar and wind power along with carbon pricing to reach the Paris Climate targets will make electricity cheaper than carbonaceous fuels, resulting in a fundamental transformation of energy systems towards a dominance of electricity-based end uses.

1. What are the role and potential of electrification for global and long-term deep decarbonization strategies?
2. What are the dynamics, requirements and full-systems implications of deep electrification?
3. Do IAMs over-emphasize bioenergy, CCS and CDR, and underappreciate the pace of technological progress in solar energy and energy end-use technologies?

3.6.3 Results

A profound and rapid energy transformation is required to put the world on a pathway for limiting warming in line with the climate targets of the Paris Agreement. Formidable technological progress in solar PV, wind power and battery technologies have been among the most encouraging developments towards this transformation. Renewable electricity supply is already cost-competitive in many parts of the world, and electric vehicle technology is making rapid strides towards increasing competitiveness. At the same time, the sustainability and regulatory challenges of large-scale bioenergy use are becoming increasingly evident, and so are difficulties to upscale carbon capture and storage. A climate change mitigation strategy centred around renewables-based electrification becomes increasingly plausible.

1. Our analysis shows that climate policy strongly shifts the economics in favor of electricity as an energy carrier. The key enabling assumptions for very high electrification shares in our scenario are (1) limited biomass, (2) limited CCS, and (3) limited other options CDR. Electrification shares could become even higher in the long-term with further technological breakthroughs, e.g. in battery technology, in aviation, primary steel production or other industrial processes;
2. The detailed analysis of individual end uses reveals greater demand-side electrification potential than suggested in the previous integrated assessment modeling literature. Fuel demands for aviation, shipping, some industrial processes as well as feedstocks for the chemical industry are the most significant sources of residual demands for carbonaceous energy carriers;
3. The transition to a renewables-based electrification of energy systems is only possible in a favorable policy environment. First and foremost, comprehensive carbon pricing is crucial for internalizing the climate benefits of renewable electricity vis-a-vis fossil-based fuels. Secondly, the increasing share of VRE in power supply requires adjustments of the electricity market design to incentivize deployment of storage and flexibilization of demand. Thirdly, a deep electrification of energy systems requires political coordination in the build-up of new

infrastructure, such as grid interconnectors to pool VRE generation over larger geographical areas, or charging stations for electric vehicles.

3.6.4 Scenarios

- DeepElec_SSP2_ HighRE_Budg1100
- DeepElec_SSP2_ HighRE_Budg1300
- DeepElec_SSP2_ HighRE_Budg900
- DeepElec_SSP2_Base
- DeepElec_SSP2_def_Budg1100
- DeepElec_SSP2_def_Budg1300
- DeepElec_SSP2_def_Budg900
- DeepElec_SSP2_NDC
- DeepElec_SSP2_NPi

3.6.5 Models

- REMIND 2.1

3.7 Trade-off between cost-efficiency and sovereignty

3.7.1 Publications

- Bauer N, Bertram C, Schultes A, Luderer G, Kriegler E, Popp A, Edenhofer O. 2020. Quantifying the trade-off between cost-efficiency and sovereignty in international climate mitigation cooperation. Nature, 588, 261-266.

3.7.2 Guiding questions

1. How can sovereignty, efficiency and fairness be balanced?
2. Can fair burden sharing (defined as equal percentage income reduction across regions) achieved without transfers by differentiated carbon prices.
3. What is the shape of the sovereignty-efficiency trade-off?
4. What are implications of differentiated carbon prices?
5. What role could additional sector-specific policies play?

3.7.3 Results

A strategy of international financial transfers guided by moderate deviations from uniform carbon pricing could achieve the goal without straining either the economies or sovereignty of nations.

1. Yes, but very high differentiation is required, especially for high policy ambition. The efficiency losses this entails (measured in cumulative discounted income losses) are smaller than the net-present value of required transfers to achieve fairness with equal carbon prices.
2. The trade-off is highly non-linear, so that already allowing for small transfers achieves much of the efficiency gains.
3. Relatively large market distortions are induced at relatively moderate carbon price differentiation. Resultiung leakage between regions and asynchronicity of mitigation timing across regions, such as reaching carbon neutrality, are most sensitive at moderate carbon price differentiation. As price differentiation is increased the additional effect on market distortion and asynchronous mitigation timing become smaller. Hence, small deviations from uniform carbon pricing have the largest effect on reducing transfers, but also the largest impact on leakage and putting a wedge in regional tiing of mitigation measures.
4. Complementing moderately differentiated carbon prices with additional sector-specific policies could further reduce or eliminate distortions and environmental trade-offs. The effects of specific policies become context dependent.

3.7.4 Scenarios

- Diff_1300Gt_hybrid_def
- Diff_1300Gt_no-transfer_def
- Diff_1300Gt_uniform-pricing_def
- Diff_No-policy_baseline

3.7.5 Models

- REMIND-MAgPIE 2.0-4.1

3.8 Deeper near-term emissions cuts induced by economic damages from on-going climate change

3.8.1 Publications

- Schultes, Anselm; Piontek, Franziska; Soergel, Bjoern; Rogelj, Joeri; Baumstark, Lavinia; Kriegler, Elmar; Edenhofer, Ottmar; Luderer, G. 2020. Economic damages from on-going climate change imply deeper near-term emission cuts. *Environmental Research Letters, submitted*.

3.8.2 Guiding questions

The study explores emissions and carbon prices in scenarios combining a climate target in line with the Paris agreement with climate damages with different degrees of persistency. Multiple dimensions of uncertainty are assessed.

1. How does a least-total cost framework, combining a climate target and climate damages, affect optimal emissions and carbon prices?
2. What role does the very uncertain persistence of damages play?
3. How do the different dimensions of uncertainty (impacts, climate, socioeconomic) contribute to overall uncertainty?

3.8.3 Results

Accounting for damages increases near-term ambition of transformation pathways, increasing the emissions gap. This is mainly driven by the long-term persistence of damages.

1. In a cost-benefit setting, 2030 social costs of carbon increase strongly with the assumed persistence of the damages. Even for low degrees of persistence (5 years) the SCC is significantly higher than the value put forward by the Interagency Working Group on the Social Costs of Greenhouse Gases.
2. When accounting for damages, mean 2030 carbon prices almost double compared to the standard cost-effectiveness analysis for a 2° target, increasing the emissions gap to the currently pledged nationally determined contributions by two thirds.
3. In the long run, accounting for damages requires lower carbon prices to reach the 2° target than in the cost-effective pathway.

3.8.4 Scenarios

- LeastTotalCost_Base_brkLR15_SSP1_P50
- LeastTotalCost_Base_brkLR15_SSP2_P50
- LeastTotalCost_Base_brkLR15_SSP5_P50
- LeastTotalCost_Base_brkSR15_SSP1_P50
- LeastTotalCost_Base_brkSR15_SSP2_P50
- LeastTotalCost_Base_brkSR15_SSP5_P50
- LeastTotalCost_CBA_brkLR15_SSP2_P50
- LeastTotalCost_CBA_brkSR15_SSP2_P50
- LeastTotalCost_CEA_brkLR15_SSP2_P50

- LeastTotalCost_CEA_brkSR15_SSP2_P50
- LeastTotalCost_LTC_brkLR15_SSP1_P50
- LeastTotalCost_LTC_brkLR15_SSP2_P50
- LeastTotalCost_LTC_brkLR15_SSP5_P50
- LeastTotalCost_LTC_brkSR15_SSP1_P50
- LeastTotalCost_LTC_brkSR15_SSP2_P50
- LeastTotalCost_LTC_brkSR15_SSP5_P50
- LeastTotalCost_NDC_brkLR15_SSP2_P50
- LeastTotalCost_NDC_brkSR15_SSP2_P50
- LeastTotalCost_NPi_brkLR15_SSP1_P50
- LeastTotalCost_NPi_brkLR15_SSP2_P50
- LeastTotalCost_NPi_brkLR15_SSP5_P50
- LeastTotalCost_NPi_brkSR15_SSP1_P50
- LeastTotalCost_NPi_brkSR15_SSP2_P50
- LeastTotalCost_NPi_brkSR15_SSP5_P50

3.8.5 Models

- REMIND 2.1

3.9 Sustainable Development Pathway

3.9.1 Publications

- Soergel, B., Kriegler, E., Weindl, I., Rauner, S., Dirnaichner, A., Ruhe, C., … Popp, A. 2020. *Climate action within the 2030 Agenda: A holistic sustainable development pathway*. 28.

3.9.2 Guiding questions

This study investigates how to reach the UN Sustainable Development Goals alongside the 1.5°C climate target. It identifies the key policy interventions required for this purpose, and quantifies their individual and combined effects on SDG outcomes.

1. Are faster economic development, better education, technological progress, resource efficiency, less resource-intensive lifestyles, and ambitious climate policies sufficient to achieve the SDGs?
2. If no, what are the other key policy interventions required for substantial progress towards the SDGs?
3. If all these interventions are combined, can the SDGs be achieved by 2030 (and 2050)?

3.9.3 Results

The policy interventions included in existing transformation pathways are insufficient to meet the SDGs. However, additional targeted sustainable development interventions can substantially boost progress towards the SDGs.

1. A continuation of current trends and policies will fail to meet the SDGs. Even faster economic development, better education, technological progress, higher resource efficiency, less resource-intensive lifestyles, and ambitious climate policies will not be sufficient.
2. The following key interventions enable a more holistic sustainable development pathway: (i) An ambitious international “climate & development” finance scheme, (ii) a progressive redistribution of carbon pricing revenues to alleviate inequality and poverty, (iii) sufficient and healthy nutrition, improved access to modern energy in low-income countries, and an ambitious reduction of energy demands in high-income countries.
3. The above interventions drive substantial progress towards the SDGs, but due to the narrow time horizon substantial gaps will remain by 2030. However, many of these gaps can be closed by 2050, reconciling the provisioning for human well-being with respecting the climate targets and other planetary boundaries.

3.9.4 Scenarios

- SusDev_SDP-PkBudg1000
- SusDev_SSP1-NDC
- SusDev_SSP1-PkBudg900
- SusDev_SSP2-NDC
- SusDev_SSP2-PkBudg900
- SusDev_SDP-NPi
- SusDev_SSP1-NPi
- SusDev_SSP2-NPi

3.9.5 Models

- REMIND 2.1-4.2

3.10 Emissions Reduction Under the World Energy Council Scenario Framework

3.10.1 Publications

- Kober T., Panos E., Volkart K. 2018. Energy System Challenges of Deep Global CO_2 Emissions Reduction Under the World Energy Council's Scenario Framework. In: Giannakidis G., Karlsson K., Labriet M., Gallachóir B. (eds) Limiting Global Warming to Well Below 2°C.
- Kober, T., Schiffer, H.-W., Densing, M., Panos, E. 2020. Global energy perspectives to 2060 - WEC's world energy scenarios 2019. Energy Strategy Reviews, 31, pp. 100523. https://doi.org/10.1016/j.esr.2020.100523

3.10.2 Guiding questions

The report from World Energy Council, "Exploring Innovation Pathways to 2040", presents three global storylines to 2040, with supporting systems thinking maps, comparative analysis and regional summaries. It includes a discussion of new insights, reflecting deeper shifts in the energy system innovation landscape, and provides a broader view on "how to use" the scenarios.

1. Modern_Jazz Scenario: How the energy system transtition to decarbonisation can be facilitated by a market-led digitally disrupted word with faster-paced and more even conomic growth?
2. Unfinished_Symphony & Symphony_1.5C Scenarios: What is the effect of a strong, coordinated policy-led world, with long-term planning and unified global action to address connected challenges, including inequitable access and affordable decarbonisation, on the energy system transition towards Paris Agreements 2015?
3. Hard_Rock Scenario: Can a fragmented world with inward looking policies, lower growth and less global cooperation, move towards a low-carbon energy system?

3.10.3 Results

Signals of each scenario have been detected in all regions of the world through the use of a variety of leadership surveys and systematic horizon-scanning methods. There has been a marked shift in perception about the scenario Hard Rock, which is no longer seen as an extreme scenario. Perspectives are also more divided about the outlook for effective global cooperation, which is assumed in the scenario Unfinished Symphony. The entrepreneurial scenario Modern Jazz has generated a lot of questions about new societal dynamics relating to increasing inequality, active consumers and effective market design.

1. Achieving Paris Agreements targets remains elusive, with none of the 2019 scenarios meeting the temperature increase targets.
2. Infrastructure innovation and investment, and proactive policies are necessary to secure affordable decarbonisation and socially just energy transition. New net-zero carbon technology pathways (including hydrogen) and carbon abatement mechansisms emerge and start to scale by 2040. Energy efficiency gains are critical to manage energy demand from industrial, residential, commercial sectors to avoid reducing climate change momentu. Consumer-centricity of the energy system increases in all scenarios to provide energy-plus service. Electrification and a mobility revolution has the potential to disrupt the entire system landscape in the longer term.
3. Energy business leaders should identify new customer-centric growth opportunities in electrification, storage, PtX and hydrogen economy. Policy makers need to identify new integrated policy innovation opportunities and implement sector-coupling policies to enable

faster, socially affordable and deeper decarbonisation of the whole economy. Policy makers also need to establish new economics of whole energy system transition that looks beyond zero marginal cost pricing and enable demand side participation and better connectivity of the actors of the energy system. The international community needs to renew efforts to facilitate technology transfer, recognise and enhance adaptability and resilience of interdependent energy-food-water systems, and reduce the risk of fragmentation by encouring cross-border, cross-sector and cross-vector strategic partnerships to accelerate progress along net-zero pathways.

3.10.4 Scenarios

- Hard_Rock
- Modern_Jazz
- Unfinished_Symphony

3.10.5 Models

- GMM-17

3.11 Sustainable development implications of climate change mitigation

3.11.1 Publications

- Shinichiro F, Tomoko H, Kiyoshi T, Hancheng D, Jing-Yu L, Haruka O, et al. 2020. Measuring the sustainable development implications of climate change mitigation. Environmental Research Letters.

3.11.2 Guiding questions

SDG implications of climate policy:

1. What are the trade off and synergies in SDGs and climate policy?

3.11.3 Results

Land-related SDGs can be negatively affected by climate policy.

1. Need for consideration of land-related emissions reduction.

3.11.4 Scenarios

- 1.5C
- 2.5C
- 2C
- WB2C

3.11.5 Models

- AIM/Hub-Global 2.0

3.12 Implications of the Paris Agreement in the Context of Long-Term Climate Mitigation Goals

3.12.1 Publications

- Shinishiro Fujimori, Xuanming Su, Jing-Yu Liu, Tomoko Hasegawa, Kiyoshi Takahashi, Toshihiko Masui, Maho Takimi. 2017. Implications of the Paris Agreement in the Context of Long-Term Climate Mitigation Goals. SpringerPlus 5:1620.

3.12.2 Guiding questions

NDCs are released and assessed the first NDC implications.

1. How much are the long term goals are affected by the NDCs?
2. Energy and land use implications on NDCs.

3.12.3 Results

NDC delays the reductions compared with cost optimal pathways.

1. 2 degree goal is still feasible under NDC but cost becomes large.
2. More negative emissions technologies and deep decarbonization is needed in the latter half of century.

3.12.4 Scenarios

- 450ppmCancunP
- 450ppmeINDC
- 450ppmRCP
- Baseline
- INDCSamePrice
- Baseline

3.12.5 Models

- AIM/Hub-Global 2.0

3.13 The Transition in Energy Demand Sectors to Limit Global Warming to 1.5 °C

3.13.1 Publications

- Méjean, Aurélie, Céline Guivarch, Julien Lefèvre, and Meriem Hamdi-Cherif. 2019. The Transition in Energy Demand Sectors to Limit Global Warming to 1.5 °C. Energy Efficiency 12 (2): 441–62. https://doi.org/10.1007/s12053-018-9682-0

3.13.2 Guiding questions

1. What does the 1.5°C target imply for the transition in energy demand sectors?
2. How does the date of the peak of emissions affect the emission pathway of different sectors?
3. When should the peak of emissions occur in order to remain on track with the 1.5°C target?

3.13.3 Results

Stringent policies in energy demand sectors, especially transport and industry, are needed in the short run to trigger an immediate peak of emissions and increase the probability to meet the 1.5°C objective.

1. Bringing forward the peak of global emissions does not lead to a homothetic adjustment of all sectoral emission pathways: an early peak of global emissions implies the faster decarbonization of the electricity sector and early emission reductions in energy-demand sectors – mainly industry and transportation.
2. The results suggest that it is impossible to delay the peak of global emissions until 2030 while remaining on a path compatible with the 1.5 °C objective.

3.13.4 Scenarios

- base_DemandHigh_FossilHigh_TechHigh
- base_DemandHigh_FossilLow_TechHigh
- base_DemandHigh_FossilLow_TechLow
- base_DemandLow_FossilHigh_TechHigh
- base_DemandLow_FossilHigh_TechLow
- base_DemandLow_FossilLow_TechHigh
- base_DemandLow_FossilLow_TechLow
- peak2016_DemandHigh_FossilHigh_TechHigh
- peak2016_DemandHigh_FossilLow_TechHigh
- peak2016_DemandHigh_FossilLow_TechLow
- peak2016_DemandLow_FossilHigh_TechHigh
- peak2016_DemandLow_FossilHigh_TechLow
- peak2016_DemandLow_FossilLow_TechHigh
- peak2016_DemandLow_FossilLow_TechLow
- peak2020_DemandHigh_FossilHigh_TechHigh
- peak2020_DemandHigh_FossilLow_TechHigh
- peak2020_DemandHigh_FossilLow_TechLow
- peak2020_DemandLow_FossilHigh_TechHigh

- peak2020_DemandLow_FossilHigh_TechLow
- peak2020_DemandLow_FossilLow_TechHigh
- peak2020_DemandLow_FossilLow_TechLow
- peak2025_DemandHigh_FossilHigh_TechHigh
- peak2025_DemandHigh_FossilLow_TechHigh
- peak2025_DemandHigh_FossilLow_TechLow
- peak2025_DemandLow_FossilHigh_TechHigh
- peak2025_DemandLow_FossilHigh_TechLow
- peak2025_DemandLow_FossilLow_TechHigh

3.13.5 Models

- IMACLIM 1.1

3.14 Socioeconomic factors and future challenges of the goal of limiting the increase in global average temperature to 1.5 °C

3.14.1 Publications

- <Literature placeholder>

3.14.2 Guiding questions

Explore the impacts of socioeconomic factors to SDG indicators.

1. Under various assumptions what factors can be the major to change SDGs?

3.14.3 Results

There are multiple channels that change SDGs implications.

