To pdf - MESSAGE-GLOBIOM

From IAMC-Documentation

Reference card - MESSAGE-GLOBIOM

Contents

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

Legend:

☐ not implemented
☑ **implemented**
☑ **implemented (not default option)**

About

Name and version	MESSAGE-GLOBIOM 1.0
Institution and users	International Institute for Applied Systems Analysis (IIASA), Austria, http://data.ene.iiasa.ac.at/message-globiom/. main users: IIASA, the MESSAGE model is distributed via the International Atomic Energy Agency (IAEA) to member countries
Documentation	MESSAGE-GLOBIOM documentation consists of a referencecard and detailed model documentation

Model scope and methods

Model documentation: Model scope and methods - MESSAGE-GLOBIOM

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.

Concept Hybrid model (energy engineering and land use partial equilibrium models soft-linked to macro-economic general equilibrium model)

Solution method Hybrid model (linear program optimization for the energy systems and land-use modules, non-linear program optimization for the macro-economic module)

Anticipation Myopic/Perfect Foresight (MESSAGE can be run both with perfect foresight and myopically, while GLOBIOM runs myopically)

Temporal dimension Base year:2010, time steps:1990, 1995, 2000, 2005, 2010, 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100, 2110, horizon: 1990-2110

Note: From 1990 to 2010 MESSAGE employs 5-year time steps with 10-year steps employed thereafter

Spatial dimension Number of regions:11+1

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)
12. GLB (international shipping)

Policy implementation GHG and energy taxes; GHG emission cap and permits trading; energy taxes and subsidies; micro-financing (for energy access analysis); regulation: generation capacity, production and share targets

Socio economic drivers

Model documentation: Socio-economic drivers - MESSAGE-GLOBIOM

Exogenous drivers

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

Development

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

Macro economy

Model documentation: Macro-economy - MESSAGE-GLOBIOM

Economic sectors

- ☐ Agriculture
- ☐ Industry

	☐ Energy ☐ Transport	☐ Services

Note: MACRO represents the economy in a single sector with the production function including capital, labor and energy nests

Cost measures	☑ **GDP loss** ☐ Welfare loss ☑ **Consumption loss**	☑ **Area under MAC** ☑ **Energy system costs**
Trade	☑ **Coal** ☑ **Oil** ☑ **Gas** ☑ **Uranium** ☑ **Electricity**	☐ Bioenergy crops ☑ **Food crops** ☐ Capital ☑ **Emissions permits** ☐ Non-energy goods

Note: bioenergy is only traded after processing to a secondary fuel (e.g. liquid biofuel)

Energy

Model documentation: Energy - MESSAGE-GLOBIOM

Resource use	☑ **Coal** ☑ **Oil** ☑ **Gas**	☑ **Uranium** ☑ **Biomass**
Electricity technologies	☑ **Coal** ☑ **Gas** ☑ **Oil** ☑ **Nuclear** ☑ **Biomass** ☑ **Wind**	☑ **Solar PV** ☑ **CCS** ☑ **CSP** ☑ **Geothermal** ☑ **Hydropower**

Note: CCS can be combined with coal, gas and biomass power generation technologies

Conversion technologies	☑ **CHP** ☐ Heat pumps ☑ **Hydrogen**	☑ **Fuel to gas** ☑ **Fuel to liquid**
Grid and infrastructure	☑ **Electricity** ☑ **Gas** ☑ **Heat**	☑ **CO2** ☑ **H2**
Energy technology substitution	☑ **Discrete technology choices** ☑ **Expansion and decline constraints**	☑ **System integration constraints**

Energy service sectors	☑ **Transportation** ☑ **Industry** *Note: non-energy use (feedstock) of energy carriers is separately represented, but generally reported under industry*	☑ **Residential and commercial**

Land-use

Model documentation: Land-use - MESSAGE-GLOBIOM; Non-climate sustainability dimension - MESSAGE-GLOBIOM

Other resources

Model documentation: Non-climate sustainability dimension - MESSAGE-GLOBIOM

Other resources	☑ **Water** ☐ Metals *Note: cement is not modeled as a separate commodity, but process emissions from cement production are represented*	☑ **Cement**

Emissions and climate

Model documentation: Emissions - MESSAGE-GLOBIOM; Climate - MESSAGE-GLOBIOM

Green house gasses	☑ **CO2** ☑ **CH4** ☑ **N2O**	☑ **HFCs** ☑ **CFCs** ☑ **SF6**
Pollutants	☑ **NOx** ☑ **SOx** ☑ **BC** ☑ **OC**	☐ Ozone ☑ **CO** ☑ **NH3** ☑ **VOC**
Climate indicators	☑ **CO2e concentration (ppm)** ☑ **Radiative Forcing (W/m^2)**	☑ **Temperature change (°C)** ☐ Climate damages $ or equivalent

Model Documentation - MESSAGE-GLOBIOM

The IIASA IAM framework consists of a combination of five different models or modules - 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 - which complement each other and are specialized in different areas. All models and modules together build the IIASA IAM framework, also referred to as MESSAGE-GLOBIOM owing to the fact that the energy model MESSAGE and the land use model GLOBIOM are its most important components. The five models provide input to and iterate between each other during a typical SSP scenario development cycle.

1) Model scope and methods - MESSAGE-GLOBIOM

MESSAGE represents the core of the IIASA IAM framework Figure 1 and its main task is to optimize the energy system so that it can satisfy specified energy demands at the lowest costs. MESSAGE carries out this optimization in an iterative setup with MACRO, which provides estimates of the macro-economic demand response that results of energy system and services costs computed by MESSAGE. For the six commercial end-use demand categories depicted in MESSAGE (see Demand of MESSAGE-GLOBIOM), MACRO will adjust useful energy demands, until the two models have reached equilibrium (see Macro-economy section of MESSAGE-GLOBIOM). This iteration reflects price-induced energy efficiency improvements that can occur when energy prices increase.

GLOBIOM provides MESSAGE with information on land use and its implications, like the availability and cost of bio-energy, and availability and cost of emission mitigation in the AFOLU (Agriculture, Forestry and Land Use) sector (see Land-use of MESSAGE-GLOBIOM). To reduce computational costs, MESSAGE iteratively queries a GLOBIOM emulator which can provide possible land-use outcomes during the optimization process instead of requiring the GLOBIOM model to be rerun continuously. Only once the iteration between MESSAGE and MACRO has converged, the resulting bioenergy demands along with corresponding carbon prices are used for a concluding online analysis with the full-fledged GLOBIOM model. This ensures full consistency in the modelled results from MESSAGE and GLOBIOM, and also allows the production of a more extensive set of reporting variables.