1. Technological improvement in energy supply is the most important.

3.14.4 Scenarios

- SFCM_SSP2_Bio_1p5Degree
- SFCM_SSP2_Bio_2Degree
- SFCM_SSP2_Bio_Baseline
- SFCM_SSP2_EEEI_1p5Degree
- SFCM_SSP2_EEEI_2Degree
- SFCM_SSP2_EEEI_Baseline
- SFCM_SSP2_LifeStyle_1p5Degree
- SFCM_SSP2_LifeStyle_2Degree
- SFCM_SSP2_LifeStyle_Baseline
- SFCM_SSP2_Ref_1p5Degree
- SFCM_SSP2_Ref_2Degree
- SFCM_SSP2_Ref_Baseline
- SFCM_SSP2_ST_CCS_1p5Degree
- SFCM_SSP2_ST_CCS_2Degree
- SFCM_SSP2_ST_CCS_Baseline
- SFCM_SSP2_ST_bio_1p5Degree
- SFCM_SSP2_ST_bio_2Degree
- SFCM_SSP2_ST_bio_Baseline
- SFCM_SSP2_ST_nuclear_1p5Degree
- SFCM_SSP2_ST_nuclear_2Degree
- SFCM_SSP2_ST_nuclear_Baseline
- SFCM_SSP2_ST_solar_1p5Degree
- SFCM_SSP2_ST_solar_2Degree
- SFCM_SSP2_ST_solar_Baseline
- SFCM_SSP2_ST_wind_1p5Degree
- SFCM_SSP2_ST_wind_2Degree

- SFCM_SSP2_ST_wind_Baseline
- SFCM_SSP2_SupTech_1p5Degree
- SFCM_SSP2_SupTech_2Degree
- SFCM_SSP2_SupTech_Baseline
- SFCM_SSP2_combined_1p5Degree
- SFCM_SSP2_combined_2Degree
- SFCM_SSP2_combined_Baseline

3.14.5 Models

- AIM/CGE 2.0

3.15 C3IAM

3.15.1 Publications

- <Literature placeholder>

3.15.2 Guiding questions

<placeholder>

3.15.3 Results

<placeholder>

3.15.4 Scenarios

- SSP1_5.0
- SSP1_BAU
- SSP1_NDC
- SSP2_5.0
- SSP2_BAU
- SSP2_NDC
- SSP3_5.5
- SSP3_BAU
- SSP3_NDC

3.15.5 Models

- C3IAM 1.0

3.16 EPPA Study

3.16.1 Publications

- <Literature placeholder>

3.16.2 Guiding questions

<placeholder>

3.16.3 Results

<placeholder>

3.16.4 Scenarios

- 1.5CNow_Gradual
- 1.5CNow_OptTax
- 2CNow_Gradual
- 2CNow_OptTax
- Paris1.5C_OptTax
- Paris2C_Gradual
- Paris2C_OptTax
- ParisFlat
- ParisForever
- Ref

3.16.5 Models

- EPPA 6

3.17 GCAM Study

3.17.1 Publications

- <Literature placeholder>

3.17.2 Guiding questions

<placeholder>

3.17.3 Results

<placeholder>

3.17.4 Scenarios

- 20% abatement (FF&I)
- 20% abatement (GHG)
- 450 concentration
- 50% abatement (FF&I)
- 50% abatement (GHG)
- 550 concentration
- 650 concentration
- Core baseline
- High CO2 price
- Low CO2 price
- Policy baseline

3.17.5 Models

- GCAM 4.0

3.18 HEB Study

3.18.1 Publications

- <Literature placeholder>

3.18.2 Guiding questions

<placeholder>

3.18.3 Results

<placeholder>

3.18.4 Scenarios

- Deep
- Moderate

3.18.5 Models

- HEB 2.0

3.19 IMA15

3.19.1 Publications

- Van Vuuren, D. P., Stehfest, E., Gernaat, D. E. H. J., Van Den Berg, M., Bijl, D. L., De Boer, H. S., Daioglou, V., Doelman, J. C., Edelenbosch, O. Y., Harmsen, M., Hof, A. F. & Van Sluisveld, M. A. E. 2018. Alternative pathways to the 1.5 °c target reduce the need for negative emission technologies. Nature Climate Change, 8, 391-397.

3.19.2 Guiding questions

CDR strategies face several difficulties such as reliance on underground CO_2 storage and competition for land with food production and biodiversity protection. The question arises whether alternative deep mitigation pathways exist?

1. How essential are bioenergy with carbon capture and storage, and other negative-emission technologies for the 1.5 degree target?

3.19.3 Results

The study illustrates how a combination of alternative 1.5°C pathways can significantly reduce the need for CDR. They are based on the inclusion of options which are not normally considered in integrated assessment analyses, such as lifestyle change, significant reductions of greenhouse gas emissions other than CO_2, swift electrification of energy demand and low population growth. While each of these alternatives will still require rapid societal changes and faces its own specific barriers, several also show important synergies with other sustainability goals.

1. While this study shows that alternative options can greatly reduce the volume of CDR to achieve the 1.5 °C goal, nearly all scenarios still rely on BECCS and/or reforestation (even the hypothetical combination of all alternative options still captured 400 $GtCO_2$ by reforestation). Therefore, investment in the development of CDR options remains an important strategy if the international community intends to implement the Paris target.

3.19.4 Scenarios

- IMA15-AGInt
- IMA15-Def
- IMA15-Eff
- IMA15-LiStCh
- IMA15-LoNCO2
- IMA15-Pop
- IMA15-RenElec
- IMA15-TOT

3.19.5 Models

- IMAGE 3.0.1

3.20 MERGE ETL Study

3.20.1 Publications

- <Literature placeholder>

3.20.2 Guiding questions

<placeholder>

3.20.3 Results

<placeholder>

3.20.4 Scenarios

- BAU
- DAC15_50
- DAC2_66

3.20.5 Models

- MERGE-ETL 6.0

3.21 Global energy assessment

3.21.1 Publications

- GEA 2012. Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.
- Riahi, K., Dentener, F., Gielen, D., Grubler, A., Jewell, J., Klimont, Z., Krey, V., Mccollum, D., Pachauri, S., Rao, S., Van Ruijven, B., Van Vuuren, D. P. & Wilson, C. 2012. Chapter 17 - Energy Pathways for Sustainable Development. Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.
- Mccollum, D. L., Krey, V., Riahi, K., Kolp, P., Grubler, A., Makowski, M. & Nakicenovic, N. 2013. Climate policies can help resolve energy security and air pollution challenges. Climatic Change, 119, 479-494.
- Rogelj, J., Mccollum, D. L. & Riahi, K. 2013. The UN's 'Sustainable Energy for All' initiative is compatible with a warming limit of 2C. Nature Climate Change, 3, 545-551.
- Rao, S., Pachauri, S., Dentener, F., Kinney, P., Klimont, Z., Riahi, K. & Schoepp, W. 2013. Better air for better health: Forging synergies in policies for energy access, climate change and air pollution. Global Environmental Change, 23, 1122-1130.

3.21.2 Guiding questions

The main purpose of the GEA has been to establish a state-of-the-art assessment of the science of energy in light of the inevitable transformation that is required to address major challenges and avoiding potentially catastrophic future consequences for human kind and planetary systems. The transformation pathways developed within the framework of the GEA are designed to explore technical measures, policies, and related costs and benefits for meeting the following energy objectives:

- Improving energy access: Universal access to electricity and clean cooking by 2030;
- Reduce air pollution and improve human health: Achieve global compliance with World Health Organization (WHO) air quality standards (PM2.5 concentration < 35 μg/m3) by 2030;
- Avoid dangerous climate change: Limit global average temperature change to 2°C above preindustrial levels with a likelihood >50%;
- Enhance energy security: Reduce energy import dependence; increase diversity and resilience of energy supply (both by 2050).

1. Which are the fundamental key-messages common to the scenario ensemble?
2. Is universal access to modern energy carriers and cleaner cooking achievable by 2030 while limiting long term global warming to 2°C?

3.21.3 Results

The pathways show that it is technically possible to achieve improved energy access, air quality, and energy security simultaneously while avoiding dangerous climate change. In fact, a number of alternative combinations of resources, technologies, and policies are found capable of attaining these objectives. From a large ensemble of possible transformations, three distinct groups of pathways (GEA-Supply, GEA-Mix, and GEA-Efficiency) have been identified and analysed.

1. Limiting climate change to to 2°C will require a technological transformation of the global energy system over the next several decades, as well as the rapid introduction of policies and fundamental political changes toward concerted and coordinated efforts to integrate global concerns into local and national policy priorities. The GES analysis demonstrates that a sustainable future requires a transforamtion from today's energy systems to those with: (i) radical improvements in energuy systems, especially in the end-use, and (ii) greater shares of reneable energies and advanced energy systems with carbon capture and storage (CCS) for both fossil fuels and biomass.
2. Achieving universal access to clean cooking fuels and electricity requires that between US$36 billion and US$41 billion be spent annually over the next two decades. In addition to furthering human development and poverty alleviation goals, universal access is necessary for attaining World Health Organization guidelines for air quality in all countries by 2030. At the same time, in order to ensure a high likelihood of limiting global warming to 2°C, global CO2 emissions need to peak by about 2020 and then be reduced 30–70% by 2050 relative to 2000. Under the GEA pathways, energy security improves in the world as a whole and in the majority of regions: imports decline and supply diversity increases.

3.21.4 Scenarios

- GEA_Eff_1p5C
- GEA_Eff_1p5C_Delay2020
- GEA_Eff_2C_Delay2020
- GEA_Eff_AdvNCO2_1p5C
- GEA_Eff_base
- GEA_Mix_1p5C_AdvNCO2_PartialDelay2020
- GEA_Mix_1p5C_AdvTrans_PartialDelay2020
- GEA_Mix_2C_AdvNCO2_PartialDelay2020
- GEA_Mix_2C_AdvTrans_PartialDelay2020
- GEA_Mix_base

3.21.5 Models

- MESSAGE V.3

3.22 Low energy demand

3.22.1 Publications

- Grubler A, Wilson C, Bento N, Boza-Kiss B, Krey V, McCollum DL, Rao ND, Riahi K, Rogelj J, De Stercke S, Cullen J, Frank S, Fricko O, Guo F, Gidden M, Havlík P, Huppmann D, Kiesewetter G, Rafaj P, Schoepp W, Valin H. 2018. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nature Energy 3:515-527.

3.22.2 Guiding questions

Scenarios that limit global warming to 1.5 °C describe major transformations in energy supply and ever-rising energy demand. Here, we provide a contrasting perspective by developing a narrative of future change based on observable trends that results in low energy demand.

1. How does a narrative of future change based on observable trends which results in low energy demand look like?
2. Which quantitative changes in activity levels and energy intensity are required in the Global North and South for all major energy services consistent with the low energy demand narative?
3. Is it possible to limit global warming to 1.5 °C without relying on controversial negative emissions technologies such as bioenergy with carbon capture and storage (BECCS)?
4. What are sustainable development co-benefits of a low energy demand transformation?

3.22.3 Results

1. We find that global final energy demand by 2050 can be reduced to 245 EJ, around 40% lower than today's levels despite rising population, income and activity and show how changes in the quantity and type of energy services drive structural change in intermediate and upstream supply sectors (energy and land use).
2. Down-sizing the global energy system dramatically improves the feasibility of low-carbon supply-side transformation by renewables and electrification. Our scenario meets 1.5°C climate and other sustainable development goals, without relying on controversial negative emission technologies.

3.22.4 Scenarios

- LowEnergyDemand
- LowEnergyDemand_1.3_IPCC

3.22.5 Models

- MESSAGEix-GLOBIOM 1.0

3.23 Advanced demand-sector technologies and energy demand reduction in achieving ambitious carbon budget

3.23.1 Publications

- Napp, T. A., Few, S., Sood, A., Bernie, D., Hawkes, A., & Gambhir, A. 2019. The role of advanced demand-sector technologies and energy demand reduction in achieving ambitious carbon budgets. *Applied Energy*, *238*, 351–367. https://doi.org/10.1016/j.apenergy.2019.01.033

3.23.2 Guiding questions

Addressing residual emissions in ‘challenging-to-decarbonise’ sectors such as the industrial and aviation sectors relies on the development and commercialization of innovative advanced technologies, currently still in their infancy.

1. What is the role of advanced technologies in achieving deep decarbonisation of the energy system?
2. What are the technology-specific details (i.e. technologies used, contribution) of how rapid and deep carbon intensity reductions can be achieved in the energy demand sectors?
3. To what extent do demand side measures reduce the need for negative emissions?

3.23.3 Results

Key advanced technologies in the industrial sector include hydrogen-based steel, electrification (e.g. of glass and ceramics kilns, electrification of pulp and electric boilers in chemicals) and Carbon Capture and Storage from cement production. In the transport sector, electric trucks, hydrogen ships and planes and the hyperloop present a way to achieve deep decarbonisation of this sector. In the absence of advanced low-carbon technologies, residual or unabated emissions in 2100 remain at 4 Gt CO_2/yr for the transport sector and 4 Gt CO_2/yr for the industrial sector. With the inclusion of advanced low-carbon technologies, these are reduced to 0 Gt CO2/yr and 2 Gt CO_2/yr for the transport and industrial sectors, respectively (in the highest carbon price scenario).

1. Reducing residual emissions from demand-sectors is crucial for achieving <2 °C.
2. Advanced technologies and energy demand reduction reduces reliance on BECCS by ∼18%.
3. Targeted innovation in the demand sectors is required to realize this potential.

3.23.4 Scenarios

- AdvTech, Cen Dem, PE off (V3) CO2 budget 1.5
- AdvTech, Cen Dem, PE off (V3) CO2 price $100 (5% p.a.)
- AdvTech, Cen Dem, PE off (V3) CO2 price $150 (5% p.a.)
- AdvTech, Cen Dem, PE off (V3) CO2 price $200 (5% p.a.)
- AdvTech, Cen Dem, PE off (V3) CO2 price $250 (5% p.a.)
- AdvTech, Low Dem, PE off (V4) CO2 budget 1.5
- AdvTech, Low Dem, PE off (V4) CO2 price $100 (5% p.a.)
- AdvTech, Low Dem, PE off (V4) CO2 price $150 (5% p.a.)
- AdvTech, Low Dem, PE off (V4) CO2 price $200 (5% p.a.)

- AdvTech, Low Dem, PE off (V4) CO_2 price $250 (5% p.a.)

3.23.5 Models

- TIAM-Grantham 1.0

3.24 MESSAGE Study

3.24.1 Publications

- <Literature placeholder>

3.24.2 Guiding questions

<placeholder>

3.24.3 Results

<placeholder>

3.24.4 Scenarios

- SSP2_int_lc_15
- SSP2_int_lc_50
- SSP2_int_mc_15
- SSP2_int_mc_50
- SSP2_noint_lc_15
- SSP2_noint_lc_50
- SSP2_noint_mc_15
- SSP2_noint_mc_50
- SSP2_openres_lc_15
- SSP2_openres_lc_50
- SSP2_openres_mc_15
- SSP2_openres_mc_50

3.24.5 Models

- MESSAGEix-GLOBIOM_GEI 1.0

3.25 CEMICS CDR portfolio study

3.25.1 Publications

- Strefler, S., Bauer, N., Humpenöder, F., Klein, D., Popp, A., Kriegler, E. 2020. Carbon dioxide removal are not born equal. Submitted

3.25.2 Guiding questions

The study analyses how portfolios of carbon dioxide removal options can limit environmental side-effects.

1. To what extent does a portfolio of carbon dioxide removal options limit environmental side-effects?
2. Can these side-effects be further reduced at acceptable economic costs if CDR is limited?

3.25.3 Results

A mix of CDR options should be deployed as environmental side-effects increase with deployment, but do not accumulate across different options.

1. Controlled CDR is sufficient to keep 2C and 1.5C in reach.
2. A portfolio of CDR options can substantially reduce environmental side-effects.
3. The strategic value of CDR is already large at small CDR amounts

3.25.4 Scenarios

- CEMICS_SSP1-1p5C-fullCDR
- CEMICS_SSP1-1p5C-limCDR
- CEMICS_SSP1-1p5C-noCDR
- CEMICS_SSP1-2C-fullCDR
- CEMICS_SSP1-2C-limCDR
- CEMICS_SSP1-2C-noCDR
- CEMICS_SSP1-NPI
- CEMICS_SSP2-1p5C-fullCDR
- CEMICS_SSP2-1p5C-limCDR
- CEMICS_SSP2-1p5C-noCDR
- CEMICS_SSP2-2C-fullCDR
- CEMICS_SSP2-2C-limCDR
- CEMICS_SSP2-2C-noCDR
- CEMICS_SSP2-NPI

3.25.5 Models

- REMIND-MAgPIE 2.1-4.2

3.26 TIAM Study

3.26.1 Publications

- <Literature placeholder>

3.26.2 Guiding questions

<placeholder>

3.26.3 Results

<placeholder>

3.26.4 Scenarios

- AdvTech_CenDem_PEoff (V3) CO2 budget 1.5
- AdvTech_CenDem_PEoff (V3) CO2 price $100 (5% p.a.)
- AdvTech_CenDem_PEoff (V3) CO2 price $150 (5% p.a.)
- AdvTech_CenDem_PEoff (V3) CO2 price $200 (5% p.a.)
- AdvTech_CenDem_PEoff (V3) CO2 price $250 (5% p.a.)
- AdvTech_LowDem_PEoff (V4) CO2 budget 1.5
- AdvTech_LowDem_PEoff (V4) CO2 price $100 (5% p.a.)
- AdvTech_LowDem_PEoff (V4) CO2 price $150 (5% p.a.)
- AdvTech_LowDem_PEoff (V4) CO2 price $200 (5% p.a.)
- AdvTech_LowDem_PEoff (V4) CO2 price $250 (5% p.a.)
- Baseline

3.26.5 Models

- TIAM-Grantham 1.0

3.27 TIAM UCL Study

3.27.1 Publications

- <Literature placeholder>

3.27.2 Guiding questions

<placeholder>

3.27.3 Results

<placeholder>

3.27.4 Scenarios

- SSP2_1_75D-66
- SSP2_2D-66
- SSP2_BASE

3.27.5 Models

- TIAM-UCL 4.1.1

3.28 TIAM World Study

3.28.1 Publications

- <Literature placeholder>

3.28.2 Guiding questions

<placeholder>

3.28.3 Results

<placeholder>

3.28.4 Scenarios

- 20% abatement (FF&I)
- 20% abatement (GHG)
- 450 concentration
- 50% abatement (FF&I)
- 50% abatement (GHG)
- 550 concentration
- 650 concentration
- Core baseline
- High CO2 price
- Low CO2 price
- Policy baseline

3.28.5 Models

- TIAM-WORLD 1.0

3.29 C-ROADS Study

3.29.1 Publications

- <Literature placeholder>

3.29.2 Guiding questions

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3.29.3 Results

<placeholder>

3.29.4 Scenarios

- Ratchet-1.5-allCDR
- Ratchet-1.5-limCDR
- Ratchet-1.5-limCDR-noOS
- Ratchet-1.5-noCDR
- Ratchet-1.5-noCDR-noOS
- Reference

3.29.5 Models

- C-ROADS-5.005

3.30 EN-ROADS Study

3.30.1 Publications

- <Literature placeholder>

3.30.2 Guiding questions

<placeholder>

3.30.3 Results

<placeholder>

3.30.4 Scenarios

- Ratchet-1.5-allCDR
- Ratchet-1.5-limCDR
- Reference

3.30.5 Models

- En-ROADS-96

3.31 McKinsey Study

3.31.1 Publications

- <Literature placeholder>

3.31.2 Guiding questions

<placeholder>

3.31.3 Results

<placeholder>

3.31.4 Scenarios

- 1.5C A
- 1.5C B
- 1.5C C

3.31.5 Models

- McKinsey 1.0

3.32 E3ME Study

3.32.1 Publications

Mercure, J. F., Pollitt, H., Viñuales, J. E., Edwards, N. R., Holden, P. B., Chewpreecha, U., … Knobloch, F. 2018. Macroeconomic impact of stranded fossil fuel assets. *Nature Climate Change*, *8*(7), 588–593. https://doi.org/10.1038/s41558-018-0182-1

Holden, B., Edwards, N. R., Ridgwell, A., Wilkinson, R. D., Fraedrich, K., Lunkeit, F., … Viñuales, E. (n.d.). *Climate-carbon cycle uncertainties and the Paris Agreement*.

3.32.2 Guiding questions

<placeholder>

3.32.3 Results

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3.32.4 Scenarios

- 1.5C
- 2C
- 1.5C OPEC sell-out
- 2C OPEC sell-out
- Baseline

3.32.5 Models

- E3ME 6.1

4. Sectoral scenario studies (national and global)

4.1 Energy supply (only global)

4.1.1 IRENA Global Renewables Outlook

Publications

- IRENA. 2020. Global Renewables Outlook: Energy transformation 2050. International Renewable Energy Agency, Abu Dhabi. ISBN 978-92-9260-238-3

Guiding questions

The "Planned Energy Scenario (PES)" is the primary reference case for IRENA's Global Renewables Outlook, providing a perspective on energy system developments based on governments' current energy plans and other planned targets and policies (as of 2019), including Nationally Determined Contributions under the Paris Agreement unless the country has more recent climate and energy targets or plans.

1. What type of energy pathway do current and planned policies of governments result in?
2. What is the impact of energy-related CO_2 emissions under current plans and policies?
3. Do current plans and polices result in meeting Paris-Agreement targets?

Results

Current and planned policies of government do not align with long-term Paris Agreement targets.

1. Under current plans and policies, energy demand increases by about 20% by 2050, however this is lower than the rate observed in historical trends.
2. Under current plans and policies, energy-related CO_2 emissions remain more or less flat to 2050, despite increasing energy demand - a result of a combination of greater use of renewables and fuel-switching.
3. Under current plans and policies, global temperature rise could exceed 2.5°C by 2050, and continue to rise thereafter

Scenarios

- Planned Energy Scenario (PES)
- Tranforming Energy Scenario (TES)

Models

- REmap GRO2020

4.1.2 IEA

Publications

- IEA, 2017. Energy Technology Perspectives 2017: Catalyzing Energy Technology Transformations. International Energy Agency (IEA), Paris, France, 443 pp.
- IEA, 2017. World Energy Outlook 2017. International Energy Agency (IEA), Paris, France, 782 pp.

Guiding questions

<placeholder>

Results

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Models | Scenarios

- IEA Energy Technology Perspective Model 2017 | B2DS
- IEA World Energy Model 2017 | Faster Transition Scenario
- WEM 2019 | SDS

4.1.3 Shell

Publications

- Shell International B.V. 2018. Shell Scenarios: Sky – Meeting the Goals of the Paris Agreement. Shell International B.V. 36 pp.

Guiding questions

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Results

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Models | Scenarios

- Shell World Energy Model 2018 | Sky

4.2 Transport

4.2.1 Advance WP2

Publications

- Edelenbosch et al. 2017. Decomposing passenger transport futures: Comparing results of global integrated assessment models. Transportation Research Part D: Transport and Environment 55, 281-293.
- Edelenbosch, O. Y., et al. 2017.Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models. Energy 122, 701-710.

Guiding questions

This study aims to contribute for better understanding of the role of demand sector changes to achieve long-term climate mitigation targets, such as 2°C or 1.5°C.

1. To what extent can the following factors contribute to reduce emissions in the transport sector: activity reduction, energy efficiency, and fuel switching?
2. Which factors and technologies contribute to reduce emissions in the industry sector?
3. What are the opportunities or pitfalls in the specific sub-sectors in the industry, such as cement, iron, steel, or paper?
4. What challenges are specific to those sectors?

Results

The demand for energy services is projected to increase significantly in all three sectors as a result of population and economic growth. For instance, assuming no new climate policies, energy demand in the transport and industry sectors is projected to more than double.

If stringent climate policy consistent with the 2° C target is implemented, all demand sectors show strong potential for energy demand reductions. Drastic technology innovation to increase energy efficiency or boost use of low-carbon fuels are important to fully exploit this potential.

1. While all factors, activity reduction, energy efficiency, and fuel switching, can contribute to emission reduction in transport, in the long-term agrressive technology change for improved energy efficiency and fuel switching are required to meet internationally set climate targets.
2. In the industry sector alternative fuel use, both in the form of electricity and low carbon fuels, increases significantly in response to climate policy, especially during the second half of the century.

The ability to switch to alternative fuels to mitigate GHG emissions differs across models with technologically detailed models being less flexible in switching from fossil fuels to electricity.

3. Using industry sub-sector details like material, technology and energy to support the projected mitigation potential can provide improved insight in the feasibility of how emission reductions can be achieved.

Specifically, opportunities for material efficiency and technological change are subsector specific and at the same time affect the mitigation potential of the industry as a whole. In the cement sector for example reduction of use clinkers will depend on substitution material availability.

Scenarios

- ADVANCE_WP2_IND-450-FullTech
- ADVANCE_WP2_IND-Base-FullTech
- ADVANCE_WP2_TRA-450-FullTech
- ADVANCE_WP2_TRA-Base-FullTech
- ADVANCE_WP2_TRA-Ctax-FullTech

Models

- AIM/CGE 2.2
- DNE21+ V.ADVANCE
- IMAGE 3.0
- MESSAGE-Transport V.5
- WITCH-GLOBIOM 4.2

4.2.2 Transportation Infrastructures in a Low Carbon World

Publications

- Fisch-Romito, Vivien, and Céline Guivarch. 2019. Transportation Infrastructures in a Low Carbon World: An Evaluation of Investment Needs and Their Determinants. Transportation Research Part D: Transport and Environment 72 (July): 203–19. https://doi.org/10.1016/j.trd.2019.04.014.

Guiding questions

What are the main determinants of transportation infrastructure needs in a low carbon world?

1. How does investment needs are related to the overall demand for transport in climate policy scenarios?
2. What is the main determinant of transport infrastructure investments?

Results

The expenditure needed for transportation infrastructure is lower in low-carbon pathways than in baseline scenarios, both at the global and regional scales

1. The overall decrease of investment in transport infrastructure is brought about in particular by a reduction in transport activity. Modal shift from road to rail can be a lever to reduce investment needs only if combined with action on rail infrastructure occupancy.
2. Rail utilization rates and road construction costs are determining factors for investment in all regions.

Scenarios

- SSP1_NoPolicy_TranspBase
- SSP1_NoPolicy_TranspOpt
- SSP1_RCP34_TranspBase
- SSP1_RCP34_TranspOpt
- SSP1_RCP45_TranspBase
- SSP1_RCP45_TranspOpt
- SSP3_NoPolicy_TranspBase
- SSP3_NoPolicy_TranspOpt
- SSP3_RCP34_TranspBase
- SSP3_RCP34_TranspOpt
- SSP3_RCP45_TranspBase
- SSP3_RCP45_TranspOpt

Models

- IMACLIM 1.1

4.2.3 Key factors to reduce transport-related air pollutants & CO_2 emissions in Asian region

Publications

- Bao S, Nishiura O,Fujimori S,Oshiro K,Zhang R. 2020. Identification of key factors to reduce transport-related air pollutants and CO_2 emissions in Asian region, Sustainability.

Guiding questions

Explore the Asian transport-oriented air pollutants emissions and its interaction with climate policy

1. How much the climate policy and transport behaviour changes can reduce air pollutants in Asia

Results

Carbon pricing has the largest impacts on air pollutant emissions.

1. Transport policy and behavior has large impacts on air pollutants.

Scenarios

- Advanced_tech_high
- APS_strong
- Baseline
- Carbon_pricing
- Ene_Efficiency_High
- Occupancy_high
- SpeedHigh
- Sustainable development (SD)

Models

- AIM/Transport-National 1.0

4.2.4 AIM Transport

Publications

- Runsen Zhang et al 2018 Environ. Res. Lett. 13 054008

Guiding questions

This paper aims to investigate the interaction between transport policies, mitigation potential and the cost of meeting the goal of limiting warming to below 2 °C and 1.5°C.

1. Which transport policy has the most significant reduction potential?
2. Can transport policies reduce mitigation potential generated by climate mitigation policies to limit global warming to 2 °C and 1.5°C?
3. Is the contribution of transport policies more effective for stringent climate change targets in the 1.5°C scenario?

Results

This paper is intended to detect the potential for different transport policy interventions to reduce emissions and mitigation cost for the 2°C and 1.5°C targets.

1. Technological transformations such as vehicle technological innovations and energy efficiency improvements provide the most significant reduction potential.
2. Low-carbon transport policies can reduce the carbon price, gross domestic product loss rate, and welfare loss rate generated by climate mitigation policies
3. The degree of contribution of transport policies is more effective for stringent climate change targets.

Scenarios

- TERL_15D_LowCarbonTransportPolicy
- TERL_15D_NoTransportPolicy
- TERL_2D_LowCarbonTransportPolicy
- TERL_2D_NoTransportPolicy
- TERL_Baseline_LowCarbonTransportPolicy
- TERL_Baseline_NoTransportPolicy

Models

- AIM/CGE 2.1

4.2.5 REMIND Transport Study

Publications

- Rottoli, M., Dirnaichner, A., Pietzcker, R., & Luderer, G. (n.d.). Alternative electrification pathways for light duty vehicles in the energy transition.

Guiding questions

We apply a newly developed highly detailed transport sector model to spell out transport sector scenarios with different sectoral policies and overall mitigation ambition. In the transport sector, we look both at different technological focal points as well as transformative lifestyles.

1. Which interventions and policies are required in the transport sector to overcome burdens for technological transformation towards battery electric vehicles, fuel-cell vehicles or synfuel driven cars?
2. What are the consequences for the energy system for each of the technological options?
3. What can be the role of demand reduction to meet the mitigation targets compared to technological innovation?

Results

Deep CO2 emission reductions in the transport sector can be achieved with all alternative technological options until 2050. However, the upfront costs and energy requirements as well as the required demand-side policies vary strongly depending on the favoured technology.

1. For battery electric vehicle, increasing consumer acceptance is key for higher market shares. Besides infrastructure build-up and technological innovation for batteries, active anti-combustion engine policies have to be considered. For fuel-cell vehicles, premiums or other subsidies are required to reach competitive vehicle prices, as well as pessimistic assumptions on the development of battery electric vehicles. For synthetic fuels, the challenges are fully shifted to the supply side.
2. Direct electrification via battery electric vehicles poses the smallest burden on the electricity supply. Sufficient hydrogen supply for fuel-cell vehicles is possible without major mark-ups to the electricity production, however, we did not analyse the role of competing demands from other sectors. Although the model is able to provide enough electricity to produce synfuels to power at least 50% of the transport sector by 2050, the required investments are high and biomass-based and nuclear power plants might have to play a role. The burden on the power sector and the grid is significant due to the major increase in renewables required, with challenges in terms of stability of the grid and security of supply.
3. Significant reductions in energy and material demands are possible by shifting to public transport and non-motorized modes in cities. To avoid larger environmental impacts inflicted by the scale-up of alternative technologies, sustainable policies should also aim at reducing overall demand.

Scenarios

- Transport_Budg1100_BE
- Transport_Budg1100_BE-LS

- Transport_Budg1100_Conv
- Transport_Budg1100_Conv-LowD
- Transport_Budg1100_ConvCase
- Transport_Budg1100_ConvCaseWise
- Transport_Budg1100_ConvSyn
- Transport_Budg1100_ElecEra
- Transport_Budg1100_ElecEraWise
- Transport_Budg1100_ElecPush
- Transport_Budg1100_ElecPush-LowD
- Transport_Budg1100_FC
- Transport_Budg1100_H2Push
- Transport_Budg1100_HydrHype
- Transport_Budg1100_HydrHypeWise
- Transport_Budg1100_IC
- Transport_Budg1100_IC-LS
- Transport_Budg1100_ICsyn
- Transport_Budg1100_SynSurge
- Transport_Budg1100_SynSurgeWise
- Transport_NDC
- Transport_NDC_Conv
- Transport_NDC_ConvCase
- Transport_NDC_ConvCaseWise
- Transport_NDC_IC
- Transport_NPi
- Transport_NPi_Conv
- Transport_NPi_IC

Models

- REMIND-Transport 2.1

4.3 Buildings

4.3.1 Energy consumption of buildings in 2100

Publications

- Levesque A, Pietzcker R.C, Baumstark L, De Stercke S, Grübler A, Luderer G. 2018. How much energy will buildings consume in 2100? A global perspective within a scenario framework. Energy 148 514-527

Guiding questions

The scenarios investigate the range of possible pathways for buildings energy demand in response to socio-economic drivers

1. How large are the differences in buildings energy demand across SSP scenarios in the absence of climate change mitigation?
2. What are the main patterns of the future buildings' energy demand landscape?
3. Are there significant differences between developing and developed countries?

Results

The extent to which energy demand will grow in the future strongly depends upon socio-economic assumptions. Nevertheless, we can observe similar patterns across scenarios

1. Our results show growth in buildings' energy demand across all SSPs. This growth is especially strong when considering useful energy projections. In terms of final energy, the extent of the demand increase differs widely across scenarios: from 116 EJ/yr in 2010 to a range of 120-378 EJ/yr by 2100, underlining the importance of socio-economic, climatic and lifestyles development on long-term projections.
2. Despite the differences in aggregate energy demand, common patterns arise between scenarios. The final energy distribution across end-uses changes radically between 2010 and 2100. While in 2010, cooking and space heating constituted the main end-uses in developing and developed countries respectively, in 2100, appliances and lighting will be the dominant end-use, representing 30-60% of total demand.
3. In developing countries, space cooling will be as important as appliances and lighting, while in developed countries space heating is the next largest end use, accounting for roughly a fourth of demand. Our results indicate that developing countries will experience a deep electrification. Electrification will also concern developed countries due to the saturation of thermal needs and the growing demand for appliances and lighting.

Scenarios

- SSP1
- SSP2
- SSP3
- SSP4

- SSP5

Models

- EDGE-Buildings 1.0

4.3.2 Halving energy demand from buildings & low consumption practices

Publications

- Levesque A, Pietzcker R.C, Luderer G. 2019. Halving energy demand from buildings: The impact of low consumption practices, Tech For & Socl Chg 146 253-266

Guiding questions

Reductions of energy demand have an important role to play in a sustainable energy transition. Here we explore the extent to which the emergence of low energy consuming practices, encompassing new behaviours and the adoption of more efficient technologies, could contribute to lowering energy demand

1. To which extent can buildings energy demand be decreased by the adoption of low-consumption practices?
2. Which low-consumption practices have a significant impact on buildings energy demand?

Results

The adoption of low consumption practices can save more than half of the energy consumed in buildings

1. Half the buildings energy demand could be saved by 2050 and 61% by 2100
2. The decrease in energy demand is driven by new practices for hot water usage, insulation and by the increased use of efficient air conditioners and heat pumps.

Scenarios

- Practices-low
- Practices-reference
- Practices-verylow

Models

- EDGE-Buildings 2.0

4.3.3 Deep decarbonisation of building's energy services in demand & supply

Publications

- Levesque A, Pietzcker R.C, Baumstark L, Luderer G. 2020. Deep decarbonisation of buildings energy services through demand and supply transformations. Submitted.

Guiding questions

Decarbonising buildings energy demand will pass through two types of strategies: first through an overall reduction of energy demand, that could to some extent be reaped at negative costs; and second through a reduction of the carbon content of energy via fuel switching and supply side decarbonisation. This study assesses the contributions of each of these strategies for the decarbonisation of the buildings sector in line with a 1.5°C global warming.

1. What is the respective importance of energy demand reductions and carbon-content reductions for the decarbonisation of buildings in a 1.5°C scenario?
2. What is the impact of reducing the energy efficiency gap on energy demand and emissions?

Results

This study makes clear how important the reduction of the carbon content of energy is for the decarbonisation of buildings energy demand.

1. The reduction of the carbon content of energy accounts for 81% of the emission reductions in the sector compared to a baseline scenario without policy intervention. Energy demand reductions contribute the remaining 19% despite energy demand reductions of 31%.
2. The impact of closing the energy efficiency gap is of similar magnitude on buildings energy demand than carbon pricing in a 1.5°C scenario by 2050. Without supply side decarbonisation, efficiency improvements almost entirely suppress the doubling of emissions that would otherwise be expected, but fail to induce an absolute decline in emissions.

Scenarios

- Base
- Budg600
- Budg600-EG
- EG

Models

- REMIND-Buildings 2.0

4.3.4 Long term, cross-country effects of buildings insulation policies

Publications

- O.Y. Edelenbosch, D. Rovelli, A. Levesque, G. Marangoni and M. Tavoni. 2020. Long term, cross-country effects of buildings insulation policies. Technological Forecasting and Social Change (under review).

Guiding questions

What is the global potential for improved insulation of buildings as a climate policy measure, when taking in to account regional building stock dynamics and climate effects?

1. Can we identify the important regional drivers of building stock development, and how do these impact the projected building stock globally and in the long-term?
2. How does the regional development of building stock impact the projected insulation investments?
3. What is the impact of delayed policy implementation?

Results

The model shows that the majority of buildings standing in 2050 will be built after 2015. Especially in regions outside of the OECD the increasing shares of new buildings is striking. While space cooling demand is expected to grow due to economic development, the level of insulation of new buildings remains low in these regions. New construction polices could thereby have a significant impact.

1. We identify the current stock, economic growth, population, population age, and building lifetimes as key drivers that explain historically seen differences in buildings stock development. The model shows as a result large regional variation in building vintages across the world in 2050.
2. The model projections show that while globally the majority of buildings in 2050 are built after 2015, in Europe, the opposite is true. This has major consequences for policy impact of building codes. In Europe and other OECD countries, renovating the existing building stock results in significantly higher savings than implementing new construction policies, due to the slower stock turnover and the relatively high current isulation levels of new build buildings. Subsequently, Europe and other OECD countries are more vulnerable to lock in effects, therefore in these regions acting fast and implementing ambitious (nZEB level) standards is fundamental to reduce building sector emissions. In China and Africa, on the other hand, focusing on new construction policies can be extremely effective, saving on itself up to respectively 43% and 64% of space heating and cooling final energy demand in 2050
3. Assuming an electricity emission factor of 96 g/MJ (average of SSP2 baseline results for 2050 of the 6 marker models) and standard emission factors of other fuels globally implementation of the EPDB standards would save approximately 3 Gt worldwide. Delaying policy implementation with 10 years would reduce savings with about 1 Gt. In this case the largest relative losses due to delayed implementation occur in Europe, Russia and NCD countries.

Scenarios

- SSP1
- SSP2
- SSP2_2020_0.3_All

- SSP2_2020_0.3_NC
- SSP2_2020_1.0_All
- SSP2_2020_1.0_NC
- SSP3

Models

- EDGE-Buildings 3.0

4.3.5 Energy Systems: Demand perspective

Publications

- Michael Hartner, Sebastian Forthuber, Lukas Kranzl,Sara Fritz, Eric Aichinger, Andreas Müller. 2019. H2020 SET-Nav, D.5.8: WP5 Summary report - Energy Systems: Demand perspective (http://www.set-nav.eu/sites/default/files/common_files/deliverables/D5.8%20SET-Nav_WP5_Summary_report_final.pdf)

Guiding questions

In order to assess pathways towards a low carbon emission energy system, four pathway scenario narratives aiming at an overall CO_2 emission reduction target for the energy system as a whole of roughly -85% in the year 2050 compared to the year 2015 were developed in the SET-Nav project and transformed into projections for the building sector.

1. Which factors trigger renovation rate and depth and how might building related energy policies and other framework conditions affect energy demand in buildings?
2. Which factors trigger heating system choice (including district heating) and the uptake of on-site RES and how might energy policies and other framework conditions affect the energy supply mix of buildings and related generation of on-site RES?
3. How will these developments interact with the overall energy system?

Results

The total final energy demand decreases significantly in all pathways compared to the year 2015, varying from -36% to -32%. Reductions are mainly achieved for space heating, whereas space cooling demand increases significantly. Assuming a strong decarbonisation of the electricity and district heating supply systems of around -95%, the pathway calculations for the demand side in the SET-Nav project show that deep carbonization until 2050 is possible, although strong policy interventions in some form are needed as early as possible to set the path for all actors in each sector.

1. The pathway analysis show that the final energy consumption for space heating and hot water can be significantly reduced until 2050 through thermal refurbishments of the existing building stock, leading to a conservation of renewable resources and facilitation the integration of heat pumps. Ambitious CO_2 emission targets of more than 90% until the year 2050 can be reached. Our modelling results show that policies regarding the efficiency in the building can significantly influence the investment decision of building occupants and owners. However strong early measures to increase the thermal efficiency of the European building stock are needed to reach climate targets in line with the Paris agreement.
2. Very ambitious decarbonisation scenarios also go hand in hand with an early phase out of natural gas in the long term, triggering large investments in alternative technologies for heating. Electricity demand increases significantly due to a stronger diffusion of heat pumps. District heating can be a substitute for natural gas in urban areas and allows to integrate central low carbon heat sources. Heat pumps and solar systems are key technologies to reach low emissions in the building stock. The use of biomass is crucial; however, biomass potentials are limited.
3. The decarbonisation of the buildings stock is strongly linked to the electricity system. Only if the electricity system is decarbonized in parallel overall CO_2 emission reduction targets can be

reached. While final energy demand for heating is expected to still dominate the overall final energy demand in buildings, electricity demand peaks can be significantly influenced by space cooling.

Scenarios

- directed_vision_181015
- diversification_180904
- localization_181015
- national_champions_181011
- reference_181031

Models

- Invert/EE-Lab 1.9

4.3.6 Reducing building CO_2 emissions 80% by 2050

Publications

- Langevin J, Harris CB, Reyna JL. 2019. Assessing the potential to reduce building CO_2 emissions 80% by 2050. Joule 3(10): 2403-2424. https://doi.org/10.1016/j.joule.2019.07.013

Guiding questions

The study assesses the feasibility of reducing U.S. building energy CO_2 emissions 80% by 2050 - consistent with the U.S. Mid-Century Strategy - using a reproducible and granular model of U.S. building energy use

1. Can building energy-related CO_2 emissions be reduced 80% by 2050 relative to 2005 levels under plausible scenarios of efficient technology deployment, electrification, and renewable electricity penetration?
2. Which energy end uses and building types most influence reductions in overall building CO_2 emissions?
3. Which specific building technologies achieve the largest cost-effective CO_2 emissions reductions?

Results

A combination of aggressive efficiency measures, electrification, and high renewable energy penetration can reduce building energy CO_2 emissions by 72%–78% relative to 2005 levels, just short of the 2050 target.