Air pollution implications of the energy system are computed in MESSAGE by applying technology-specific pollution coefficients from GAINS (see Pollutants and non-GHG forcing agents for MESSAGE-GLOBIOM and Air pollution and health of MESSAGE-GLOBIOM).

In general, cumulative global GHG emissions from all sectors are constrained at different levels to reach the forcing levels (cf. right-hand side Figure 1). The climate constraints are thus taken up in the coupled MESSAGE-GLOBIOM optimization, and the resulting carbon price is fed back to the full-fledged GLOBIOM model for full consistency. Finally, the combined results for land use, energy, and industrial emissions from MESSAGE and GLOBIOM are merged and fed into MAGICC (see Climate of MESSAGE-GLOBIOM), a global carbon-cycle and climate model, which then provides estimates of the climate implications in terms of atmospheric concentrations, radiative forcing, and global-mean temperature increase. Importantly, climate impacts and impacts of the carbon cycle are currently not accounted for in the IIASA IAM framework. The entire framework is linked to an online database infrastructure which allows straightforward visualisation, analysis, comparison and dissemination of results (Fricko et al., 2016 [1]).

[1]

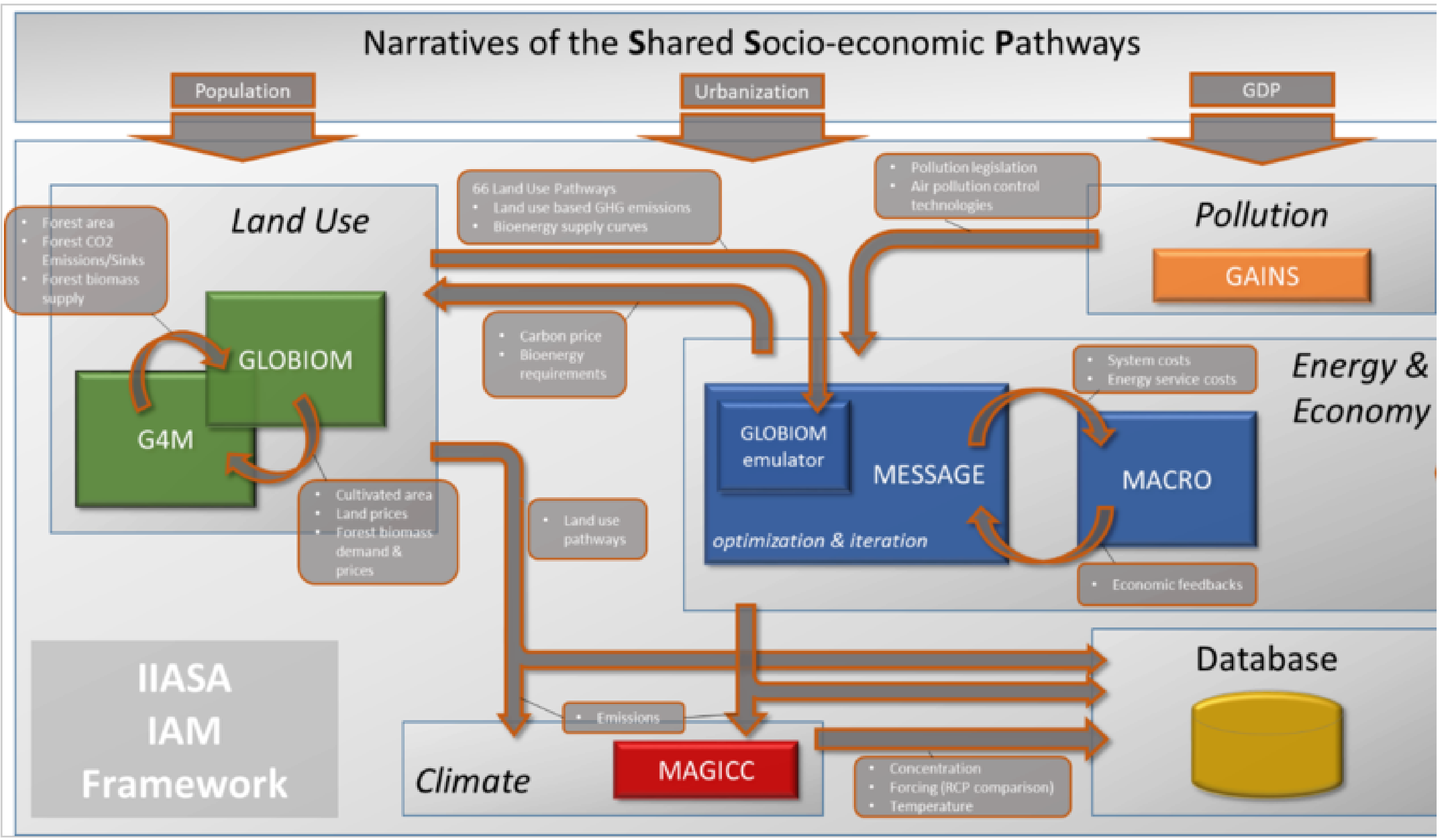

Figure 1: Overview of the IIASA IAM framework. Coloured boxes represent respective specialized disciplinary models which are integrated f
internally consistent scenarios. Figure from Riahi et al. (2016).

1.1) Model concept, solver and details - MESSAGE-GLOBIOM

1.3) Temporal dimension - MESSAGE-GLOBIOM

MESSAGE models the time horizon 1990 to 2110 in 5- and 10 year time steps where the first 5 periods (1990, 1995, 2000, 2005, 2010) are 5-year periods and the remaining 10 periods are 10-year periods (2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100, 2110). The first four periods up to 2005 are fully calibrated, i.e. the model has no flexibility to change in these five periods. The 2010 period is partly calibrated so far, some recent trends are included in this time period, but some flexibility remains. In scenario applications the 2010 period is typically fixed to its baseline development so that future climate and energy policy cannot induce changes in the past. The reporting years are the final years of periods which implies that investments that lead to the capacities in the reporting year are the average annual investments over the entire period the reporting year belongs to.

MESSAGE can both operate perfect foresight over the entire time horizon, limited foresight (e.g., one or two periods into the future) or myopically, optimizing one period at a time (Keppo and Strubegger, 2010 [2]). Most frequently MESSAGE is run with perfect foresight, but for specific applications such as delayed participation in a global climate regime without anticipation (Krey and Riahi, 2009 [3]; O'Neill et al., 2010 [4]) limited foresight is used.

1.4) Spatial dimension - MESSAGE-GLOBIOM

MESSAGE has global coverage and divides the world into 11 regions (see Figure 2 below).

The country definitions of the 11 MESSAGE regions are described in the table below (Table 1).

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Figure 2: Map of 11 MESSAGE-GLOBIOM regions

Table 1: Country definitions of the 11 MESSAGE regions

11 MESSAGE regions	Definition	List of countries
NAM	North America	Canada, Guam, Puerto Rico, United States of America, Virgin Islands
WEU	Western Europe	Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom
PAO	Pacific OECD	Australia, Japan, New Zealand
EEU	Central and Eastern Europe	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, The former Yugoslav Rep. of Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Yugoslavia, Estonia, Latvia, Lithuania
FSU	Former Soviet Union	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
CPA	Centrally Planned Asia and China	Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Viet Nam
SAS	South Asia	Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka
PAS	Other Pacific Asia	American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua, New Guinea, Philippines, Republic of Korea, Singapore, Solomon Islands, Taiwan (China), Thailand, Tonga, Vanuatu, Western Samoa
MEA	Middle East and North Africa	Algeria, Bahrain, Egypt (Arab Republic), Iraq, Iran (Islamic Republic), Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Yemen
LAM	Latin America and the Caribbean	Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela
AFR	Sub-Saharan Africa	Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Democratic Republic of Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe

In addition to the 11 geographical regions, there is a global trade region where market clearing of global energy markets is happening, international shipping bunker fuel demand, uranium resource extraction and the nuclear fuel cycle are modeled.

1.5) Policy - MESSAGE-GLOBIOM

A number of different energy- and climate-related policies are, depending on the scenario setup and the research question addressed, explicitly represented in MESSAGE. This includes the following list of policies:

- GHG emission pricing
- GHG emission caps and trading permits
- Renewable energy portfolio standards (e.g., share of renewable energy in electricity generation)
- Renewable energy and other technology capacity targets
- Energy import taxes
- Fuel subsidies and micro-financing for achieving universal access to modern energy services in developing countries
- Air pollution legislation packages (fixed legislation, current and planned legislation, stringent legislation, maximum feasible reduction)

In general, these policies are implemented via constraints or cost coefficients (negative and positive) in the optimization problem. In the case of air pollution policies, the different legislation packages are implemented via a set of emission coefficients and associated costs derived from the GAINS model. The cost coefficients are, however, not part of the optimization procedure, but instead allow an ex-post quantification of air pollution policy costs for a specific energy scenario.

2) Socio-economic drivers - MESSAGE-GLOBIOM

Socio-economic drivers are typically informed by a scenario narrative that in qualitative terms describes the overall logic behind the scenarios. In the case of MESSAGE-GLOBIOM 1.0 the Shared Socio-economic Pathways (SSPs, see O'Neill et al., 2014 [5]) provide this overall scenario logic based on which the main socio-economic drivers, population and GDP, have been quantified. The subsections of this chapter describe how these quantitative drivers are used in MESSAGE-GLOBIOM.

2.1) Population - MESSAGE-GLOBIOM

Demographic development has, next to economic growth, strong implications for the anticipated mitigation and adaptation challenges. For example, a larger, poorer population will have more difficulties to adapt to the detrimental effects of climate change (O'Neill et al., 2014 [5]). The primary drivers of future energy demand in MESSAGE are projections of total population and GDP at purchasing power parity, denoted as GDP (PPP). In addition to total population, the urban/rural split of population is relevant for the MESSAGE-Access version of the model which distinguishes rural and urban population with different household incomes in developing country regions.

Demographic projections used in MESSAGE-GLOBIOM are based on the Shared Socio-economic Pathways (SSPs) at the country level SSP database (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=welcome). Population growth evolves in response to how fertility, mortality, migration, and education of various social strata are assumed to change over time. In SSP2, global population peaks at 9.4 billion people around 2070, and slowly declines thereafter (KC and Lutz, 2015 [6]). However, modest improvements of educational attainment levels result in declines in education-specific fertility rates, leading to incomplete economic convergence across different world regions. This is particularly an issue for Africa. Overall, the population development in SSP2 is designed to be situated in the middle of the road between SSP1 and SSP3, see KC and Lutz (2015) [6] for details. (Fricko et al., 2016 [1])

2.2) Economic activity - MESSAGE-GLOBIOM

In addition to population economic development has a strong impact on the challenges to mitigation and adaptation. Generally, a poorer, less educated population will have more difficulties to adapt to the detrimental effects of climate change (O'Neill et al., 2014 [5]). The primary drivers of future energy demand in MESSAGE are projections of total population and GDP per capita at purchasing power parity, denoted as GDP (PPP). In the MESSAGE-Access version of the model households are represented by income level (and rural/urban split) in developing country regions.

MESSAGE-GLOBIOM utilizes GDP (PPP) projections based on the Shared Socio-economic Pathways (SSPs) that are available at the country level SSP database (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=welcome). In the SSPs, GDP development follows regional historical trends (Dellink et al., 2015 [7]). In SSP2 specifically, average income grows by a factor of six and reaches about 60,000 USD/capita by the end of the century (all GDP/capita figures use USD2005 and purchasing-power-parity – PPP). The SSP2 GDP projection is situated in-between the estimates for SSP1 and SSP3, which reach global average income levels of 82,000 USD2005 and 22,000 USD2005, respectively, by the end of the century.

SSP2 depicts a future of global progress where developing countries achieve significant economic growth. Today, average per capita income in the global North is about five times higher than in the global South. In SSP2, developing countries reach today's average income levels of the OECD between 2060 and 2090, depending on the region. Overall, the GDP developments in SSP2 are designed to be situated in the middle of the road between SSP1 and SSP3, see Dellink et al (2015) [7] for details. (Fricko et al., 2016 [1])

3) Macro-economy - MESSAGE-GLOBIOM

The detailed energy supply model (MESSAGE) is soft-linked to an aggregated, single-sector macro-economic model (MACRO) which has been derived from the so-called Global 2100 or ETA-MACRO model (Manne and Richels, 1992 [8]), a predecessor of the MERGE (http://www.stanford.edu/group/MERGE/) model. The reason for linking the two models is to consistently reflect the influence of energy supply costs, as calculated by MESSAGE, in the mix of production factors considered in MACRO, and the effect of changes in energy prices on energy service demands. The combined MESSAGE-MACRO model (Messner and Schrattenholzer, 2000 [9]) can generate a consistent economic response to changes in energy prices and estimate overall economic consequences (e.g., GDP or consumption loss) of energy or climate policies.