1. By 2050, aggressive building efficiency, incentivized electrification, and high renewable penetration can reduce building energy CO_2 emissions up to 78% relative to 2005
2. CO_2 emissions reductions are driven by the heating, water heating, and envelope end uses in existing residential buildings
3. Prospective envelope, controls, and fuel switching heating and water heating technologies achieve the largest cost-effective CO_2 emissions reductions

Scenarios

- 1: RB 1T
- 2: RB 1T-2T
- 3: RB 1T-2T-3T
- 4: RB 1T-2T-3T (FS0)
- 5: RB 1T-2T-3T (FS20)
- 6: HR 1T-2T-3T
- 7: HR 1T-2T-3T FS0
- 8: HR 1T-2T-3T FS20
- 9: HR 3T (FS0)
- 10: HR 3T (FS20)

Models

- Scout-0.4.3

4.3.7 Annual Energy Outlook 2018

Publications

- U.S. Energy Information Administration, Annual Energy Outlook. 2018. DOE/EIA-0383. $25 carbon dioxide allowance fee Side Case (Washington, DC, February 2018). https://www.eia.gov/outlooks/archive/aeo18/

Guiding questions

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3. Prospective envelope, controls, and fuel switching heating and water heating technologies achieve the largest cost-effective CO_2 emissions reductions

Scenarios

- Baseline-AEO2018-HR

Models

- Scout-0.4.3

4.3.8 Zero emission technologies in a national building stock

Publications

- Sandberg N H, Naess J S, Brattebø H, Andresen I, Gustavsen A. 2020. What aggregated energy and GHG emission savings can be obtained by large-scale implementation of zero emission technologies in a national building stock? Submitted to Energy Policy.

Guiding questions

This study uses the dynamic building stock energy model RE-BUILDS 2.0 to estimate the potential energy and GHG emission savings from large-scale deployment of Zero Emission Building technologies in the Norwegian building stock

1. What development is to be expected in energy use and related GHG emissions in the Norwegian building stock towards 2050, in a Baseline scenario following recent trends?
2. What is the potential for additional savings from large-scale implementation of zero emission building technologies in new and renovated buildings towards 2050?
3. In the Norwegian context with domestic hydropower electricity production connected to the European electricity market with higher shares of non-renewable electricity production - what emission intensity factor should be applied for electricity and how does it affect the results?

Results

There is a large potential for energy and GHG emission savings from the Norwegian building stock, and large-scale deployment of zero emission building technologies will be important to reach the potential.

1. The Baseline scenario results in a 10% (7TWh) reduction in delivered energy, even though the simulated stock growth is 21% due to expected population growth. This is because a large share of the old and inefficient buildings is either demolished and replaced by new energy efficient construction or renovated and energy upgraded.
2. The most optimistic scenario results in additional energy savings of 30 TWh, or in total a 56% decrease in delivered energy from 2020 to 2050. Hence, stricter future regulations and practise will have important aggregated effects.
3. The applied emission intensity for electricity is critical for the estimated emissions. The results reveal a large relative GHG emission saving potential from all the five alternative emission factors for electricity that are applied. The absolute value, however, is 25 times higher when assuming the marginal emission factor than when assuming the average Norwegian consumption mix. In this context, we consider the marginal approach to better reflect the real saving potential, as a large reduction in electricity consumption in the Norwegian building stock affects the electricity production at the margin or makes available hydropower electricity to use in transport or other sectors.

Scenarios

- NOR_Baseline_a
- NOR_Baseline_b
- NOR_Baseline_c

- NOR_Baseline_d
- NOR_Baseline_e
- NOR_ZEB1_a
- NOR_ZEB1_b
- NOR_ZEB1_c
- NOR_ZEB1_d
- NOR_ZEB1_e
- NOR_ZEB2_a
- NOR_ZEB2_b
- NOR_ZEB2_c
- NOR_ZEB2_d
- NOR_ZEB2_e

Models

- RE-BUILDS 2.0

4.3.9 Daily enthalpy gradients and the effects of climate change on the thermal energy demand of buildings in the United States

Publications

- Fonseca, J., & Schlueter, A. 2020. Daily enthalpy gradients and the effects of climate change on the thermal energy demand of buildings in the United States. Applied Energy, 262, 114458. https://doi.org/10.1016/j.apenergy.2019.114458

Description

<placeholder>

Results

<placeholder>

Scenarios

- High Impact - 50th percentile
- High Impact - 97.5th percentile
- High Impact - 2.5th percentile
- Low Impact - 2.5th percentile
- Low Impact - 50th percentile
- Low Impact - 97.5th percentile
- Medium Impact - 2.5th percentile
- Medium Impact - 50th percentile
- Medium Impact - 97.5th percentile

Models

- DEG-USA 1.0
- HBLM-USA 1.0

4.4 Land use

4.4.1 The central role of peatland protection and restoration in climate change mitigation

Publications

- Humpenöder, F., Karstens, K., Lotze-Campen, H., Leifeld, J., Menichetti, L., Barthelmes, A., & Popp, A. 2020. Peatland protection and restoration are key for climate change mitigation. Environmental Research Letters, 15(10), 104093. https://doi.org/10.1088/1748-9326/abae2a

Guiding questions

The study presents the first quantitative model-based projections of future peatland dynamics and associated GHG emissions in the context of a 2°C mitigation pathway.

1. How do projections of AFOLU GHG emissions change if emissions from degraded peatlands are accounted for?
2. How do land-demanding mitigation options like bioenergy production affect intact peatlands in the future?
3. What is the potential of peatland protection and restoration to reduced peatland-related emissions?

Results

Peatland protection and restoration are key for climate change mitigation

1. Without dedicated peatland policy and even in the case of peatland protection, our results indicate that the land system would remain a net source of CO2 throughout the 21st century.
2. This result is in contrast to the outcome of current mitigation pathways, in which the land system turns into a net carbon sink by 2100.
3. According to our results, the land system would turn into a global net carbon sink by 2100, as projected by current mitigation pathways, if about 60% of present-day degraded peatlands would be rewetted in the coming decades, next to the protection of intact peatlands.

Scenarios

- SSP2_RCP2.6
- SSP2_RCP2.6+PeatProt
- SSP2_RCP2.6+PeatRestor

Models

- MAgPIE 4.2

5. National scenario studies

5.1 Africa

5.1.1 Pathways for low-carbon development in Africa

Publications

- van der Zwaan, B., Kober, T., Longa, F. D., van der Laan, A., & Jan Kramer, G. 2018. An integrated assessment of pathways for low-carbon development in Africa. Energy Policy, 117, 387–395. https://doi.org/10.1016/j.enpol.2018.03.017

Guiding questions

In this paper we investigate the prospects for the large-scale use of low-emission energy technologies in Africa. We use the TIAM-ECN model for our study, which renewables are detailed for energy systems research through a technology-rich cost-minimisation procedure.

1. How can modern forms of energy be supplied to the continent while controlling global climate change through low-emission development strategies (LEDS)?
2. Is Africa capable of “leap-frogging” the use of fossil fuels, that is, launching energy systems that from the outset mostly rely on renewable forms of energy, rather than following the pathways of developed countries?
3. What is the cost-optimal configuration of renewable energy expansion in Africa?

Results

The results from our analysis fully support an Africa-led effort to substantially enhance the use of the continent's renewable energy potential.

1. Results suggest that the current aim of achieving 300GW of additional renewable electricity generation capacity by 2030 is perhaps unrealistic, even given high GDP and population growth: we find figures that are close to half this level.
2. We find evidence for leap-frogging opportunities, by which renewable energy options rather than fossil fuels could constitute the cost-optimal solution to fulfil most of Africa's growing energy requirements
3. The use of renewable energy resources such as hydro, solar and wind power receives a major impetus under stringent climate change control. Biomass experiences a turn-around, as its use in traditional carbon-intensive (non-sustainable) ways for e.g. cooking and heating (mostly in solid form, essentially fuel wood and charcoal) is replaced by modern low-carbon (sustainable) usage in many sectors, notably cooking and its combustion in solid (waste) form in thermal power plants.

Scenarios

- 2DC
- CAP
- REF
- TAX

Models

- TIAM-ECN AFR 1.1

5.1.2 Kenya – are large-scale renewable energy deployment and dedicated low-carbon energy policy necessary?

Publications

- Dalla Longa, F., & van der Zwaan, B. 2017. Do Kenya’s climate change mitigation ambitions necessitate large-scale renewable energy deployment and dedicated low-carbon energy policy? Renewable Energy, 113, 1559–1568. https://doi.org/10.1016/j.renene.2017.06.026

Guiding questions

Kenya’s climate change mitigation ambitions are analysed from an energy system perspective, with a focus on the role of renewable and other low-carbon energy technologies on achieving Kenya's NDCs. We use the TIAM-ECN model to characterize plausible development pathways for the Kenyan energy mix until 2050 under different climate change mitigation scenarios.

1. Are the emission mitigation objectives of Kenya's NDC achievable and what do they entail for the energy mix?
2. What are the possible additional costs of the Kenyan energy system under stringent mitigation scenarios?
3. Are dedicated low-carbon energy policy measures necessary in all sectors to achieve Kenya's NDC ambitions?

Results

We conclude that the power sector can expand with mostly renewable energy options even in the absence of stringent greenhouse gas abatement targets. On the contrary, on the demand side a substantial deployment of low-carbon technologies is triggered only when ambitious emission reduction objectives are in place.

1. We find that Kenya’s NDC target is achievable with a timely deployment of renewable energy.
2. Additional costs in 2050 range between 0.5% and 2% of Kenya’s GDP in our mitigation scenarios.
3. Stringent climate change policies are needed mostly in the residential and transport sectors, while the power sector can expand with low-carbon technologies even without GHG abatement targets.

Scenarios

- CAP
- NDC
- REF
- TAX

Models

- TIAM-ECN KEN 1.1

5.1.3 Prospects for hydropower in Ethiopia: energy-water nexus analysis

- van der Zwaan, B., Boccalon, A., & Dalla Longa, F. 2018. Prospects for hydropower in Ethiopia: An energy-water nexus analysis. Energy Strategy Reviews, 19, 19–30. https://doi.org/10.1016/j.esr.2017.11.001

Guiding questions

We investigate the prospects for large-scale hydropower deployment in Ethiopia by the middle of the century under climate change mitigation scenarios, using two distinct modelling approaches.

1. What are the expected levels of hydropower production in Ethiopia by the middle of the century, under stringent climate change control policy?
2. Can energy-system cost-minimization and hydrological models be combined to provide useful insights on hydropower development as a climate change mitigation option?
3. What is the key policy recommendation for the future development of hydropower in Ethiopia?

Results

With two distinct modelling approaches we find high projections for future hydropower generation, despite domestic water use and irrigated agriculture water demand expansions, and irrespective of hydrological effects from climate change in terms of a drop in average precipitation nationwide.

1. Our projections indicate hydropower production levels between 71 and 87 TWh/yr by 2050 in a stringent climate change control scenario in which Ethiopia contributes substantially to global efforts to reach the 2°C target of the Paris Agreement.
2. Our combined energy cost-minimisation and hydrological balance analysis shows that our models can be jointly used for the assessment of hydropower as climate change mitigation option, and can assist in the design of policies that integrate the energy and water sectors.
3. Our case study did not yield direct reasons for the Ethiopian government to swiftly stop pursuing its current ambitious national hydropower development plan, but we encourage it to adequately internalise an extensive range of factors - including environmental, geopolitical and social - that may induce it to take a different course.

Scenarios

- Baseline
- RCP2.6

Models

- TIAM-ECN ETH 1.1

5.1.4 Alternatives for climate mitigation in Madagascar

Publications

- Nogueira, L. P., Longa, F. D., & van der Zwaan, B. 2020. A cross-sectoral integrated assessment of alternatives for climate mitigation in Madagascar. Climate Policy, 1–17. https://doi.org/10.1080/14693062.2020.1791030

Guiding questions

Using the integrated assessment model TIAM-ECN, we analyse how Madagascar's nationally determined contribution (NDC) to the Paris Agreement can be implemented in both the energy and non-energy sectors.

1. What is the role of mitigation in AFOLU and in the Malagasy energy system to achieve the NDC target of 2030 and beyond?
2. Given the links between AFOLU and energy sectors in Madagascar, which co-benefits (related to Sustainable Development Goals) can be maximized under the different mitigation scenarios?
3. Which energy technologies are key for the transition towards a low-carbon economy in Madagascar?

Results

We find that land use is the main sector in which large greenhouse gas (GHG) emission reductions must be achieved, but there are opportunities to also exploit the country's abundant domestic low-carbon energy resources.

1. Biomass may well remain the most important energy resource in Madagascar until 2050, mainly driven by residential cooking demand. Solid biomass stoves with efficient combustion should be promoted hand-in-hand with alternative fuels, e.g. electricity and bioethanol.
2. Promoting GHG mitigation in both AFOLU and energy sectors maximizes co-benefits, which enables achieving a higher number of sustainable development goals (SDGs).
3. Providing electricity for household services is an important part of climate change mitigation. Investments in power distribution infrastructure and decentralized electricity generation are needed to achieve electrification of rural households.

Scenarios

- NDC
- NDC+
- REF

Models

- TIAM-ECN MDG 1.1

5.2 Americas

5.2.1 Are conventional energy megaprojects competitive?

Publications

- Köberle, A. C., Garaffa, R., Cunha, B. S. L., Rochedo, P., Lucena, A. F. P., Szklo, A., & Schaeffer, R. 2018. Are conventional energy megaprojects competitive? Suboptimal decisions related to cost overruns in Brazil. Energy Policy, 122, 689–700. https://doi.org/10.1016/j.enpol.2018.08.021
- Fragkos, P., Laura van Soest, H., Schaeffer, R., Reedman, L., Köberle, A. C., Macaluso, N., … Iyer, G. 2021. Energy system transitions and low-carbon pathways in Australia, Brazil, Canada, China, EU-28, India, Indonesia, Japan, Republic of Korea, Russia and the United States. *Energy, 216*, 119385. https://doi.org/10.1016/j.energy.2020.119385
- R Rochedo, P. R., Soares-Filho, B., Schaeffer, R., Viola, E., Szklo, A., Lucena, F. P., … Rathmann, R. 2018. The threat of political bargaining to climate mitigation in Brazil. *Nature Climate Change*. https://doi.org/10.1016/j.energy.2020.119385
- Schaeffer, R., Köberle, A., van Soest, H. L., Bertram, C., Luderer, G., Riahi, K., … Potashnikov, V. 2020. Comparing transformation pathways across major economies. *Climatic Change*, *162*(4), 1787–1803. https://doi.org/10.1007/s10584-020-02837-9
- Köberle, A. C., Rochedo, P. R. R., Lucena, A. F. P., Szklo, A., & Schaeffer, R. 2020. Brazil's emission trajectories in a well-below 2 °C world: the role of disruptive technologies versus land-based mitigation in an already low-emission energy system. *Climatic Change*, *162*(4), 1823–1842. https://doi.org/10.1007/s10584-020-02856-6

Guiding questions

This study analyses the competitiveness of energy megaprojects when accounting for construction cost overruns (CCO).

1. Do optimistic assumptions on techno-economic performance of megaprojects favour their inclusion in the solution of integrated assessment models (IAMs), preventing higher shares of non-hydro renewables, energy efficiency and other low-carbon options?
2. Do the inclusion of regional cost overruns and delays for energy megaprojects can affect the solution of a cost-optimization model for the expansion of energy infrastructure in Brazil?

Results

CCO inclusion in IAMs reflects a more realistic baseline scenario, indicating renewable energy sources as the least-cost options for the energy supply system expansion, and reducing GHG emissions.

1. CCO inclusion in IAMs may raise the cost of the baseline scenario, thereby reducing the perceived cost of climate change mitigation by showing that the business-as-usual scenarios assumed as costless actually have a hefty cost associated with them.
2. At least in Brazil, the focus should be on small(er)-scale solutions for power generation. Such projects may have a higher investment cost per unit of capacity but run a much lesser risk of facing significant delays and cost overruns.

3. The real appraisement of CCO of megaprojects can indicate non-hydro renewables, energy efficiency and other low-carbon options as the least-cost technologies for the energy supply system expansion, even in the absence of carbon mitigation policies, reducing GHG emissions.

Scenarios

- BL
- OR

Models

- COPPE_MSB-Brazil 2.0

5.2.2 Integration of Renewable Energy Sources in the Mexican Energy System

Publications

- Sarmiento, L., Burandt, T., Löffler, K., & Oei, P.-Y. 2019. Analyzing Scenarios for the Integration of Renewable Energy Sources in the Mexican Energy System—An Application of the Global Energy System Model (GENeSYS-MOD). Energies, 12(17), 3270. https://doi.org/10.3390/en12173270

Guiding questions

This paper uses numerical techno-economic modelling to analyse the effect of current national renewable targets and climate goals on the cost and structural composition of the Mexican energy system.

1. How do costs and power mixes change in response to variations in energy and climate policies? Specifically, what are the effects of current renewable targets and climate goals vis-a-vis a scenario without the implementation of climate policies and another attaining full decarbonization.
2. Second, what is the 2050 cost-optimal share of renewables in the Mexican energy mix for the power, heating and transportation sectors?
3. Are the climate goals and renewable targets aligned and how much do these deviates from the full decarbonization and policy free scenarios?

Results

Results from the study show that Mexican renewable targets are insufficient and sub-optimal: the model shows that the optimal share of renewables for the generation of electricity is 80%, that is, 30% higher than current commitments in the national strategy for the promotion of clean fuels and technologies. Even more, the share of renewables in the power mix between BAU and National Targets is very similar. This indicates that current renewable targets do not even deviate from a scenario without climate policies, meaning that there is a misalignment between climate goals and renewable targets.

1. A significant dependence of the energy system on photovoltaics and natural gas can be observed.
2. The 2050 cost-optimal share of renewables for the production of electricity, transportation and industrial heating is respectively 75%, 90% and 5%.
3. As national renewable targets for the power sector are lower than the cost-optimal share of renewables, equivalent to the shares in a scenario without climate policies and completely disconnected from national climate goals, these should be modified.

Scenarios

- 100% Renewable 1.0
- BAU 1.0
- Climate Goals 1.0
- National Targets 1.0

Models

- GENeSYS-MOD-MEX 2.1

5.2.3 Long-term Deep Decarbonisation Pathways for Ecuador

Publications

- Villamar, D, Soria, R, Rochedo, P, Szklo, A, Imperio, M, Carvajal, P, Schaeffer, R. Long-term Deep Decarbonisation Pathways for Ecuador: Insights from an Integrated Assessment Model. Energy Strategy Reviews (under review)

Guiding questions

What would be the future energy and emissions pathway for Ecuador, framed in a decarbonization trajectory aligned with the 1.5C target of the Paris Agreement?

1. How would Ecuador face the post petroleum era and its energy transition in the next decades? Is it an opportunity for a sustainable energy development?
2. Is there a decarbonisation pathway for Ecuador that does not oppose the country's long-term economic development?
3. Which are the technologies required for decarbonizing Ecuador's energy and land sectors?

Results

Ecuador's NDC are not aligned with the "well below" 2°C target, but achieving deep decarbonisation is possible through bioenergy, electrification and reforestation.

1. In the reference scenario, oil still remains as the main energy source, fossil fuels increase its share in the power generation matrix and a rampant deforestation is observed to make room for pastures and grasslands
2. However, to achieve negative emissions, biomass is a key energy fuel, including disruptive technologies as bioenergy with carbon capture and storage (BECCS).
3. Also, renewable energies dominate the power generation, allowing a massive electrification of transportation, buildings and industry, suitable to decarbonize the country.

Scenarios

- DDP_High
- MinC

Models

- ELENA-Ecuador 1.0

5.2.4 Economic and social implications of low-emission development pathways in Brazil

Publications

- La Rovere, E. L., Wills, W., Grottera, C., Dubeux, C. B. S., & Gesteira, C. 2018. Economic and social implications of low-emission development pathways in Brazil. Carbon Management, 9(5), 563–574. https://doi.org/10.1080/17583004.2018.1507413

Guiding questions

<placeholder>

Results

<placeholder>

Scenarios

- 1.5C
- GPS
- MA1T
- MA2T
- Reference

Models

- IMACLIM-BR 1.0

5.2.5 Publication

Publications

- < placeholder >

Guiding questions

< placeholder >

Results

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Scenarios

- 100% RE
- 100% renewable primary energy
- central
- central low fuel price
- central low RE cost
- central, low fossil fuel price
- central, low renewables cost
- delayed electrification
- low demand
- low land
- net negative

Models

- RIO-USA 1.0

5.2.6 Publication

Publications

- < placeholder >

Guiding questions

< placeholder >

Results

< placeholder >

Scenarios

- 100% RE
- 100% renewable primary energy
- central
- central low fuel price
- central low RE cost
- central, low fossil fuel price
- central, low renewables cost
- delayed electrification
- low demand
- low land
- net negative

Models

- RIO-USA 1.0
- EnergyPATHWAYS-USA 1.0

5.2.7 Study

Publications

- <Literature placeholder>

Guiding questions

<placeholder>

Results

<placeholder>

Scenarios

- CCS_XNDC
- DD1
- DD2
- HdNC_XNDC

Models

- IMACLIM-ARG 1.0

5.3 Asia

5.3.1 Asian INDC Assessments: The Case of Thailand.

Publications

- Limmeechokchai, B., Chunark, P., Fujimori, S., & Masui, T. 2017. Asian INDC Assessments: The Case of Thailand. In Post-2020 Climate Action (pp. 157–178). https://doi.org/10.1007/978-981-10-3869-3_10

Guiding questions

Explore the NDC implications in Asian countries (Thailand, Vietnam and India)

1. NDC impacts on energy and economy

Results

NDC has not much impacts on economy

1. NDC has not much impacts on economy

Scenarios

- BaU
- RED1
- RED2
- RED3
- RED4

Models

- AIM/Hub-Thailand 2.0

5.3.2 The Role of Renewable Energies in Vietnam with respect to the INDCs

- Tran, T. T., Fujimori, S., & Masui, T. 2017. Realizing the Intended Nationally Determined Contribution: The Role of Renewable Energies in Vietnam. In Post-2020 Climate Action (pp. 179–200). https://doi.org/10.1007/978-981-10-3869-3_11

Guiding questions

Explore the NDC implications in Asian countries (Thailand Vietnam and India).