MACRO is a macroeconomic model maximizing the intertemporal utility function of a single representative producer-consumer in each world region. The optimization result is a sequence of optimal savings, investment, and consumption decisions. The main variables of the model are the capital stock, available labor, and energy inputs, which together determine the total output of an economy according to a nested CES (constant elasticity of substitution) production function. Energy demand in the six commercial demand categories of MESSAGE (see Energy demand of MESSAGE-GLOBIOM) is determined within the MACRO model, and is consistent with energy supply from MESSAGE, which is an input to the model.

The model's most important driving input variables are the projected growth rates of total labor, i.e., the combined effect of labor force and labor productivity growth and the annual rates of reference energy intensity reduction. The latter is calibrated to the developments in a MESSAGE baseline scenario to ensure consistency between the two models. Labor supply growth is also referred to as reference or potential GDP growth. In the absence of price changes, energy demands grow at rates that are the approximate result of potential GDP growth rates, reduced by the rates of overall energy intensity reduction. Price changes of the six demand categories can alter this path significantly.

MACRO's production function includes six commercial energy demand categories represented in MESSAGE. To optimize, MACRO requires cost information for each demand category. The exact definitions of these costs as a function over all positive quantities of energy cannot be given in closed form because each point of the function would be a result of a full MESSAGE run. However, the optimality conditions implicit in the formulation of MACRO only require the functional values and its derivatives at the optimal point to be consistent between the two sub-models. Since these requirements are therefore only local, most functions with this feature will simulate the combined energy-economic system in the neighborhood of the optimal point. The regional costs (energy use and imports) and benefits (energy exports) of providing energy in MACRO are approximated by a Taylor expansion to first order of the energy system costs as calculated by MESSAGE. From an initial MESSAGE model run, the total energy system cost (including costs/revenues from energy trade) and additional abatement costs (e.g., abatement costs from non-energy sources) as well as the shadow prices of the six commercial demand categories by region are passed to MACRO. In addition to the economic implications of energy trade, MACRO also includes the implications of GHG permit trade.

For a more elaborate description of MACRO, including the system of equations and technical details of the implementation, please consult the annex presenting the mathematical formulation of MACRO in Appendices of MESSAGE-GLOBIOM.

3.4) Trade - MESSAGE-GLOBIOM

4) Energy - MESSAGE-GLOBIOM

MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) is a linear programming (LP) energy engineering model with global coverage. As a systems engineering optimization model, MESSAGE is used for medium- to long-term energy system planning, energy policy analysis, and scenario development

(Messner and Strubegger, 1995 [10]). The model provides a framework for representing an energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services such as light, space conditioning, industrial production processes, and transportation. In addition, MESSAGE links to GLOBIOM (GLObal BIOsphere Model, cf. Section Land-use of MESSAGE-GLOBIOM) to consistently assess the implications of utilizing bioenergy of different types and to integrate the GHG emissions from energy and land use and to the aggregated macro-economic model MACRO (cf. Section Macro-economy of MESSAGE-GLOBIOM) to assess economic implications and to capture economic feedbacks.

MESSAGE covers all greenhouse gas (GHG)-emitting sectors, including energy, industrial processes as well as - through its linkage to GLOBIOM - agriculture and forestry. The emissions of the full basket of greenhouse gases including CO2, CH4, N2O and F-gases (CF4, C2F6, HFC125, HFC134a, HFC143a, HFC227ea, HFC245ca and SF6) as well as other radiatively active gases, such as NOx, volatile organic compounds (VOCs), CO, SO2, and BC/OC is represented in hte model. MESSAGE is used in conjunction with MAGICC (Model for Greenhouse gas Induced Climate Change) version 6.8 (cf. Section Climate of MESSAGE-GLOBIOM) for calculating atmospheric concentrations, radiative forcing, and annual-mean global surface air temperature increase.

The model is designed to formulate and evaluate alternative energy supply strategies consonant with the user-defined constraints such as limits on new investment, fuel availability and trade, environmental regulations and market penetration rates for new technologies. Environmental aspects can be analysed by accounting, and if necessary limiting, the amounts of pollutants emitted by various technologies at various steps in energy supplies. This helps to evaluate the impact of environmental regulations on energy system development.

It's principal results comprise, among others, estimates of technology-specific multi-sector response strategies for specific climate stabilization targets. By doing so, the model identifies the least-cost portfolio of mitigation technologies. The choice of the individual mitigation options across gases and sectors is driven by the relative economics of the abatement measures, assuming full temporal and spatial flexibility (i.e., emissions-reduction measures are assumed to occur when and where they are cheapest to implement).

The Reference Energy System (RES) defines the total set of available energy conversion technologies. In MESSAGE terms, energy conversion technology refers to all types of energy technologies from resource extraction to transformation, transport, distribution of energy carriers, and end-use technologies.

Because few conversion technologies convert resources directly into useful energy, the energy system in MESSAGE is divided into 5 energy levels:

- Resource (r) - raw resources (e.g., coal, oil, natural gas in the ground or biomass on the field)
- Primary (a) energy - raw product at a generation site (e.g., crude oil input to the refinery)
- Secondary (x) energy - finalized product at a generation site (e.g., gasoline or diesel fuel output from the refinery)
- Final (f) energy - finalized product at its consumption point (e.g., gasoline in the tank of a car or electricity leaving a socket)
- Useful (u) energy - finalized product satisfying demand for services (e.g., heating, lighting or moving people)

Technologies can take in from one level and put out at another level or on the same level. The energy forms defined in each level can be envisioned as a transfer hub, that the various technologies feed into or pump away from. The useful energy demand is given as a time series. Technologies can also vary per time period.

The mathematical formulation of MESSAGE ensures that the flows are consistent: demand is met, inflows equal outflows and constraints are not exceeded.

4.1) Energy resource endowments - MESSAGE-GLOBIOM

4.1.1) Fossil energy resources - MESSAGE-GLOBIOM

Fossil Fuel Reserves and Resources

The availability and costs of fossil fuels influences the future direction of the energy system, and therewith future mitigation challenges. Understanding the variations in fossil fuel availability and the underlying extraction cost assumptions across the SSPs is hence useful. Our fossil energy resource assumptions are derived from various sources (Rogner, 1997 [11]; Riahi et al., 2012 [12]) and are aligned with the storylines of the individual SSPs. While the physical resource base is identical across the SSPs, considerable differences are assumed regarding the technical and economic availability of overall resources, for example, of unconventional oil and gas. What ultimately determines the attractiveness of a particular type of resource is not just the cost at which it can be brought to the surface, but the cost at which it can be used to provide energy services. Assumptions on fossil energy resources should thus be considered together with those on related conversion technologies. In line with the narratives, technological change in fossil fuel extraction and conversion technologies is assumed to be slowest in SSP1, while comparatively faster technological change occurs in SSP3 thereby considerably enlarging the economic potentials of coal and unconventional hydrocarbons (Table 2, Figure 3). However, driven by tendency toward regional fragmentation the focus in SSP3 is assumed to be on developing coal technologies which in the longer term leads to a replacement of oil products by synthetic fuels based on coal-to-liquids technologies. In contrast, for SSP2 we assume a continuation of recent trends, focusing more on developing extraction technologies for unconventional hydrocarbon resources, thereby leading to higher potential cumulative oil extraction than in the other SSPs (Figure 3, middle panel).

Table 2 shows the assumed total quantities of fossil fuel resources in the MESSAGE model for the base year 2005. Figure 3 gives these resource estimates as supply curves. In addition, the assumptions are compared with estimates from the Global Energy Assessment (Rogner et al., 2012 [13]) as of the year 2009. Estimating fossil fuel reserves is built on both economic and technological assumptions. With an improvement in technology or a change in purchasing power, the amount that may be considered a “reserve” vs. a “resource” (generically referred to here as resources) can actually vary quite widely.

‘Reserves’ are generally defined as being those quantities for which geological and engineering information indicate with reasonable certainty that they can be recovered in the future from known reservoirs under existing economic and operating conditions. ‘Resources’ are detected quantities that cannot be profitably recovered with current technology, but might be recoverable in the future, as well as those quantities that are geologically possible, but yet to be found. The remainder are ‘Undiscovered resources’ and, by definition, one can only speculate on their existence. Definitions are based on Rogner et al. (2012) [13].

Table 2: Assumed global fossil fuel reserves and resources in the MESSAGE model. Estimates from the Global Energy Assessment also added for comparison

Source	MESSAGE (Rogner et al., 1997 [1])	Rogner et al., 2012 [2]	
	Reserves+Resources [ZJ]	Reserves [ZJ]	Resources [ZJ]
Coal	259	17.3 – 21.0	291 – 435
Conventional Oil	9.8	4.0 – 7.6	4.2 – 6.2
Unconventional Oil	23.0	3.8 – 5.6	11.3 – 14.9
Conventional Gas	16.8	5.0 – 7.1	7.2 – 8.9
Unconventional Gas	23.0	20.1 – 67.1	40.2 – 122

The following table (Table 3) presents the fossil resource availability in ZJ (2010-2100) for coal, oil and gas, for SSP1, SSP2 and SSP3, respectively.

Table 3: Fossil resource availability for SSP1, SSP2, and SSP3

Type	SSP1 [ZJ]	SSP2 [ZJ]	SSP3 [ZJ]
Coal	93	92	243
Oil	17	40	17
Gas	39	37	24

Coal is the largest resource among fossil fuels; it accounts for more than 50% of total fossil reserve plus resource estimates even at the higher end of the assumptions, which includes considerable amounts of unconventional hydrocarbons. Oil is the most vulnerable fossil fuel at less than 10 ZJ of conventional oil and possibly less than 10 ZJ of unconventional oil. Natural gas is more abundant in both the conventional and unconventional categories.

Figure 3 presents the cumulative global resource supply curves for coal, oil and gas in the IIASA IAM framework. Green shaded resources are technically and economically extractable in all SSPs, purple shaded resources are additionally available in SSP1 and SSP2 and blue shaded resources are additionally available in SSP2. Coloured vertical lines represent the cumulative use of each resource between 2010 and 2100 in the SSP baselines (see top panel for colour coding), and are thus the result of the combined effect of the assumptions on fossil resource availability and conversion technologies in the SSP baselines.