1. NDC impacts on energy and economy.

Results

NDC has not much impacts on economy.

1. NDC has not much impacts on economy.

Scenarios

- AddRE-HighINDC
- BaU
- HighRE-HighINDC
- HighRE-LowINDC
- LowRE-HighINDC
- LowRE-LowINDC

Models

- AIM/Hub-Vietnam 2.0

5.3.3 Implications of Japan’s 2030 target for long-term low emission pathways

Publications

- Oshiro, K., Kainuma, M., & Masui, T. (2017). Implications of Japan’s 2030 target for long-term low emission pathways. Energy Policy, 110, 581–587. https://doi.org/10.1016/j.enpol.2017.09.003

Guiding questions

Exploring the impact of Japan’s NDC target for the long-term goal by 2050 as well as the feasibility of the 2030 target itself.

1. Is the ambition level of the NDC target sufficient given the 2050 goal to reduce GHG emission by 80%?
2. What are the key mitigation options for meeting both 2030 and 2050 goals?
3. What is the implication of different 2030 target level for the longer-term transformation pathways?

Results

NDC implementation is effective for energy system changes, while additional mitigation actions are required to meet the longer-term goals.

1. Implementation of the NDC could consolidate a transition from the baseline trajectory for decarbonization, but more actions are needed after 2030.
2. Energy efficiency and decarbonization of energy supply are key options both for 2030 and 2050 goals, while strong electrification is needed mainly after 2030.
3. Without enhancing the 2030 target, rapid and huge transformation of energy system after 2030 would be required.

Scenarios

- MILES_baseline
- MILES_INDC80

Models

- AIM/Enduse-Japan 2.1

5.3.4 Energy transformation cost for the Japanese mid-century strategy

Publications

- Fujimori, S., Oshiro, K., Shiraki, H., & Hasegawa, T. 2019. Energy transformation cost for the Japanese mid-century strategy. Nature Communications, 10(1), 4737. https://doi.org/10.1038/s41467-019-12730-4

Guiding questions

Exploring the policy costs reduction by using the economic model integrating an energy system model's outputs, using Japan's mid-century climate mitigation target as an example.

1. Economic impacts of meeting Japan's 2050 goal to reduce GHG emissions by 80% by 2050.
2. The comparison of the level of economic impact between the integrated model and conventional economic model alone.
3. Which sectors are main contributor to the differences between these two modelling approaches?

Results

The economic impact estimated with the integrated model were significantly lower than those in the conventional economic model.

1. The GDP losses in 80% reduction goal by 2050 in Japan were estimated around 1% based on the integrated model.
2. The GDP losses estimated with the integrated model were significantly lower than those in the conventional economic model
3. Industry and service sector energy consumption are the main factors causing these differences.

Scenarios

- 80NPi
- BaU
- NoCCS_80NPi
- NoCCS_BaU
- NoNuc_80NPi
- NoNuc_BaU

Models

- AIM/CGE-Enduse-Japan 1.0

5.3.5 Japan’s long term climate mitigation target and the relevance of uncertain nuclear policy

Publications

- Silva Herran, D., Fujimori, S., & Kainuma, M. 2019. Implications of Japan’s long term climate mitigation target and the relevance of uncertain nuclear policy. Climate Policy, 19(9), 1117–1131. https://doi.org/10.1080/14693062.2019.1634507

Guiding questions

Assessment of 80% emission reduction target by 2050 in Japan considering scenarios with limited nuclear power deployment, and limited mitigation capacity.

1. Is it possible to achieve Japan's 2050 mitigation goal with limited availability of key mitigation measures?
2. What is the role of limited availability of nuclear power in achieving the 2050 goal?
3. What are the macroeconomic and energy security implications?

Results

Target of 80% emissions reduction by 2050 was assessed with a CGE model in scenarios assuming limited availability of key mitigation measures.

1. 80% emissions reduction by 2050 is feasible for all scenarios irrespective of which mitigation measure is limited, but with varying levels of economic and energy systems impacts; considerable reductions in energy consumption are needed in addition to energy supply dominated by low carbon sources.
2. The long-term target is feasible even with early phase out of nuclear power, and its absence can be counterbalanced by natural gas and CCS deployment.
3. The macroeconomic impact (GDP loss) was the largest when CCS is unavailable, and relatively small when nuclear power is limited or phased out; energy security indicators improved compared to the baseline in mitigation scenarios; expanding the availability of renewable resources lowers the macroeconomic impacts but doesn't affect the relative relevance of limiting mitigation measures.

Scenarios

- AEEI_L_NDC80
- Default_NDC80
- NoCCS_NDC80
- Nuc_H_NDC80
- Nuc_L_NDC80
- Nuc_no_NDC80
- PrFossil_L_NDC80
- RE_CostRed_L_NDC80
- Reference
- vreH_Default_NDC80

- vreH_NoCCS_NDC80
- vreH_Nuc_L_NDC80
- vreH_Reference

Models

- AIM/Hub-Japan 2.1

5.3.6 Decarbonizing China’s energy system: electricity, transportation, heat, industrial sectors

Publications

- Burandt, T., Xiong, B., Löffler, K., & Oei, P. Y. 2019. Decarbonizing China’s energy system – Modeling the transformation of the electricity, transportation, heat, and industrial sectors. Applied Energy, 255, 113820. https://doi.org/10.1016/j.apenergy.2019.113820

Guiding questions

This paper describes three potential decarbonization pathways to analyse different effects for the electricity, transport, heating, and industrial sectors until 2050. Using an enhanced version of the multi-sectoral, open-source Global Energy System Model, enables us to assess the impact of different CO_2 budgets on the upcoming energy system transformation. A detailed provincial resolution allows for the implementation of regional characteristics and disparities within China. Conclusively, we complement the model-based analysis with a quantitative assessment of current barriers for the needed transformation.

1. What are suitable pathways for the decarbonization of the Chinese energy system?
2. What role does sector-coupling play in the fulfilment of climate goals?
3. What effects will such a low-carbon transition have on the Chinese coal consumption?

Results

Results indicate that overall energy system CO_2 emissions and in particular coal usage have to be reduced drastically to meet (inter-) national climate targets. Specifically, coal consumption has to decrease by around 60% in 2050 compared to 2015. The current Nationally Determined Contributions proposed by the Chinese government of peaking emissions in 2030 are, therefore, not sufficient to comply with a global CO_2 budget in line with the Paris Agreement. Renewable energies, in particular photovoltaics and onshore wind, profit from decreasing costs and can provide a more sustainable and cheaper energy source. Furthermore, increased stakeholder interactions and incentives are needed to mitigate the resistance of local actors against a low-carbon transformation.

1. China’s Nationally Determined Contributions do not comply with the Paris Agreement.
2. Sector coupling increases the electricity demand by 100% (2 °C) to 400% (1.5 °C).
3. Incentives for local actors are needed for a sustainable low-carbon transformation.

Scenarios

- Ambitious 1.0
- Limited Effort 1.0
- Paris Agreement 1.0

Models

- GENeSYS-MOD-CHN 2.3

5.3.7 Macroeconomic pathways of the Saudi economy: global mitigation action versus the opportunity of national energy reforms

Publications

- Soummane, Salaheddine, Frédéric Ghersi, and Julien Lefèvre. 2019. Macroeconomic pathways of the Saudi economy: The challenge of global mitigation action versus the opportunity of national energy reforms. Energy policy 130 (2019): 263-282. https://www.sciencedirect.com/science/article/pii/S0301421519302356

Guiding questions

We analyse the mid-term macroeconomic challenge to Saudi Arabia of a global low-carbon transition reducing oil revenues, versus the opportunity of national energy reforms.

1. What are the macroeconomic implications for Saud Arabia of oil prices compatible with the Paris Agreement?
2. Can domestic energy price reforms and energy efficiency measures mitigate the impact of oil rent losses for Saudi Arabia?

Results

Low oil prices are associated with macroeconomic losses for Saudi Arabia. By 2030, shifting from the NPS to the SDS oil price of the IEA lowers economic growth, increases unemployment and public debt. Energy price reforms and efficiency measures can mitigate the economic impact of oil rent losses.

1. By 2030, the Saudi economy loses 1.4 GDP points, 1.6 employment points and USD 504 billion trade surplus accumulation from shifting from IEA's NPS to IEA's SDS oil prices. Its cumulated public deficit rises to 92.8% of GDP.
2. National reforms gradually aligning Saudi energy prices on international prices and inducing structural change of Saudi activity away from energy-intensive industries mitigate these costs if a share of the public income from energy-price deregulation is directed to investment.
3. However, they reduce the cumulated trade surplus and fail to control public deficit accumulation. Sensitivity analysis confirms the capacity of national energy reforms to mitigate the activity cost of global mitigation action, but aggravates the threat of an escalating public deficit.

Scenarios

- Baseline
- Low-Oil-Price
- Reformed

Models

- KLEM-SAU 1.0

5.3.8 Publication

Publications

- <Literature placeholder>

Guiding questions

The housing module of the Sustainable Alternative Futures for India (SAFARI) model contributes the first annually, dynamically computed estimate of India's affordable housing shortage. We consider improved benchmarks for quality of life and estimate shortage up to 2050.

1. How much of the annual and dynamic housing shortage will be met at current rates of affordable housing construction (BAU)? At what increased construction rates will this shortage be met?
2. What are the energy and resource implications of meeting this shortage along with India's growing consumption patterns?
3. With India's urbanization trends, what type of built form would result in the fewest land, emissions, and energy trade-offs and most quality-of-life benefits when combined with urban transport?

Results

While current government estimates of India's affordable housing shortage can be met in a business-as-usual scenario, our dynamically computed estimate based on improved quality of life benchmarks will need increased construction rates. However, the land, energy and emission trade-offs can be limited through better urban planning.

1. Current construction rates are not sufficient to meet India's affordable housing shortage based on our recalibrated benchmarks. A 50-60 % increase in annual construction will be required to meet the shortage by 2030-2040.
2. The increase in energy demands and emissions is predominantly driven by India's growing consumption patterns of higher-income housing rather than from bridging affordable housing shortage.
3. Compact form with high urban green space per capita and public transport results in the least land conversion, and emissions and energy trade-offs. Urban sprawl with higher shares of private transport results in the greatest land conversion and emissions and energy trade-offs.

Scenarios

- SAFARI_BAU
- SAFARI_HFA_AMB
- SAFARI_HFA_CUR
- SAFARI_HFA_HighEff
- SAFARI_HFA_LeastEff
- SAFARI_HFA_SDG
- SAFARI_HFA_SDG_Compact
- SAFARI_HFA_SDG_Sprawl

Models

- SAFARI 1.0

5.3.9 Asian INDC Assessments: The Case of Thailand

Publications

- Limmeechokchai, B., Chunark, P., Fujimori, S., & Masui, T. 2017. Asian INDC Assessments: The Case of Thailand. In Post-2020 Climate Action (pp. 157–178). https://doi.org/10.1007/978-981-10-3869-3_10

Guiding questions

< placeholder >

Results

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Scenarios

- BaU

Models

- AIM/Hub-Thailand 2.0

5.3.10 India INDC Assessment: Emission Gap Between Pledged Target and 2 °C Target

Publications

- Shukla, P. R., Mittal, S., Liu, J.-Y., Fujimori, S., Dai, H., & Zhang, R. (2017). India INDC Assessment: Emission Gap Between Pledged Target and 2 °C Target. In Post-2020 Climate Action (pp. 113–124). https://doi.org/10.1007/978-981-10-3869-3_7

Guiding questions

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Results

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Scenarios

- INDC
- Reference
- Two-Degree

Models

- AIM/Hub-India 2.0

5.3.11 An Assessment of Indonesia's Intended Nationally Determined Contributions

Publications

- Fujimori, S., Siagian, U. W. R., Hasegawa, T., Yuwono, B. B., Boer, R., Immanuel, G., & Masui, T. 2017. An Assessment of Indonesia's Intended Nationally Determined Contributions. In Post-2020 Climate Action (pp. 125–142). https://doi.org/10.1007/978-981-10-3869-3_8

Guiding questions

< placeholder >

Results

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Scenarios

- Baseline
- CM

Models

- AIM/Hub-Indonesia 2.0

5.3.12 Low carbon development in China

Publications

- Chen W, Yin X, Zhang H. 2016. Towards low carbon development in China: a comparison of national and global models. Climatic Change, 136(1): 95-108. DOI:10.1007/s10584-013-0937-7
- Wang H, Chen W, Zhang H, et al. 2019. Modeling of power sector decarbonization in China: comparisons of early and delayed mitigation towards 2-degree target. Climatic Change, 2019: 1-14. DOI:10.1007/s10584-019-02485-8

Guiding questions

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Results

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Scenarios

- INDC
- INDC_2030_290
- INDC_2030_400
- NPi
- NPi_2020_290
- NPi_2020_400

Models

- TIMES-China 2.0

5.3.13 Deep decarbonization in India

Publications

- P.R.Shukla, Dhar, S., Pathak, M., Mahadevia, D. and Garg, A. 2015. Pathways to deep decarbonization in India, pp. 62. Sustainable Development Solutions Network (SDSN) and Institute for Sustainable Development and International Relations (IDDRI)

Guiding questions

< placeholder >

Results

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Scenarios

- Conventional
- Sustainable

Models

- ANSWERMARKAL-INDIA 1.0

5.3.14 Energy efficiency and CO2 emissions reduction potential in the buildings sector in China

Publications

- Zhou Nan, Nina Khanna, Wei Feng, Jing Ke, Mark Levin. 2018. Scenarios of energy efficiency and CO_2 emissions reduction potential in the buildings sector in China to year 2050. Nature Energy 3(11), 978.

Guiding questions

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Results

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Scenarios

- Reference Scenario
- Techno-economic potential scenario

Models

- DREAM-China 1.1

5.3.15 Study

Publications

- <Literature placeholder>

Guiding questions

<placeholder>

Results

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Scenarios

- CET-1
- Ref-1

Models

- CGE-IMRT 1.0

5.4 Europe

5.4.1 Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system

Publications

- Blanco, H., Nijs, W., Ruf, J., & Faaij, A. 2018. Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system using cost optimization. Applied Energy, 232, 617–639. https://doi.org/10.1016/j.apenergy.2018.09.216

Guiding questions

This study assesses the role of hydrogen and Power-to-Liquid by using the JRC-EU-TIMES model that includes 31 countries. The scenarios achieve 95–100% CO_2 reduction by 2050 within the entire EU27+ energy system. The scenarios from the open model explore the impacts of CO_2 neutrality that is reached through a net-zero sum of carbon dioxide emissions from energy and industrial processes and carbon dioxide removals.

1. What is priority uses of hydrogen and Power-to-Liquid when aiming at net-zero carbon?
2. How relevant are hydrogen and Power-to-Liquid fuels and how are they produced?
3. What are the technology challenges when underground storage of CO_2 is restricted, given that also biomass use is limited?

Results

Electrification occurs already in the baseline scenario and electricity meets 45% of final energy demand in the other scenarios (including non-energy uses and bunkers). Electricity generation up to 2050 increases by a factor 3. Close to 50% of the future electricity demand is for electrolysers. In 2050, the consumption of electricity for hydrogen production can reach up to 3 600 TWh which is comparable to the current size of the electricity sector.

1. Hydrogen represents an attractive option for steel (direction reduction) and heavy-duty trucks. Power-to-Liquid can complement Biomass-to-Liquid increasing the liquid yield and satisfy the demand for sectors that are more difficult to electrify like aviation or marine transport.
2. Hydrogen makes up around 15% and Power-to-Liquid fuels make up 10 to 20% of final energy consumption (including non-energy uses and bunkers). Hydrogen based synfuels or synthetic hydrocarbons are produced by combining hydrogen that originates almost entirely from electricity and CO_2 that originates mostly as a by-product from the production of 2nd generation biofuel.
3. When underground storage of CO_2 is reduced from 0.8 to 0.3 $GtCO_2$/yr, around 8 EJ of fossil fuel is replaced by solar electricity to provide sufficient hydrogen and e-fuels. The use of Direct Air Capture reduces but remains important for carbon removal. When underground storage of CO_2 is limited to zero, only 95% reduction of CO_2 is possible and Direct Air Capture does not play a role any longer.

Scenarios

- Hydrogen_Economy_T95

- Open_Baseline
- Open_Zero_Carbon
- Open_Zero_Carbon_HighCCS

Models

- JRC-EU-TIMES 1.1.1

5.4.2 Deployment scenarios for low carbon energy technologies

Publications

- Nijs, W., Ruiz Castello, P., Tarvydas, D., Tsiropoulos, I., & Zucker, A. 2019. Deployment scenarios for low carbon energy technologies - Publications Office of the EU. Retrieved from https://op.europa.eu/en/publication-detail/-/publication/1c25c504-1878-11e9-8d04-01aa75ed71a1/language-en

Guiding questions

The Low Carbon Energy Observatory (LCEO) aims to provide top-class data, analysis and intelligence on developments in low carbon energy supply technologies. Up to now, 25 reports are available from the Publications Office of the European Union. In-house scenarios have been developed with the JRC-EU-TIMES model to explore energy prospects within the EU to reach 80-100% reduction of CO_2.

1. What are the implications of an 80% CO_2 reduction when using all technology options, including massive use of permanent storage of CO_2?
2. What are the implications of an 80% CO_2 reduction when permanent underground storage of CO_2 is not an option?
3. What are the mitigation options that allow reaching 100% CO_2 reduction?

Results

It is not possible to reach net-zero carbon emissions in the EU in the absence of CO_2 sequestration. With limited amounts of underground CO_2 storage (0.3 $GtCO_2$/yr), the results show large amounts of RES, hydrogen and e-fuels.

1. In scenario ‘LCEO Diversified’, almost 60% of the total CO_2 is stored or used, mostly captured from power production. Permanent storage of CO_2 occurs in the countries where underground storage of CO_2 has not been restricted yet. Such transformations would require a rapid scale-up of CCS technologies.
2. In scenario 'LCEO ProRES', energy is mainly produced with renewable resources. Power-to-Liquid (e-fuel) complements biofuels in sectors with no easy electric alternative like aviation. Biomass is in most cases equipped with CCS, whether it is for power, heat or biofuels.
3. In scenario ‘LCEO Zero Carbon’ the further reduction of fossil fuels is compensated by an increase of electricity production from solar (+65%) and from wind (+20%). Underground sequestration of CO_2 (0.3 $GtCO_2$/yr) is mainly done with CO_2 from Direct Air Capture. Part of the CO_2 captured from biomass and Direct Air Capture is reused to produce e-fuels (0.2 $GtCO_2$/yr). The energy use of buildings consists almost entirely of electricity and ambient and district heat.

Scenarios

- LCEO ProRES SET Plan
- LCEO Baseline
- LCEO Diversified
- LCEO Zero Carbon

Models

- JRC-EU-TIMES 1.1.1

5.4.3 Low Carbon Futures of the pan-European Energy System

Publications

- Quantitative Scenarios for Low Carbon Futures of the pan-European Energy System. (n.d.).

Guiding questions

This report presents the pan-European storylines of the Horizon 2020 project "openENTRANCE", which aim at developing suitable pathways towards a decarbonized European energy system.

1. How do the previously defined storylines fare in a quantitative optimization setting?
2. What role does sector-coupling play in the fulfilment of climate goals?
3. How do outside effects such as technological innovation and societal commitment change the outcome of quantitative decarbonization pathways?