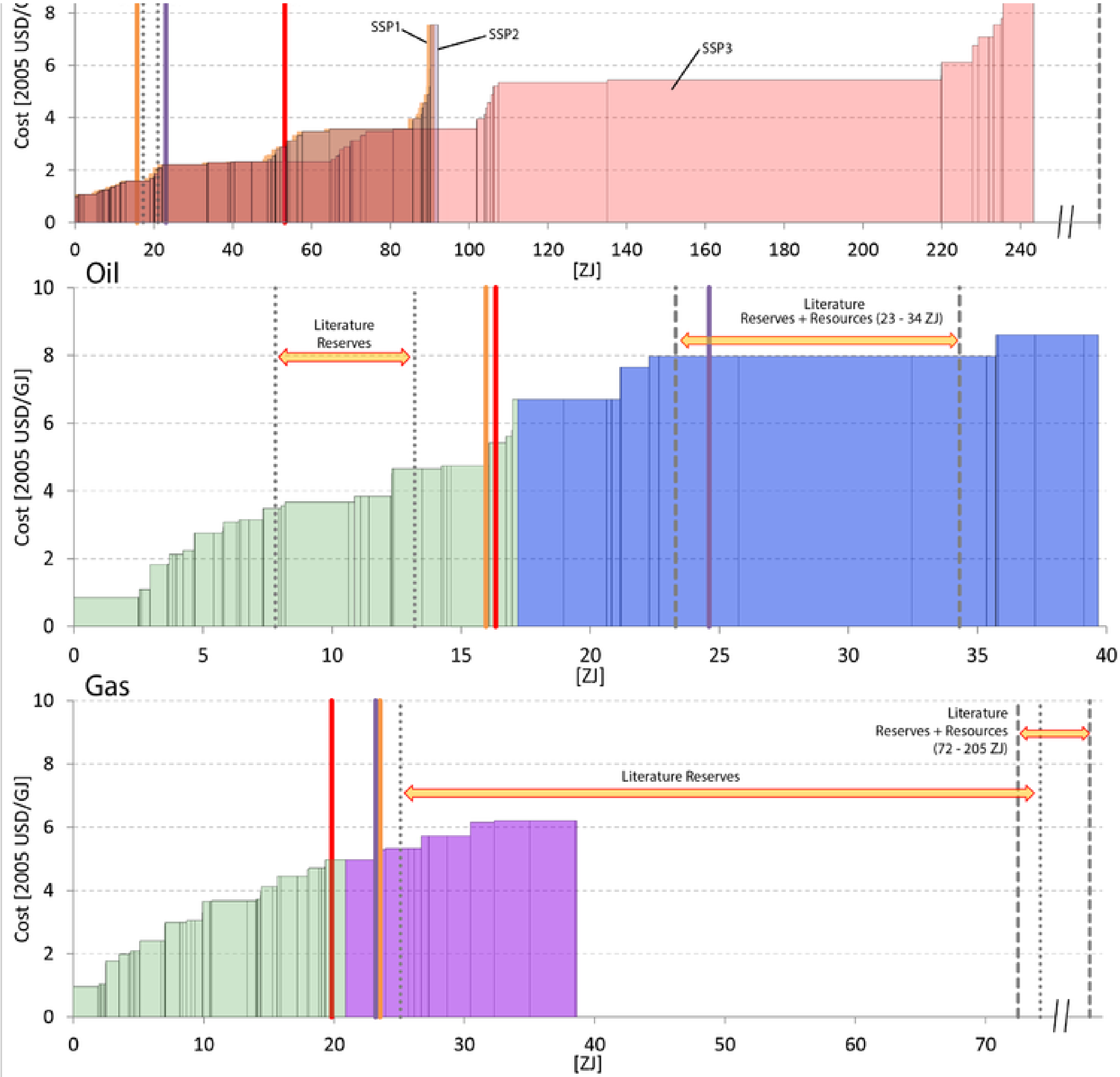


Figure 3: Cumulative global resource supply curves for coal (top), oil (middle), and gas (bottom) in the IIASA IAM framework

Conventional oil and gas are distributed unevenly throughout the world, with only a few regions dominating the reserves. Nearly half of the reserves of conventional oil is found in Middle East and North Africa, and close to 40% of conventional gas is found in Russia and the former Soviet Union states. The situation is somewhat different for unconventional oil of which North and Latin America potentially possess significantly higher global shares. Unconventional gas in turn is distributed quite well throughout the world, with North America holding most (roughly 25% of global resources). The distribution of coal reserves shows the highest geographical diversity which in the more fragmented SSP3 world contributes to increased overall reliance on this resource. Russia and the former Soviet Union states, Pacific OECD, North America, and Centrally Planned Asia and China all possess more than 10 ZJ of reserves.

4.1.2) Uranium and other fissile resources - MESSAGE-GLOBIOM

Nuclear Resources

Estimates of available uranium resources in the literature vary considerably, which could become relevant if advanced nuclear fuel cycles (e.g., the plutonium cycle including fast breeder reactors, the thorium cycle) are not available. In MESSAGE advanced nuclear cycles such as the plutonium cycle and nuclear fuel reprocessing are in principle represented, but their availability varies following the scenario narrative. Figure 4 below shows the levels of uranium resources assumed available in MESSAGE scenarios, building upon the Global Energy Assessment scenarios (see Riahi et al., 2012 [12]). These span a considerable range of the estimates in the literature, but at the same time none of them fall at the extreme ends of the spectrum (see Rogner et al., 2012 [13], Section 7.5.2 for a more detailed discussion of uranium resources). Nuclear resources and fuel cycle are modeled at the global level.

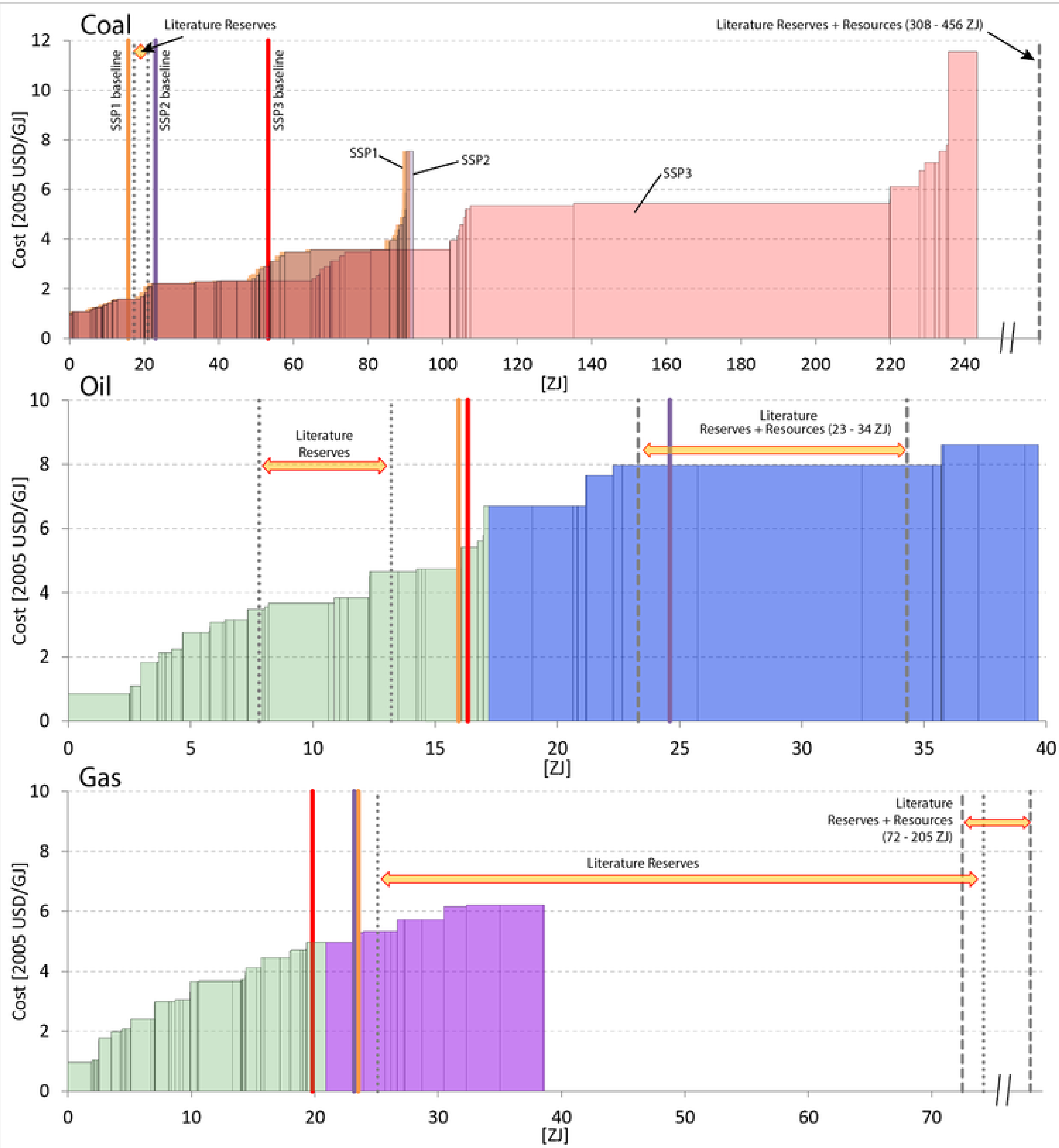
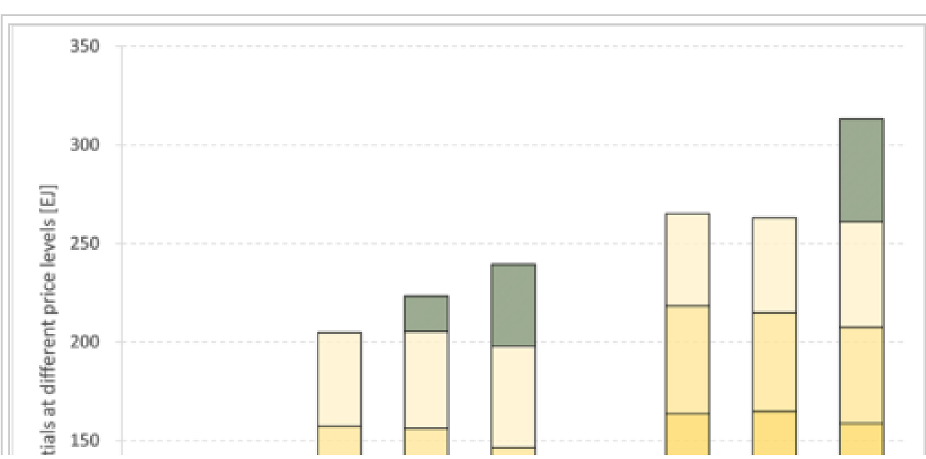