Results

The pan-European openENTRANCE scenario results show that a strong policy enforcement of climate goals in the short-term does drastically affect the speed of the energy transition. However, this is accompanied with the risk (from today's point-of-view), that the technology breakthrough and lifestyle change of society actually takes place in time.

1. If we are going to limit the global temperature increase to 1.5 °C, significant efforts need to start now!
2. Already in 2030, the emissions in Europe must be around 1/3 of today's level only!
3. Removing the last 1/3 of the emissions from 2030 to 2050 expects increases of CO_2 prices several times and remains at high levels in 2050!

Scenarios

- Directed Transition 1.0
- Gradual Development 1.0
- Societal Commitment 1.0
- Techno-Friendly 1.0

Models

- GENeSYS-MOD 2.9

5.4.4 REMIND-EU Study

Publications

- Rodrigues, R., Pietzcker, R., Luderer, G., Fragkos, P., Capros, P., Fotiou, T., … McDowall, W. 2020. Alternative roads to achieve mid-century CO2 net neutrality in Europe. *Energy*.

Guiding questions

<placeholder>

Results

<placeholder>

Scenarios

- Eff_1p5
- Eff_Weak
- Eff_min80
- Efficient_1p5
- Efficient_Weak
- Efficient_min80
- Incumb_1p5
- Incumb_Weak
- Incumb_min80
- NewPl_1p5
- NewPl_Weak
- NewPl_min80

Models

- REMIND_EU 2.0

5.4.5 Socio-economic and energy data to generate business-as-usual scenarios

Publications

- Roberts, S. H., Axon, C. J., Goddard, N. H., Foran, B. D., & Warr, B. S. 2019. Modelling socio-economic and energy data to generate business-as-usual scenarios for carbon emissions. Journal of Cleaner Production, 207, 980–997. https://doi.org/10.1016/j.jclepro.2018.10.029

Guiding questions

Scenarios are widely used for informing policy development and for creating BAU scenarios to help understand possible effects of different policy interventions. However, the term BAU is frequently misused. We showed how econo-physical BAU scenarios can be developed by examining the historical behaviour of coefficients which manifest the relationship between components of an economy.

1. What level of economic growth should be used in BAU scenarios?
2. What level of emissions reduction follows the selected level of economic growth in BAU scenarios?
3. Can this approach be applied to other economies?

Results

We endogenised economic growth for the UK economy by mimicking national level policies that focus on a target level of unemployment. We manifest a GDP growth of 2% falling to 1% which contrasts with an exogenous growth of 2.3% of a comparator BAU scenario. We suggest that it may be possible to achieve a greater reduction in the BAU CO2 emissions in the UK fifth carbon budget than currently projected.

1. Our methodology manifests a GDP growth of 2% falling to 1%, which is largely dependent on the evolution of jobs in the service industry. This contrasts with GDP growth in others' scenarios of 2.3% simply based on a historical rolling average.
2. We find that CO_2 emissions continue their historical fall reaching 390 MtCO2/y in 2027 before rising to 400 MtCO2/y in 2035.
3. Growth, and consequential emissions, is crucially dependant on the evolution of jobs in the service industry. We find simply behaviour for jobs in the service industry comparing economies of the UK, the USA, Australia, Taiwan (ROC) and Colombia.

Scenarios

- JPC to 0.8 of asymptote
- JPC to asymp. with high population projection
- JPC to asymp. with low population projection
- JPC to asymptote

Models

- 7see Mk5-20 GB

5.4.6 Consequences of selecting technology pathways on cumulative carbon dioxide emissions for the United Kingdom

Publications

- Roberts, S. H., Foran, B. D., Axon, C. J., Warr, B. S., & Goddard, N. H. 2018. Consequences of selecting technology pathways on cumulative carbon dioxide emissions for the United Kingdom. Applied Energy, 228, 409–425. https://doi.org/10.1016/j.apenergy.2018.06.078

Guiding questions

The fifth carbon budget (5CB) of the UK Committee on Climate Change includes a significant level of carbon capture and storage (CCS), but is this feasible? Current energy systems modelling methods do not explore, or are unable to account for, physical (thermodynamic) limits to the rate of change of infrastructure. We applied our novel system dynamics model to substantiate the policy's ability to meet emissions targets while maintaining financial productivity and socially expected employment levels. In our study we compared physically constrained scenarios that accentuate either CCS, fastest plausible nuclear new build, or fastest plausible build rate of offshore wind.

1. Can expansion of nuclear new build at the fastest plausible rate achieve greater emissions reduction compared with the 5CB and at what cost?
2. Can the fastest feasible rate of expansion of offshore wind replace CCS within in the 5CB?
3. Given gaps appearing between intended and actual policy implementation, what is the best overall strategy?

Results

The outcome of our study, within the constraints of the 5CB, is that it is possible to exceed the stated legislated goals of the Committee on Climate Change if implemented at the suggested rate and scope. We estimate a cumulative carbon dioxide saving from 2017 of approximately 400 Mt by 2032 compared with business as usual.

1. Expansion of nuclear new build at the fastest plausible rate does not achieve as large a cumulative reduction in emissions compared with the 5CB and there is a notable delay owing to the long lead-time of construction, but it does cost less than CCS.
2. We show that replacing CCS with offshore wind at double the expansion rate within the 5CB is a feasible investment strategy. This can be achieved at reduced whole-economy capital investment cost (GFCF).
3. If delays or cancellation occur to the deployment programmes of CCS technologies or nuclear new build, we suggest the electricity and decarbonisation targets can by met by a fast growth of offshore wind generation with no change to financial and employment levels.

Scenarios

- GB 5CB
- GB BAU1a
- GB FNNB
- GB FOfW

Models

- 7see Mk5-30 GB

5.4.7 Carbon intensity of the service industry in the UK.

Publications

- <placeholder>

Guiding questions

In accounting for carbon emissions, the conventional wisdom is that the service industry is ‘emissions light’, but this is not supported when goods and other inputs to services production are included. The service industry provides the majority of employment. Lack of attention to the way the service industry is integrated within the whole economy can hamper emissions reduction policy development, and societies will likely reject changes if rising unemployment results. Frequently, emissions reduction targets are stated without the intermediate steps or details of implementation. Our study shows how modelling the rate of introducing measures is as important as defining a target because of the implications of cumulative emissions.

1. What is the full emissions footprint of the service industry beyond the direct use of fuel alone?
2. Which of the 6 key goods used by the service industry are continuing to grow in use, giving rise to increasing emissions?
3. Why is it important to attend to the speed of emission reduction measures?
4. Can economic growth for employment and emissions reduction be achieved?

Results

Policy for emissions reductions for intersecting areas, such has buildings and use of goods, may not be sufficiently coherent to have the effect required by a net-zero target. The service industry needs to be treated as a coherent single entity to achieve emission reductions without reducing the volume of employment it provides.

1. In production accounting terms (excluding imports), the service industry is responsible for 17-24% of GHG emissions for the assessed countries since 1990, contrary to its perception as ‘emissions light’. Countries assessed were Australia, Germany, Italy, the UK and USA.
2. Emissions from four key goods underpinning the UK service industry continue growing: electronic, pharmaceutical, materials, and machinery.
3. Implementation of mitigation measures must be aggressive because although both our fast and slow scenarios with additional measures reach the same end point in annual CO_2 emissions, in cumulative terms the difference between them leads to 500 million tonnes CO_2 extra to 2050.
4. Over the next 30 years, energy and emissions policy must reconcile GDP and jobs with rates of energy-provision transformation and dematerialisation.

Scenarios

- WAM-fast
- WAM-slow
- WEM

Models

- 7see Mk6-10 GB

5.4.8 Electric storage technologies vs alternative flexibility options for the Swiss energy system

Publications

- Panos, E., Kober, T., Wokaun, A. 2019. Long term evaluation of electric storage technologies vs alternative flexibility options for the Swiss energy system, Applied Energy, 252 , https://doi.org/10.1016/j.apenergy.2019.113470

Guiding questions

We assess two long-term scenarios: a Baseline scenario, which assumes the continuation of major existing energy policy lines, and a Climate scenario, which assumes the achievement of the Swiss National Determined Contributions. The aim of the study is to identify the cost-effective transition pathway to achieve the Swiss NDC and to assess the flexibility options deployed to integrate a high share of renewable energy

1. How can the Swiss energy transition be realised regarding the technology choices in both energy supply and demand;
2. How much flexibility would need the future energy system to cope with the large penetration of renewable energy needed to meet the climate targets;
3. How the different flexibility options can be coordinated to ensure a cost-effective integration of renewables, as well as the reliable and secure operation of the energy system.

Results

The transition to a low-carbon system requires deployment of renewable energy, the integration of which needs coordinated actions across all sectors of the energy system

1. The achievement of the Swiss NDC climate targets requires a peak in emissions in 2010, while the deployment of energy savings contributes by 20% in the emissions reduction, the spread of use of electricity to heating and mobility accounts for more than two-thirds in the total abatement effort, and the integration of a large share of variable renewable energy in supply and demand is critical for decarbonisation
2. Key flexibility options are batteries (+1GW in 2050 from today levels), hydrostorage (8.8 TWh), participation of about 150 MW of virtual plant units in ancillary service markets for secondary reserve (ca total demand 600 MW), seasonal balancing via P2X pathways and the shift of 0.6 TWh of electricity via H2 and synthetic fuels, smart charging and discharging of EVs, and exercise of DSM practices that shift 13% of the electricity demand in heating and appliances at a daily basis
3. Coordination between the different flexibility options and between sectors is needed to secure a reliable operation of the energy system, as the various flexibility options have both synergistic and complementary effect. This coordination would require a shift from a supply-driven perspective towards a perspective that enables system integration.

Scenarios

- STEM_BAU
- STEM_CLI

Models

- STEM-Switzerland 2.0

5.4.9 Swiss Industry: Price Elasticities and Demand Developments for Electricity and Gas

Publications

- Kober, T., Kannan, R., Obrist, E., Panos, E., Heald, S., Clements, L., Goldman, M., Politt, H. 2019. Swiss Industry: Price Elasticities and Demand Developments for Electricity and Gas (SWIDEM), Swiss Federal Office of Energy, Bern https://www.aramis.admin.ch/Dokument.aspx?DocumentID=65688

Guiding questions

The Joint Activity Scenarios and Modelling (JASM) aims at providing a set of robust scenarios for the realization of the Swiss Energy Strategy 2050. The modelling groups of the 8 Swiss Competence Centres for Energy Research (SCCER) work together and bring in their respective experience in the field of electricity generation technologies, buildings, mobility, industry, grids, biomass, storage and economy

1. JASM_CLI, JASM_LC100: What energy system transformations are implied for Switzerland by its NDC for 2030, and what is the cost-optimal pathway reaching its indicated long-term targets for 2050 of net-zero emissions by then?
2. JASM_EPOL, SWIDEM_EPOL: Can the current Swiss energy strategy achieves the NDC targets for 2030, how much residual emissions occur in 2050 from achieving the net-zero ambition and what are their determinant factors?
3. JASM_LC80: What is the additional effort required moving from the currently declared target of -80% reduction of GHG emissions in 2050 compared to 1990 levels (JASM_LC80 scenario) to the ambition of achieving net-zero emissions in 2050 (JASM_CLI, JASM_LC100 scenarios) for Switzerland

Results

The current Swiss ambition level is not in line with long-term Paris Agreement targets. To achieve net-zero emissions in 2050 would require full decarbonization of the residential, commercial and transport sectors for which electrification, efficiency and adoption of new pathways based on P2X is required. At the same time Switzerland would need to develop negative emissions technologies by 2040.

1. The current electricity production mix in Switzerland is of an almost zero carbon intensity, as it is based on nuclear and hydro power. Due to the foreseen nuclear phase out, a significant deployment of solar PV would require as other renewable domestic resources are limited. Achieving the net-zero ambition would require a doubling of installed solar PV capacities every decade, reaching from 2 GW today to >25 GW in 2050
2. Achieving the net-zero ambition would require that the buildings sector undergo transformation towards electrified heat via heat pumps and implement aggressive renovation measures. The mobility sector needs to shift to electric vehicles and biofuels and synthetic e-fuels. Residual emissions remain in industry for processes required gaseous fuels.
3. About 4 Mt CO_2/yr. Negative emissions would require to offset emissions from the energy system. If agriculture is to be included, then the amount of the negative emissions required exceeds 8 Mt CO_2/yr. The total CO_2 captured needs range from 8 Mt to 12 Mt CO_2/yr in 2050. If storing the captured CO_2 in the Swiss territory is uncertain or impossible (technical or social acceptance

barriers), then access to international infrastructure to transport and store CO_2 abroad would be needed.

Scenarios

- JASM_BAU
- JASM_CLI
- JASM_EPOL
- JASM_LC100
- JASM_LC80
- SWIDEM_EPOL

Models

- STEM-Switzerland 2.0

5.4.10 Future energy transition to net-zero emissions: differences between France and Sweden

Publications

- Millot, A., Krook-Riekkola, A., & Maïzi, N. 2020. Guiding the future energy transition to net-zero emissions: Lessons from exploring the differences between France and Sweden. Energy Policy, 139, 111358. https://doi.org/10.1016/j.enpol.2020.111358

Guiding questions

The study identifies key factors that can drive energy transition toward a carbon neutrality goal, by comparing the past energy transition (qualitative) as well as comparing the future energy transition to carbon neutrality in Sweden by 2045 and in France by 2050 (quantitative/model-based).

1. What are the differences over time between the countries in term of final energy consumption (in general), in the carbon Neutrality scenario?
2. What are the differences over time between the countries in term of the power sector, in the carbon Neutrality scenario?
3. What are the differences over time between the countries in term of energy for Industries, in the carbon Neutrality scenario?
4. What are the differences over time between the countries in term of energy for Transportation, in the carbon Neutrality scenario?
5. What are the differences over time between the countries in term of energy for Buildings and agriculture, in the carbon Neutrality scenario?

Results

First, the energy transition to net zero emissions should be accompanied by diverse public policies like taxes, subsidies, regulation and information. Secondly, public policies should set realistic and achievable climate goals since they determine different energy system trajectories. Thirdly, these targets should be supported by a long-term vision for the energy system. Investments in critical technologies is needed. Lastly, public policies benefit from consistent, long-term support in order to make their targets credible and to foster investment in low-carbon technologies.

The cross-country comparisons were seen to be useful to highlight the similarities and differences that each country will have to take into account for their future energy systems pathways. Pair studies show what works in one country and could apply to others, while highlighting the challenges and barriers that each country faces (which might be reason for not necessary working in all countries just because it works in one country).

1. In France, an increase of natural gas is seen until 2035, thereafter natural gas is gradually replaced by biomethane and hydrogen, thus natural gas works as a transition commodity for climate mitigation in France. A similar trend could not be seen in Sweden, where natural gas today only has a minor share of the energy mix, this trend remains over the entire period. In both countries oil and coal are replaced with a combination of electrification and an increase us of bioenergy. Thus, natural gas will not per-default reduce the climate impact, not even in a short-term perspective.

2. The increase in electricity use is higher in France compared with Sweden, which could be explained by the higher level of electrification in present Swedish energy system. In France, the increase in electricity demand and phase out of old nuclear plants is met by an increase of installation in wind, solar and new nuclear power. In Sweden, the increase in electricity demand and phase out of old nuclear plants is met by an increase of installation in wind, solar and BECCS (bioenergy CHP plants and tri-biofuel plants with CCS).
3. In France, the electricity consumption in the industry sector increases significantly during the last periods mainly replacing natural gas, while it remains stable in Sweden. Similar, the consumption of bioenergy is doubled in the France, while it increases by only 8% in Sweden. The final biomass shares in 2050 remains much more significant in Sweden than in France: 45% vs 12%. The stabilization in Sweden can partly be explained by biomass already having a significant share today, and partly been seen more profitable to replace fossil fuels in the transportation sector and in BECCS plans (producing electricity, biofuels and district heating).
4. Although in the past neither country has put in place specific policies regarding the transport sector, we observe significant differences in their future evolution. In France, gas consumption increases significantly between 2015 and 2040 and is used in buses and vehicles for goods transport. By 2050, this gas is totally replaced by biomethane. In Sweden, biogas consumption remains very low and the use of biofuels increase faster compared with in France. In both countries, there is an increase in electrification of the transport sector from 2030.
5. In France, the energy demand for space heating decline over time is explained by investments in energy efficiency measures (insulation), while the demand for space heating is increasing in Sweden (when there were no energy efficiency measure options for space heating in the Swedish model). In France, gas consumption decreases significantly while biomass and biomethane consumption increases. In order to meet carbon neutrality in France, a massive shift toward heat pumps and solar heating is seen in the last period (year 2050). In Sweden, geothermal and biomass consumption increase, while electricity consumption remains stable. (In other, not yet published scenarios for Sweden, heat-pumps is installed in the district heating grids, instead of in the buildings).

Scenarios

- Sweden
- Sweden_B
- SwedenNeutrality
- SwedenNeutrality_B
- NeutralityV2_CCSLow
- Ref_DLow

Models

- TIMES-Sweden 1.0
- TIMES-France 2.0

5.4.11 Carbon neutrality in France

Publications

- < placeholder >

Guiding questions

The study contributes to reflecting on how to achieve carbon neutrality in France and how it differs from the main goals of the LTECV.

1. What energy system transformations are implied by carbon neutrality for 2050, and how do they differ from transformations in cost-optimal pathways reaching the goals of the LTECV?
2. How is the evolution sensitive to lower availability of CCS, to a higher demand and to a stringent carbon neutrality constraint?
3. What is the marginal cost of CO_2 emissions?

Results

Carbon neutrality requires deep and structural changes in the energy system and differs from the pathways to LTECV goals.

1. A pathway to carbon neutrality requires more power capacity and a more significant use of biomass (biomethane) in the transport sector.
2. Meeting the constraint of carbon neutrality requires optimistic assumptions concerning the availability of CCS, a moderate growth in energy service demand and the construction of new nuclear power plants.
3. The marginal cost of CO_2 emissions reaches above 1000€/tCO_2 which underlines the difficulty of reaching the carbon neutrality constraint.

Scenarios

- LTECV
- NeutralityV0_CCSHigh_Dhigh
- NeutralityV0_CCSLow_Flex
- NeutralityV2_CCSLow
- NeutralityV2_CCSLow_Dhigh
- NeutralityV2_NoCCS_Flex
- Ref_Dhigh
- Ref_Dlow

Models

- TIMES-France 2.0

5.4.12 Contributions of building retrofitting in five member states to EU targets for energy savings

Publications

- Mata É, Sasic Kalagasidis A, Johnsson F. 2018. Contributions of building retrofitting in five member states to EU targets for energy savings. Renewable and Sustainable Energy Reviews 93: 759-774.

Guiding questions

< placeholder >

Results

< placeholder >

Scenarios

- BAU-T

Models

- ECCABS 2.0

5.4.13 Publication

Publications

- < placeholder >

Guiding questions

< placeholder >

Results

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Scenarios

- Off_Track
- OoR
- Pack
- Pack_cap
- Yellow_Jersey
- Yellow_Jersey_cap
- YJ
- YJ_cap

Models

- TIMES-Portugal 9.2

6. Other

6. 1 Migration

6.1.1 Publications

- H. Benveniste, J. Crespo Cuaresma, M. Gidden, R. Muttarak. Tracing International Migration in Projections of Income Levels and Inequality across the Shared Socioeconomic Pathways.

6.1.2 Guiding questions

The study contributes the first explicit quantification of the effect of international migration on country-level projections of income, inequality, energy consumption, and CO_2 emissions along the 5 SSP and associated RCP, by developing versions of those projections for zero international migration. The effect of migration on income plays through changes in population sizes and remittances, i.e. transfers of money between migrants and home communities. The effect of migration on energy consumption and CO_2 emissions is derived from the one on income assuming, for a given SSP narrative, that migration does not affect the energy consumption, respectively emissions path along GDP per capita levels. These new projections can then be compared to original quantifications which include, implicitly, international migration. The difference between the two sets of projections highlights the effect of migration.

1. How does migration affect GDP projections? Does its effect on income level vary with the SSP narrative considered? Which countries does migration make better off?
2. How do migration and related remittances affect inequality both between and within countries?
3. Does migration affect energy consumption and CO2 emissions?

6.1.3 Results

Migration makes the world richer and more equal in all SSP narratives. The nature of migration and remittance corridors is shaped by the specific scenario of future development considered.