Figure 4: Global uranium resources in the MESSAGE interpretation of the SSPs compared to seven supply curves from a literature review

Figure 4 presents the global uranium resources in the MESSAGE interpretation of the SSPs compared to seven supply curves from a literature review (Schneider and Sailor, 2008 [14]). Conservative Crustal and Optimistic Crustal refer to simple crustal models of uranium distribution in the crust and the of extraction costs on the concentration. Pure-KCR refers to a fit of a simple crustal model to known conventional resources (KCR) as estimated by the Red Book 2003 (OECD/NEA 2004 [15]). PPM-Cost over the simple crustal models include a relationship between uranium grade and extraction costs. FCCCG(1) and (2) as well as DANESS refer to estimates from more complicated models of the dependency of extraction costs on uranium concentration (and therefore resource grade).

4.1.3) Bioenergy - MESSAGE-GLOBIOM

Biomass energy is another potentially important renewable energy resource in the MESSAGE-GLOBIOM model. This includes both commercial and non-commercial use. Commercial refers to the use of bioenergy in, for example, power plants or biofuel refineries, while non-commercial refers to the use of bioenergy for residential heating and cooking, primarily in rural households of today's developing countries. Bioenergy potentials differ across SSPs as a result of different levels of competition over land for food and fibre, but ultimately only vary to a limited degree (Figure 5). The drivers underlying this competition are different land-use developments in the SSPs, which are determined by agricultural productivity and global demand for food consumption. (Fricko et al., 2016 [1])



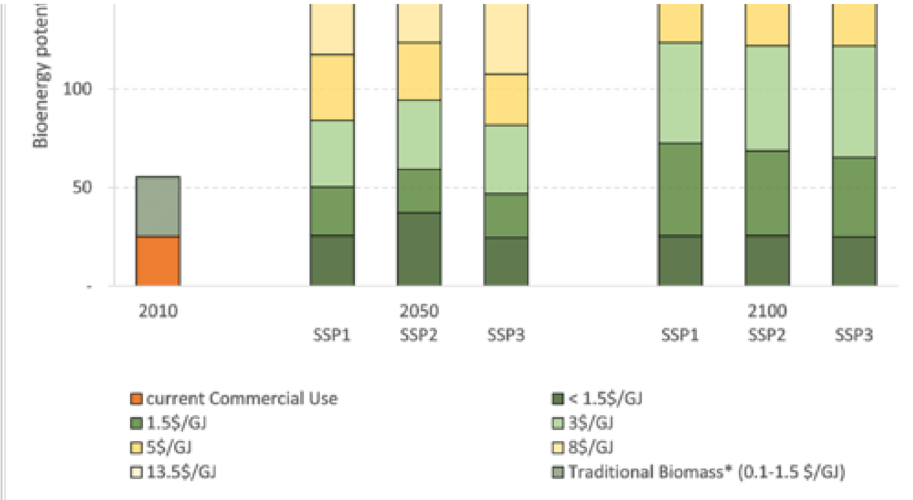


Figure 5: Global bioenergy potential

Availability of bioenergy is presented in Figure 5 at different price levels in the MESSAGE-GLOBIOM model for the three SSPs (Fricko et al., 2016 [1]). Typically non-commercial biomass is not traded or sold, however in some cases there is a market – prices range from 0.1-1.5$/GJ (Pachauri et al., 2013 [16]) ($ equals 2005 USD).

4.1.4) Non-biomass renewables - MESSAGE-GLOBIOM

Table 4 shows the assumed total potentials of non-biomass renewable energy deployment (by resource type) in the MESSAGE model. In addition, the assumptions are compared with technical potential estimates from the Global Energy Assessment (Rogner et al., 2012 [13]). In this context, it is important to note that typical MESSAGE scenarios do not consider the full technical potential of renewable energy resources, but rather only a subset of those potentials, owing to additional constraints (e.g., sustainability criteria, technology diffusion and systems integration issues, and other economic considerations) that may not be fully captured within the model. These constraints may lead to a significant reduction of the technical potential.

Table 4: Assumed global non-biomass renewable energy deployment potentials in the MESSAGE-GLOBIOM model. Estimates from the Global Energy Assessment (Rogner et al., 2012 [1]) also added for comparison

Source	MESSAGE	Rogner et al., 2012 [1]
	Deployment Potential [EJ/yr]	Technical Potential [EJ/yr]
Hydro	38	50 - 60
Wind (on-/offshore)	689/287	1250 - 2250
Solar PV	6064	62,000 - 280,000
CSP	2132	same as Solar PV above
Geothermal	23	810 - 1400

Notes: MESSAGE-GLOBIOM renewable energy potentials are based on Pietzcker et al. (2014) [17], Eurek et al. (in review) [18], Christiansson (1995) [19], and Rogner et al (2012) [13]. The potentials for non-combustible renewable energy sources are specified in terms of the electricity or heat that can be produced by specific technologies (i.e., from a secondary energy perspective). By contrast, the technical potentials from Rogner et al (2012) [13] refer to the flows of energy that could become available as inputs for technology conversion. So for example, the technical potential for wind is given as the kinetic energy available for wind power generation, whereas the deployment potential would only be the electricity that could be generated by the wind turbines.