1. Depending on the particular SSP narrative and world region considered, the effects of migration on income can be substantial, ranging from -5% to +21% at the continental level.
2. Migration tends to decrease income inequality across countries, does not tend to affect within-country inequality in origin countries and tends to decrease it in most destination countries.
3. Migration tends to increase energy consumption globally for most SSP narratives, driven by an increase in consumption in destination countries. Migration tends to increase CO_2 emissions, but also negative emissions through affluence.

6.1.4 Scenarios

- GDP_SSP1_zeromig
- GDP_SSP2_zeromig
- GDP_SSP3_zeromig
- GDP_SSP4_zeromig
- GDP_SSP5_zeromig
- GINI_SSP1_zeromig
- GINI_SSP2_zeromig

- GINI_SSP3_zeromig
- GINI_SSP4_zeromig
- GINI_SSP5_zeromig
- GINIBTW_SSP1_zeromig
- GINIBTW_SSP2_zeromig
- GINIBTW_SSP3_zeromig
- GINIBTW_SSP4_zeromig
- GINIBTW_SSP5_zeromig
- SSP1-1.9_zeromig
- SSP1_zeromig
- SSP2-4.5_zeromig
- SSP2_zeromig
- SSP3-7.0_zeromig
- SSP3_zeromig
- SSP4-6.0_zeromig
- SSP4_zeromig
- SSP5-8.5_zeromig
- SSP5_zeromig

6.1.5 Models

- MIGRATION 1.0

6.2 Behavioural change

6.2.1 Publications

- Niamir, L., Kiesewetter, G., Wagner, F., Schöpp, W., Filatova, T., Voinov, A., & Bressers, H. 2020. Assessing the macroeconomic impacts of individual behavioral changes on carbon emissions. Climatic Change, 158(2), 141–160. https://doi.org/10.1007/s10584-019-02566-8

6.2.2 Guiding questions

To shed light on individuals' energy decision-making and grassroots dynamics in transition to low-carbon economy; to assess the macroeconomic impacts of individual energy behavioural changes on carbon emission.

1. What are the macroeconomic impacts of individuals'' energy behavioural and lifestyle changes on energy demand and carbon emission?

6.2.3 Results

The findings demonstrate that the regional dimension is important in a low-carbon economy transition. Heterogeneity in individual socio-demographics (e.g. education and age), structural characteristics (e.g. type and size of dwellings), behavioural and social traits (e.g. awareness and personal norms), and social interactions amplify these differences, causing nonlinearities in diffusion of green investments among households and macro-economic dynamic.

1. The results indicate that accounting for demand side heterogeneity provides a better insight into possible transitions to a low-carbon economy and climate change mitigation. The model with household heterogeneity represented in socio-demographic, dwelling, and behavioural factors shows rich dynamics and provides more-realistic image of socio-economics by simulating economy through the social interactions of heterogeneous households. Two end-user scenarios are presented, which vary from the baseline scenario by introducing agent heterogeneity, intensity of social interactions among households (slow or fast).
2. Electricity consumption resulting from individual behavioural changes decreases between 56.2-69.5% by 2050 in the Netherlands. There is spatial heterogeneity in how behavioural changes diffuse and what regions (within a country) emerge as laggers or pioneers in bottom-up investments in energy-efficiency.

6.2.4 Scenarios

- FD
- SD

6.2.5 Models

BENCH-NLD 1.0

Part II: Model reference cards

[The model reference cards included in the SOD are preliminary and based on the reference cards developed in the FOD. These are examples for a selected set of models. They will be updated and the collection expanded to cover all global and national models that submitted scenarios to the AR6 scenario database in FGD]

Reference card – AIM-CGE

About

Name and version

AIM-CGE V2

Institution

National Institute for Environmental Studies (NIES), Japan.

Model scope and methods

Objective

AIM/CGE is developed to analyses the climate mitigation and impact. The energy system is disaggregated to meet this objective in both of energy supply and demand sides. Agricultural sectors have also been disaggregated for the appropriate land use treatment. The model is designed to be flexible in its use for global analysis.

Solution concept

General equilibrium (closed economy)

Solution horizon

Recursive dynamic (myopic)

Solution method

Simulation

Temporal dimension

Base year: 2005, time steps: Annual, horizon: 2100

Spatial dimension

Number of regions: 17

1. Japan
2. China

3. India
4. Rest of Asia
5. Rest of Europe
6. Former Soviet Union
7. Turkey
8. Canada
9. United States
10. Brazil
11. Rest of South America
12. Middle East
13. North Africa
14. Rest of Africa
15. Rest of East and South East Asia
16. EU
17. New Zealand and Australia

Climate policies

- Emission tax
- Pricing
- Cap and Trade

Energy policies

- Fuel taxes
- Fuel subsidies
- Portfolio standard

Energy technology policies

- Capacity targets
- Emission standards
- Energy efficiency standards

Agricultural policies

- Agricultural producer subsidies
- Agricultural consumer subsidies

Land-use policies

- Land protection
- Pricing carbon stocks

Socio economic drivers

Population: Yes (exogenous)

GDP: Yes (exogenous)

Employment rate: Yes (exogenous)

Labor productivity: Yes (exogenous)

Total factor productivity: Yes (endogenous)

Autonomous energy efficiency improvements: Yes (endogenous)

Macro economy

Economic sector

Industry: Yes (economic)

Energy: Yes (physical & economic)

Residential and commercial: Yes (economic)

Agriculture: Yes (physical & economic)

Trade

- Coal
- Oil
- Gas
- Electricity
- Food crops
- Emissions permits
- Non-energy goods
- Uranium

Cost measures

- GDP loss
- Welfare loss
- Consumption loss
- Equivalent Variation

Categorization by group

- Income
- Urban - rural

Resource Use

Coal: Yes (supply curve)

Conventional Oil: Yes (supply curve)

Unconventional Oil: Yes (supply curve)

Conventional Gas: Yes (supply curve)

Bioenergy: Yes (supply curve)

Technological change

Energy End-use: Exogenous technological change

Material Use: Exogenous technological change

Agriculture: Exogenous technological change

Energy Conversion: Exogenous Technological Change

Energy

Energy technology substitutability

- Mostly high substitutability in some sectors and mostly low substitutability in other sectors

Energy technology deployment

- Mostly high substitutability in some sectors and mostly low substitutability in other sectors

Electricity technologies

- Coal w/o CCS
- Coal w/ CCS
- Gas w/o CCS
- Gas w/ CCS
- Oil w/o CCS
- Bioenergy w/o CCS
- Bioenergy w/ CCS
- Geothermal power
- Nuclear power
- Solar power
- Wind power
- Wind power-onshore
- Wind power-offshore
- Hydroelectric power

Refined liquids

- Bioliquids w/o CCS
- Bioliquids w/ CCS

Grid and infrastructure

Electricity: Yes (aggregate)

Gas: Yes (aggregate)

Heat: Yes (aggregate)

CO2: Yes (aggregate)

Hydrogen: Yes (aggregate)

Energy end-use technologies

Residential and commercial

- Cooking
- Space heating

Land use

Land cover

- Cropland
- Forest
- Pasture
- Shrubland
- Cropland energy crops
- Managed forest
- Natural forest

Agriculture and forestry demands

- Agriculture food
- Agriculture food crops
- Agriculture food livestock
- Agriculture feed
- Agriculture feed crops
- Agriculture feed livestock
- Agriculture non-food
- Agriculture non-food crops
- Agriculture non-food livestock
- Agriculture bioenergy

Agricultural commodities

- Wheat
- Rice
- Oilseeds
- Other coarse grains
- Sugar crops
- Ruminant meat
- Non-ruminant meat and eggs
- Dairy products

Emissions, climate and impacts

Greenhouse gases

- HFCs
- CFCs
- SF6
- CO2 fossil fuels
- CO2 cement
- CO2 land use
- CH4 energy
- CH4 land use
- CH4 other
- N2O energy
- N2O land use
- N2O other

Pollutants

- CO energy
- CO land use
- CO other
- NOx energy
- NOx land use
- NOx other
- VOC energy
- VOC land use
- VOC other
- SO2 energy
- SO2 land use
- SO2 other
- BC energy
- BC land use
- BC other
- OC energy
- OC land use
- OC other
- NH3 energy
- NH3 land use
- NH3 other

Climate indicators

- Temperature change
- Ocean acidification
- Concentration: CH4
- Concentration: N2O
- Concentration: Kyoto gases
- Radiative forcing: CO2
- Radiative forcing: CH4
- Radiative forcing: N2O
- Radiative forcing: F-gases
- Radiative forcing: Kyoto gases

- Radiative forcing: aerosols
- Radiative forcing: land albedo
- Radiative forcing: AN3A
- Radiative forcing: total
- Sea level rise

Carbon dioxide removal

- Bioenergy with CCS
- Reforestation
- Afforestation

Climate change impacts

- Agriculture

Co-Linkages

- Energy security: Fossil fuel imports & exports (region)
- Air pollution & health: Source-based aerosol emissions

Reference card – GEM-E3

About

Name and version

GEM-E3_092019

Institution

Institute of Communication And Computer Systems (ICCS), Greece.

Model scope and methods

Objective

The model puts emphasis on: i) The analysis of market instruments for energy-related environmental policy, such as taxes, subsidies, regulations, emission permits etc., at a degree of detail that is sufficient for national, sectoral and World-wide policy evaluation. ii) The assessment of distributional consequences of programmes and policies, including social equity, employment and cohesion for less developed regions.

Solution concept

General equilibrium (closed economy)

Solution horizon

Recursive dynamic (myopic)

Solution method

Optimization

Temporal dimension

Base year: 2014, time steps: 5, horizon: 2100

Spatial dimension

Number of regions: 46

Climate policies

- Emission tax
- Pricing
- Cap and Trade

Energy policies

- Feed-in-Tariff
- Fuel taxes
- Fuel subsidies
- Portfolio standard

Energy technology policies

- Capacity targets

Socio economic drivers

Population: Yes (exogenous)

GDP: Yes (endogenous)

Employment rate: Yes (endogenous)

Labor productivity: Yes (exogenous)

Total factor productivity: Yes (exogenous)

Autonomous energy efficiency improvements: Yes (exogenous)

Macro economy

Economic sector

GEM-E3 represents 29 sectors:

Agriculture, Coal, Crude Oil, Oil, Gas, Electricity supply, Ferrous and non ferrous metals, Chemical Products, Other energy intensive, Electric Goods, Transport equipment, Other Equipment Goods, Consumer Goods Industries, Construction, Transport (Air),Transport (Land),Transport (Water), Market Services, Non Market Services, Coal fired, Oil fired, Gas fired, Nuclear, Biomass, Hydro electric, Wind, PV, CCS coal, CCS Gas

Trade

- Coal
- Oil
- Gas
- Emissions permits
- Bioenergy crops
- Food crops
- Capital
- All other major traded economic activities (40 economic sectors)
- Energy goods

The model links all countries and sectors through endogenous bilateral trade transactions.

Cost measures

- GDP loss
- Welfare loss

- Equivalent Variation

Categorization by group

- Technology adoption

Resource Use

Coal: Yes (fixed)

Unconventional Oil: Yes (fixed)

Conventional Gas: Yes (fixed)

Bioenergy: Yes (process model)

Technological change

Material Use: Exogenous technological change

Other technological change

- Other: Total factor productivity
- Labour productivity
- Capital productivity are all exogenous. Semi-endogenous TFP for clean technologies based on learning by doing and learning by research

Energy

Energy technology substitution

- Mostly high substitutability

Energy technology deployment

- Expansion and decline constraints

Electricity technologies

- Coal w/ CCS
- Gas w/o CCS
- Gas w/ CCS
- Oil w/o CCS
- Bioenergy w/o CCS
- Geothermal power
- Nuclear power
- Solar power
- Solar power-central PV
- Wind power
- Wind power-onshore
- Wind power-offshore

- Hydroelectric power

Grid and infrastructure

- Not represented

Energy end-use technologies

Passenger transportation

- Buses
- Electric LDVs
- Hybrid LDVs
- Gasoline LDVs
- Passenger trains
- Passenger aircrafts

Freight transportation

- Freight trains
- Heavy duty vehicles
- Freight aircrafts
- Freight ships

Industry

- Steel production
- Aluminium production
- Cement production
- Petrochemical production
- Paper production
- Pulp production
- Other: Equipment goods
- Non-metalic minnerals
- Consumer goods industries

Residential and commercial

- Cooking
- Space heating

Land use

Agricultural commodities

- Oilseeds

Emissions, climate and impacts

Greenhouse gases

- HFCs

- SF6
- CO2 fossil fuels
- CH4 energy
- CH4 other
- N2O energy
- N2O other

Climate indicators

GEM-E3 model does not include climate indicators.

Carbon dioxide removal

- Bioenergy with CCS
- Afforestation
- Direct air capture

Co-Linkages

- Energy access: Household energy consumption

Reference card – IMAGE

About

Name and version

IMAGE framework 3.0

Institution and users

Utrecht University (UU), Netherlands, http://www.uu.nl.
PBL Netherlands Environmental Assessment Agency (PBL), Netherlands, http://www.pbl.nl.

Model scope and methods

Objective

IMAGE is an ecological-environmental model framework that simulates the environmental consequences of human activities worldwide. The objective of the IMAGE model is to explore the long-term dynamics and impacts of global changes that result. More specifically, the model aims

1. to analyse interactions between human development and the natural environment to gain better insight into the processes of global environmental change;
2. to identify response strategies to global environmental change based on assessment of options and
3. to indicate key inter-linkages and associated levels of uncertainty in processes of global environmental change.

Solution concept

Partial equilibrium (price elastic demand)

Solution horizon

Recursive dynamic (myopic)

Solution method

Simulation

Anticipation

Simulation modelling framework, without foresight. However, a simplified version of the energy/climate part of the model (called FAIR) can be run prior to running the framework to obtain data for climate policy simulations.

Temporal dimension

Base year: 1970, time steps: 1-5 year time step, horizon: 2100

Spatial dimension

Number of regions: 26

1. Canada
2. USA
3. Mexico
4. Rest of Central America
5. Brazil
6. Rest of South America
7. Northern Africa
8. Western Africa
9. Eastern Africa
10. South Africa
11. Western Europe
12. Central Europe
13. Turkey
14. Ukraine +
15. Asian-Stan
16. Russia +
17. Middle East
18. India +
19. Korea
20. China +
21. Southeastern Asia
22. Indonesia +
23. Japan
24. Oceania
25. Rest of South Asia
26. Rest of Southern Africa

Time discounting type

- Discount rate exogenous

Time discounting average

5 (% per year)

Climate policies

- Emission tax
- Pricing
- Cap and Trade

Energy policies

- Fuel taxes
- Portfolio standard

Energy technology policies

- Capacity targets

- Emission standards
- Energy efficiency standards

Land-use policies

- Land protection
- Pricing carbon stocks

Socio economic drivers

Population: Yes (exogenous)

Urbanization rate: Yes (exogenous)

GDP: Yes (exogenous)

Income distribution: Yes (exogenous)

Autonomous energy efficiency improvements: Yes (exogenous)

Macro economy

Economic sector

Industry: Yes (physical & economic)

Energy: Yes (physical & economic)

Transportation: Yes (physical & economic)

Residential and commercial: Yes (economic)

Agriculture: Yes (physical & economic)

Forestry: Yes (physical & economic)

Trade

- Coal
- Oil
- Gas
- Uranium
- Bioenergy crops
- Food crops
- Emissions permits
- Non-energy goods

Cost measures

- Area under MAC

Categorization by group

- Urban - rural
- Income
- Technology adoption

Institutional and political factors

- Early retirement of capital allowed
- Behavioural change differentiated by country/region
- Technology costs differentiated by country/region

Resource Use

Coal: Yes (supply curve)

Conventional Oil: Yes (supply curve)

Unconventional Oil: Yes (supply curve)

Conventional Gas: Yes (supply curve)

Uranium: Yes (fixed)

Bioenergy: Yes (process model)

Water: Yes (process model)

Land: Yes (supply curve)

Technological change

Energy End-use: Endogenous technological change

Material Use: Exogenous technological change

Agriculture: Exogenous technological change

Energy conversion: Endogenous technological change

Energy

Behaviour

In the energy model, substitution among technologies is described in the model using the multinomial logit formulation. The multinomial logit model implies that the market share of a certain technology or fuel type depends on costs relative to competing technologies. The option with the lowest costs gets the largest market share, but in most cases not the full market. We interpret the latter as a representation of heterogeneity in the form of specific market niches for every technology or fuel.

Energy technology choice

- Logit choice model

Energy technology substitutability

- Mostly high substitutability

Energy technology deployment

- Expansion and decline constraints
- System integration constraints

Electricity technologies

- Coal w/o CCS
- Coal w/ CCS
- Gas w/o CCS
- Gas w/ CCS
- Oil w/o CCS
- Oil w/ CCS
- Bioenergy w/o CCS
- Bioenergy w/ CCS
- Geothermal power
- Nuclear power
- Solar power
- Solar power-central PV
- Solar power-CSP
- Wind power
- Wind power-onshore
- Wind power-offshore
- Hydroelectric power

Hydrogen production

- Electrolysis
- Coal to hydrogen w/o CCS
- Coal to hydrogen w/ CCS
- Natural gas to hydrogen w/o CCS
- Natural gas to hydrogen w/ CCS
- Oil to hydrogen w/o CCS
- Oil to hydrogen w/ CCS
- Biomass to hydrogen w/o CCS
- Biomass to hydrogen w/ CCS
- Solar thermochemical hydrogen

Refined liquids

- Bioliquids w/o CCS
- Bioliquids w/ CCS
- Oil refining

Refined gases

- Biomass to gas w/o CCS
- Biomass to gas w/ CCS

Heat generation

- CHP (coupled heat and power)
- Coal heat
- Natural gas heat
- Oil heat
- Biomass heat
- Geothermal heat

CHP also has a CCS option

Grid and infrastructure

Electricity: Yes (aggregate)

Gas: Yes (aggregate)

CO2: Yes (aggregate)

Hydrogen: Yes (aggregate)

Energy end-use technologies

Passenger transportation

- Buses
- Light Duty Vehicles (LDVs)
- Electric LDVs
- Hydrogen LDVs
- Hybrid LDVs
- Gasoline LDVs
- Diesel LDVs
- Passenger trains
- Passenger aircrafts

Freight transportation

- Freight trains
- Heavy duty vehicles
- Freight aircrafts
- Freight ships

Industry

- Steel production
- Cement production
- Plastics production

Residential and commercial

- Cooking
- Refrigeration
- Washing
- Lighting
- Space heating
- Space cooling

Land use

Land cover

- Cropland
- Forest
- Pasture
- Shrubland
- Cropland irrigated
- Cropland food crops
- Cropland feed crops
- Cropland energy crops
- Managed forest
- Natural forest
- Built-up area

Agriculture and forestry demands

- Agriculture food
- Agriculture food crops
- Agriculture food livestock
- Agriculture feed crops
- Agriculture feed livestock
- Agriculture non-food
- Agriculture non-food crops
- Agriculture non-food livestock
- Agriculture bioenergy
- Agriculture residues
- Forest industrial roundwood
- Forest fuelwood
- Forest residues

Agricultural commodities

- Wheat
- Rice
- Oilseeds
- Other coarse grains
- Sugar crops
- Ruminant meat
- Non-ruminant meat and eggs
- Dairy products

Emissions, climate and impacts

Greenhouse gases

- HFCs
- CFCs
- SF6
- PFCs
- CO2 fossil fuels
- CO2 cement
- CO2 land use
- CH4 energy
- CH4 land use
- CH4 other
- N2O energy
- N2O land use
- N2O other

Pollutants

- CO energy
- CO land use
- CO other
- NOx energy
- NOx land use
- NOx other
- VOC energy
- VOC land use
- VOC other
- SO2 energy
- SO2 land use
- SO2 other
- BC energy
- BC land use
- BC other
- OC energy
- OC land use
- OC other
- NH3 energy
- NH3 land use
- NH3 other

Climate indicators

- Temperature change
- Concentration: CO2
- Concentration: CH4
- Concentration: N2O
- Concentration: Kyoto gases
- Radiative forcing: CO2
- Radiative forcing: CH4
- Radiative forcing: N2O
- Radiative forcing: F-gases

- Radiative forcing: Kyoto gases
- Radiative forcing: aerosols
- Radiative forcing: land albedo
- Radiative forcing: AN3A
- Radiative forcing: total
- Sea level rise

Carbon dioxide removal

- Bioenergy with CCS
- Reforestation
- Afforestation

Climate change impacts

- Agriculture
- Inequality
- Energy supply
- Energy demand

Co-Linkages

- Biodiversity
- Energy security: Fossil fuel imports & exports (region)
- Energy access: Household energy consumption
- Air pollution & health: Source-based aerosol emissions
- Air pollution & health: Health impacts of air Pollution

Reference card – MESSAGE-GLOBIOM

About

Name and version

MESSAGE-GLOBIOM 1.0

Institution

International Institute for Applied Systems Analysis (IIASA), Austria, http://data.ene.iiasa.ac.at/message-globiom/.

Model scope and methods

Objective

MESSAGE-GLOBIOM is an integrated assessment framework designed to assess the transformation of the energy and land systems vis-a-vis the challenges of climate change and other sustainability issues. It consists of the energy model MESSAGE, the land use model GLOBIOM, the air pollution and GHG model GAINS, the aggregated macro-economic model MACRO and the simple climate model MAGICC

Solution concept

General equilibrium (closed economy)

Solution method

Optimization

Temporal dimension

Base year: 2030, time steps: 10, horizon: 2110

Spatial dimension

Number of regions:11

1. AFR (Sub-Saharan Africa)
2. CPA (Centrally Planned Asia & China)
3. EEU (Eastern Europe)
4. FSU (Former Soviet Union)
5. LAM (Latin America and the Carribean)
6. MEA (Middle East and North Africa)
7. NAM (North America)
8. PAO (Pacific OECD)
9. PAS (Other Pacific Asia)
10. SAS (South Asia)
11. WEU (Western Europe)

Time discounting average

1 (% per year)

Climate policies

- Emission tax
- Pricing
- Cap and Trade

Energy policies

- Portfolio standard

Energy technology policies

- Capacity targets
- Emission standards
- Energy efficiency standards

Socio economic drivers

Population: Yes (exogenous)

GDP: Yes (exogenous)

Income Distribution: Yes (exogenous)

Labor Productivity: Yes (exogenous)

Autonomous Energy Efficiency Improvements: Yes (endogenous)

Macro economy

Economic sector

Industry: Yes (physical)

Energy: Yes (physical)

Services: Yes (physical)

Trade

- Coal
- Oil
- Gas
- Uranium
- Electricity
- Emissions permits

Cost measures

- GDP loss
- Consumption loss
- Area under MAC
- Energy system cost mark-up

Categorization by group

- Income
- Urban - rural

Resource Use

Coal: Yes (supply curve)

Conventional Oil: Yes (supply curve)

Unconventional Oil: Yes (supply curve)

Conventional Gas: Yes (supply curve)

Uranium: Yes (supply curve)

Bioenergy: Yes (supply curve)

Technological change

Energy End-use: Exogenous technological change

Energy conversion: Endogenous technological change

Energy

Energy technology choice

- Linear choice (lowest cost)

Energy technology substitutability

- Mostly high substitutability

Energy technology deployment

- Expansion and decline constraints
- System integration constraints

Electricity technologies

- Coal w/o CCS

- Coal w/ CCS
- Gas w/o CCS
- Gas w/ CCS
- Oil w/o CCS
- Bioenergy w/o CCS
- Bioenergy w/ CCS
- Geothermal power
- Nuclear power
- Solar power
- Solar power-central PV
- Solar power-CSP
- Wind power
- Wind power-onshore
- Wind power-offshore
- Hydroelectric power

Hydrogen production

- Electrolysis
- Coal to hydrogen w/o CCS
- Coal to hydrogen w/ CCS
- Natural gas to hydrogen w/o CCS
- Natural gas to hydrogen w/ CCS
- Biomass to hydrogen w/o CCS
- Biomass to hydrogen w/ CCS

Refined liquids

- Bioliquids w/o CCS
- Bioliquids w/ CCS
- Coal to liquids w/o CCS
- Coal to liquids w/ CCS
- Gas to liquids w/o CCS
- Gas to liquids w/ CCS
- Oil refining

Refined gases

- Coal to gas w/o CCS
- Coal to gas w/ CCS
- Biomass to gas w/o CCS
- Biomass to gas w/ CCS

Heat generation

- CHP (coupled heat and power)
- Coal heat
- Natural gas heat
- Oil heat
- Biomass heat
- Geothermal heat
- Solarthermal heat

Grid and infrastructure

Electricity: Yes (aggregate)

Gas: Yes (aggregate)

Heat: Yes (aggregate)

CO2: Yes (aggregate)

Hydrogen: Yes (aggregate)

Energy end-use technologies

Residential and commercial

- Cooking
- Space heating

Land use

Emissions, climate and impacts

Greenhouse gases

- CO2 fossil fuels
- CO2 cement
- CO2 land use
- CH4 energy
- CH4 land use
- CH4 other
- N2O energy
- N2O land use
- N2O other
- HFCs
- CFCs
- SF6

Pollutants

- CO energy
- CO land use
- CO other
- NOx energy
- NOx other
- VOC energy
- VOC land use
- VOC other
- SO2 energy
- SO2 land use
- SO2 other

- BC energy
- BC land use
- BC other
- OC energy
- OC land use
- OC other
- NH3 energy
- NH3 land use
- NH3 other

Climate indicators

- Temperature change
- Ocean acidification
- Concentration: CO2
- Concentration: CH4
- Concentration: N2O
- Concentration: Kyoto gases
- Radiative forcing: CO2
- Radiative forcing: CH4
- Radiative forcing: N2O
- Radiative forcing: F-gases
- Radiative forcing: Kyoto gases
- Radiative forcing: aerosols
- Radiative forcing: land albedo
- Radiative forcing: AN3A
- Radiative forcing: total
- Sea level rise

Carbon dioxide removal

- Bioenergy with CCS
- Reforestation
- Afforestation

Co-Linkages

- Energy security: Fossil fuel imports & exports (region)
- Energy access: Household energy consumption
- Air pollution & health: Source-based aerosol emissions
- Air pollution & health: Health impacts of air Pollution

Reference card – POLES

About

Name and version

POLES ENGAGE (other versions are in use in other applications)

Institution

JRC - Joint Research Centre - European Commission (EC-JRC), Belgium, http://ec.europa.eu/jrc/en/poles.

Model scope and methods

Objective

POLES was originally developed to assess energy markets, combining a detailed description of energy demand, transformation and primary supply for all energy vectors. It provides full energy balances on a yearly basis using frequent data updates to as to deliver robust forecasts for both short and long-term horizons. It has quickly been used, in the late 90s, to assess energy-related CO2 mitigation policies. Over time other GHG emissions have been included (energy and industry non-CO2 from the early 2000s), and linkages with agricultural and land use models have been progressively implemented.

Solution concept

Partial equilibrium (price elastic demand)

Solution horizon

Recursive dynamic (myopic)

Solution method

Simulation

Anticipation

Myopic

Temporal dimension

Base year: 2015, time steps: Yearly, horizon: 2015-2100

Spatial dimension

Number of regions:66 Complete energy balances: 57 countries / regions covering the World, including detailed EU28, all OECD countries and main non-OECD countries

Fossil fuel supply: 80 countries / regions

Climate policies

- Emission tax
- Pricing
- Cap and Trade

Energy policies

- Feed-in-Tariff
- Fuel taxes
- Fuel subsidies

Energy technology policies

- Capacity targets
- Emission standards
- Energy efficiency standards

Land-use policies

- Pricing carbon stocks

Socio economic drivers

Population: Yes (exogenous)

GDP: Yes (exogenous)

Autonomous energy efficiency improvements: Yes (endogenous)

Macro economy

Economic sector

Industry: Yes (physical & economic)

Energy: Yes (physical & economic)

Agriculture: Yes (physical & economic)

Other economic sector

- Services (economic)

Trade

- Coal
- Oil

- Gas
- Bioenergy crops
- Emissions permits
- Electricity

Cost measures

- Area under MAC
- Investments: supply-side only

Resource Use

Coal: Yes (process model)

Conventional Oil: Yes (process model)

Unconventional Oil: Yes (process model)

Conventional Gas: Yes (process model)

Uranium: Yes (process model)

Bioenergy: Yes (supply curve)

Land: Yes (fixed)

Technological change

Energy End-Use: Exogenous technological change

Energy conversion: Endogenous technological change

Energy

Behaviour

Activity drivers depend on income per capita and energy prices via elasticities. Energy demand depends on activity drivers, energy prices and technology costs. Primary energy supply depends on remaining resources, production cost and price effects.

Energy technology choice

- Logit choice model

Energy technology substitutability

- Mostly high substitutability

Energy technology deployment

- Expansion and decline constraints

Electricity technologies

- Coal w/o CCS
- Coal w/ CCS
- Gas w/o CCS
- Gas w/ CCS
- Oil w/o CCS
- Bioenergy w/o CCS
- Bioenergy w/ CCS
- Geothermal power
- Nuclear power
- Solar power
- Solar power-central PV
- Solar power-CSP
- Wind power
- Wind power-onshore
- Wind power-offshore
- Hydroelectric power
- Ocean power
- Solar power-distributed PV

Hydrogen production

- Electrolysis
- Coal to hydrogen w/o CCS
- Coal to hydrogen w/ CCS
- Natural gas to hydrogen w/o CCS
- Natural gas to hydrogen w/ CCS
- Oil to hydrogen w/o CCS
- Biomass to hydrogen w/o CCS
- Biomass to hydrogen w/ CCS
- Nuclear thermochemical hydrogen
- Solar thermochemical hydrogen

Refined liquids

- Bioliquids w/o CCS
- Bioliquids w/ CCS
- Coal to liquids w/o CCS
- Coal to liquids w/ CCS
- Gas to liquids w/o CCS
- Gas to liquids w/ CCS
- Oil refining

Heat generation

- Biomass heat
- CHP (coupled heat and power)
- Coal heat
- Natural gas heat
- Oil heat
- Solarthermal heat

Grid and infrastructure

Gas: Yes (aggregate)

CO2: Yes (aggregate)

Energy end-use technologies

Passenger transportation

- Buses
- Light Duty Vehicles (LDVs)
- Electric LDVs
- Hydrogen LDVs
- Hybrid LDVs
- Gasoline LDVs
- Diesel LDVs
- Passenger trains
- Passenger aircrafts

Freight transportation

- Freight trains
- Heavy duty vehicles
- Freight ships

Industry

- Steel production
- Cement production
- Petrochemical production

Residential and commercial

- Cooking
- Space heating
- Space cooling

Land use

Land cover

- Cropland
- Forest
- Pasture
- Cropland irrigated
- Cropland food crops
- Cropland feed crops
- Managed forest
- Natural forest
- Built-up area

Agriculture and forestry demands

- Agriculture food
- Agriculture food crops
- Agriculture feed crops
- Agriculture bioenergy
- Forest industrial roundwood
- Forest fuelwood
- Forest residues

Emissions, climate and impacts

Greenhouse gases

- CO2 cement
- CO2 fossil fuels
- CO2 land use
- CH4 energy
- CH4 other
- N2O energy
- N2O land use
- N2O other
- HFCs
- CFCs
- PFCs
- SF6

Pollutants

- CO energy
- CO land use
- CO other
- NOx energy
- NOx land use
- NOx other
- VOC energy
- VOC land use
- VOC other
- SO2 energy
- SO2 land use
- SO2 other
- BC energy
- BC land use
- BC other
- NH3 energy
- NH3 land use
- NH3 other

Carbon dioxide removal

- Bioenergy with CCS
- Reforestation
- Afforestation

Climate change impacts

- Energy demand

Co-Linkages

- Energy security: Fossil fuel imports & exports (region)
- Energy access: Household energy consumption
- Air pollution & health: Source-based aerosol emissions

Reference card – REMIND-MagPIE

About

Name and version

REMIND-MAgPIE 2.0-4.1

Institution

Potsdam Institut für Klimafolgenforschung (PIK), Germany, https://www.pik-potsdam.de/research/sustainable-solutions/models/remind.

Model scope and methods

Objective

Construct self-consistent optimal benchmark scenarios for the transformation of the global energy-economy-land system, for different assumptions on climate policies or targets. Comparison with no-policy benchmark scenarios allows for the calculation of mitigation costs.

Solution concept

General equilibrium (closed economy)

Solution method

Optimization

Temporal dimension

Base year: 2005, time steps: 5, horizon: 2005-2100

Spatial dimension

Number of regions: 12

Time discounting average

(% per year)

Climate policies

- Emission tax
- Pricing
- Cap and Trade

Energy policies

- Fuel taxes
- Fuel subsidies
- Portfolio standard

Energy technology policies

- Capacity targets

Land-use policies

- Land protection
- Pricing carbon stocks

Socio economic drivers

Population: Yes (exogenous)

GDP: Yes (exogenous)

Employment rate: Yes (exogenous)

Labor productivity: Yes (exogenous)

Total factor productivity: Yes (exogenous)

Autonomous energy efficiency improvements: Yes (exogenous)

Macro economy

Economic sector

Energy: Yes (physical)

Agriculture: Yes (physical)

Other economic sector

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.

Trade

- Coal
- Oil
- Gas
- Uranium
- Bioenergy crops
- Capital

- Emissions permits
- Non-energy goods
- Food crops
- Energy goods

Cost measures

- Consumption loss
- GDP loss
- Welfare loss

Resource Use

Coal: Yes (supply curve)

Conventional Oil: Yes (supply curve)

Unconventional Oil: Yes (supply curve)

Conventional Gas: Yes (supply curve)

Uranium: Yes (supply curve)

Bioenergy: Yes (supply curve)

Water: Yes (process model)

Technological change

Energy End-use: Endogenous technological change

Energy

Energy technology substitutability

- Mostly high substitutability

Electricity technologies

- Coal w/o CCS
- Coal w/ CCS
- Gas w/o CCS
- Gas w/ CCS
- Oil w/o CCS
- Bioenergy w/o CCS
- Bioenergy w/ CCS
- Geothermal power
- Nuclear power
- Solar power
- Solar power-central PV
- Solar power-CSP

- Wind power
- Hydroelectric power

Hydrogen production

- Electrolysis
- Coal to hydrogen w/o CCS
- Coal to hydrogen w/ CCS
- Natural gas to hydrogen w/o CCS
- Natural gas to hydrogen w/ CCS
- Biomass to hydrogen w/o CCS
- Biomass to hydrogen w/ CCS

Refined liquids

- Bioliquids w/ CCS
- Bioliquids w/o CCS
- Coal to liquids w/ CCS
- Coal to liquids w/o CCS
- Oil refining

Refined gases

- Coal to gas w/o CCS
- Biomass to gas w/o CCS

Heat generation

- CHP (coupled heat and power)
- Coal heat
- Natural gas heat
- Oil heat
- Biomass heat
- Geothermal heat

Grid and infrastructure

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 end-use technologies

Passenger transportation

- Light Duty Vehicles (LDVs)
- Electric LDVs
- Hydrogen LDVs
- Gasoline LDVs
- Passenger trains

Freight transportation

- Heavy duty vehicles

Land use

Land cover

- Cropland
- Forest
- Pasture
- Cropland irrigated
- Cropland food crops
- Cropland feed crops
- Cropland energy crops
- Managed forest
- Natural forest
- Built-up area

Agriculture and forestry demands

- Agriculture food
- Agriculture food crops
- Agriculture food livestock
- Agriculture feed
- Agriculture feed crops
- Agriculture feed livestock
- Agriculture non-food
- Agriculture non-food crops
- Agriculture non-food livestock
- Agriculture bioenergy
- Agriculture residues

Agricultural commodities

- Wheat
- Rice
- Oilseeds
- Other coarse grains
- Sugar crops
- Ruminant meat
- Non-ruminant meat and eggs
- Dairy products

Emissions, climate and impacts

Greenhouse gases

- CO2 fossil fuels
- CO2 cement
- CO2 land use
- CH4 energy

- CH4 land use
- CH4 other
- N2O energy
- N2O land use
- N2O other
- HFCs
- CFCs
- SF6

Pollutants

- BC energy
- BC land use
- BC other
- CO energy
- CO land use
- CO other
- NH3 energy
- NH3 land use
- NOx energy
- NOx land use
- NOx other
- OC energy
- OC land use
- OC other
- SO2 energy
- SO2 land use
- SO2 other
- VOC energy
- VOC land use
- VOC other

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

Climate indicators

- Temperature change
- Concentration: CO2
- Concentration: CH4
- Concentration: N2O
- Concentration: Kyoto gases
- Radiative forcing: CO2
- Radiative forcing: CH4
- Radiative forcing: N2O
- Radiative forcing: F-gases
- Radiative forcing: Kyoto gases
- Radiative forcing: aerosols
- Radiative forcing: AN3A
- Radiative forcing: total
- Radiative Forcing (Land Albedo) - Yes (exogenous)

Carbon dioxide removal

- Bioenergy with CCS

- Afforestation
- Direct air capture
- Enhanced weathering

Co-Linkages

- Energy security: Fossil fuel imports & exports (region)
- Water availability

Reference card – WITCH

About

Name and version

WITCH 5.0

Institution

Fondazione Eni Enrico Mattei (FEEM), Italy, http://www.feem.it.
Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Italy, http://www.cmcc.it.

Model scope and methods

Objective

WITCH evaluates the impacts of climate policies on global and regional economic systems and provides information on the optimal responses of these economies to climate change. The model considers the positive externalities from leaning-by-doing and learning-by-researching in the technological change.

Solution concept

General equilibrium (closed economy)

Solution method

Optimization

Temporal dimension

Base year: 2005, time steps: 5, horizon: 2150

Spatial dimension

Number of regions: 17

Climate policies

- Emission tax
- Pricing
- Cap and Trade

Energy policies

- Fuel taxes
- Fuel subsidies

Energy technology policies

- Capacity targets
- Emission standards

Socio economic drivers

Population: Yes (exogenous)

Urbanization rate: Yes (exogenous)

GDP: Yes (endogenous)

Total factor productivity: Yes (exogenous)

Autonomous energy efficiency improvements: Yes (exogenous)

Macro economy

Economic sector

A single economy sector is represented. Production inputs are capital, labor and energy services, accounting for the Energy sector split into 8 energy technologies sectors (coal, oil, gas, wind & solar, nuclear, electricity and biofuels).

Trade

- Coal
- Oil
- Gas
- Emissions permits
- Uranium
- Electricity
- Bioenergy crops
- Capital
- Non-energy goods

Cost measures

- GDP loss
- Welfare loss
- Consumption loss
- Energy system cost mark-up

Resource Use

Coal: Yes (supply curve)

Conventional Oil: Yes (process model)

Unconventional Oil: Yes (process model)

Conventional Gas: Yes (fixed)

Uranium: Yes (fixed)

Bioenergy: Yes (supply curve)

Technological change

Energy End-use: Endogenous technological change

Agriculture: Exogenous technological change

Energy

Energy technology choice

- No discrete technology choices

Energy technology substitutability

- Mostly high substitutability

Energy technology deployment

- Expansion and decline constraints
- System integration constraints

Electricity technologies

- Coal w/o CCS
- Coal w/ CCS
- Gas w/o CCS
- Gas w/ CCS
- Oil w/o CCS
- Oil w/ CCS
- Bioenergy w/o CCS
- Bioenergy w/ CCS
- Nuclear power
- Solar power
- Solar power-central PV
- Solar power-CSP
- Wind power
- Wind power-onshore
- Wind power-offshore
- Hydroelectric power
- Solar power-distributed PV

Grid and infrastructure

Electricity: Yes (aggregate)

Energy end-use technologies

Passenger transportation

- Light Duty Vehicles (LDVs)
- Electric LDVs
- Hybrid LDVs
- Diesel LDVs

Land use

Land cover

- Cropland
- Forest
- Pasture
- Cropland irrigated

Emissions, climate and impacts

Greenhouse gases

- CO2 fossil fuels
- CO2 land use
- CH4 energy
- CH4 land use
- CH4 other
- N2O energy
- N2O land use
- N2O other
- HFCs

Pollutants

- CO energy
- CO land use
- CO other
- NOx energy
- NOx land use
- NOx other
- VOC energy
- VOC land use
- VOC other
- SO2 energy
- SO2 land use
- SO2 other
- BC energy
- BC land use
- BC other

- OC energy
- OC land use
- OC other
- NH3 energy
- NH3 land use
- NH3 other

Climate indicators

- Temperature change
- Concentration: CO2
- Concentration: CH4
- Concentration: N2O
- Concentration: Kyoto gases
- Radiative forcing: CO2
- Radiative forcing: CH4
- Radiative forcing: N2O
- Radiative forcing: F-gases
- Radiative forcing: Kyoto gases
- Radiative forcing: aerosols
- Radiative forcing: land albedo
- Radiative forcing: AN3A
- Radiative forcing: total

Carbon dioxide removal

- Bioenergy with CCS
- Reforestation
- Afforestation
- Direct air capture

Climate change impacts

- Economic output

Co-Linkages

- Air pollution & health: Source-based aerosol emissions
- Air pollution & health: Health impacts of air Pollution

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