Regional resource potentials for solar and wind are classified according to resource quality (annual capacity factor) based on Pietzcker et al. (2014 [17]) and Eurek et al. (in review [18]). Regional resource potentials as implemented into MESSAGE-GLOBIOM are provided by region and capacity factor for solar PV, concentrating solar power (CSP), and onshore/offshore wind in Johnson et al. (in review [20]). The physical potential of these sources is assumed to be the same across all SSPs. Table 5, Table 6, Table 7, Table 9 show the resource potential for solar PV, CSP, on- and offshore wind respectively. For wind, Table 8 and Table 10 list the capacity factors corresponding to the wind classes used in the resource tables. It is important to note that part of the resource that is useable at economically competitive costs is assumed to differ widely (see Section Energy Conversion of MESSAGE-GLOBIOM).

Table 5: Resource potential (EJ) by region and capacity factor for solar photovoltaic (PV) technology (Johnson et al. in review [1]). For a description of each of the regions represented in the table, see Spatial dimension of MESSAGE-GLOBIOM

	Capacity Factor (fraction per year)							
	0.28	0.21	0.20	0.19	0.18	0.17	0.15	0.14
AFR	0.0	1.1	46.5	176.6	233.4	218.2	169.9	61.9
CPA	0.0	0.0	0.0	10.3	194.3	315.5	159.4	41.9
EEU	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.0
FSU	0.0	0.0	0.0	0.2	2.8	23.6	94.9	116.6
LAM	0.1	4.9	49.4	165.6	157.5	167.4	81.4	48.5
MEA	0.2	3.1	100.8	533.6	621.8	310.1	75.3	14.5
NAM	0.0	0.3	24.3	140.4	131.0	116.3	155.7	106.4
PAO	0.0	0.0	0.1	2.2	53.1	226.4	311.2	158.9
PAS	0.0	0.0	0.0	0.2	0.8	17.0	31.2	12.8
SAS	0.0	0.0	6.1	42.7	67.2	82.3	23.7	4.1
WEU	0.0	0.1	0.2	3.0	12.8	39.4	58.3	33.3
Global	0.3	9.6	227.4	1074.7	1474.6	1516.3	1160.9	600.0

Table 6: Resource potential (EJ) by region and capacity factor for concentrating solar power (CSP) technologies with solar multiples (SM) of 1 and 3 (Johnson et al. in review [1])

	Capacity Factor (fraction of year)							
SM1	0.27	0.25	0.23	0.22	0.20	0.18	0.17	0.15
SM3	0.75	0.68	0.64	0.59	0.55	0.50	0.46	0.41
AFR	0.0	3.6	19.0	81.6	106.7	62.8	59.6	37.8
CPA	0.0	0.0	0.0	0.0	0.0	0.3	11.5	53.0
EEU	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FSU	0.0	0.0	0.0	0.0	0.0	0.1	0.4	6.1
LAM	0.0	2.0	7.0	11.8	29.3	57.1	56.8	53.5
MEA	0.1	3.7	24.8	122.4	155.3	144.5	68.4	34.0
NAM	0.0	0.0	0.0	6.3	19.7	20.2	29.6	43.2
PAO	0.0	3.0	75.1	326.9	158.3	140.4	40.2	10.2
PAS	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.6
SAS	0.0	0.0	0.0	0.1	3.9	8.7	16.1	9.8
WEU	0.0	0.0	0.0	0.0	0.2	0.7	2.4	3.0
Global	0.1	12.3	126.0	549.2	473.3	434.8	285.0	251.3

Table 7: Resource potential (EJ) by region and wind class for onshore wind (Johnson et al. in review [1])

	Wind Class					
	3	4	5	6	7	8+
AFR	38.2	21.3	13.4	6.8	2.6	2.1
CPA	24.7	11.4	5.4	2.6	0.3	0.0
EEU	6.1	5.7	0.3	0.0	0.0	0.0
FSU	52.3	83.8	5.8	0.8	0.0	0.0
LAM	33.5	15.9	9.6	5.7	3.9	3.7
MEA	56.1	22.2	6.0	2.1	0.9	0.3
NAM	28.6	66.4	23.7	1.5	0.4	0.0
PAO	18.9	18.8	3.6	1.4	1.8	0.5
PAS	5.2	2.9	0.8	0.2	0.0	0.0
SAS	12.3	7.9	2.4	1.6	0.9	0.3
WEU	16.1	10.5	6.6	8.2	3.7	0.6
World	292.1	266.8	77.5	30.9	14.3	7.5

Table 8: Capacity factor by region and wind class for onshore wind (Johnson et al. in review [1])

	Wind Class					
	3	4	5	6	7	8+
AFR	0.24	0.28	0.32	0.36	0.40	0.45
CPA	0.24	0.28	0.32	0.36	0.38	0.45
EEU	0.24	0.27	0.31	0.36	0.38	0.45
FSU	0.24	0.28	0.31	0.35	0.38	0.45
LAM	0.24	0.28	0.32	0.36	0.39	0.46
MEA	0.24	0.27	0.32	0.35	0.39	0.45
NAM	0.24	0.28	0.31	0.36	0.39	0.45
PAO	0.24	0.28	0.32	0.36	0.40	0.43
PAS	0.24	0.27	0.32	0.35	0.40	0.45
SAS	0.24	0.27	0.32	0.36	0.39	0.42
WEU	0.24	0.28	0.32	0.36	0.39	0.43

Table 9: Resource potential (EJ) by region and wind class for offshore wind (Johnson et al. in review [1])

	Wind Class					
	3	4	5	6	7	8+
AFR	3.1	2.4	2.0	2.0	1.1	1.7
CPA	3.5	4.3	2.6	0.9	1.3	0.1
EEU	0.7	0.6	1.0	0.0	0.0	0.0
FSU	1.8	4.6	14.2	13.3	4.3	0.7
LAM	7.1	7.3	5.3	2.7	2.6	5.9
MEA	3.2	0.9	0.8	0.9	0.6	0.9
NAM	4.5	18.2	24.0	16.0	7.3	2.1
PAO	5.8	11.2	15.3	9.8	2.6	2.5
PAS	5.3	6.6	4.7	1.5	0.1	0.0
SAS	1.9	0.9	0.6	0.5	0.0	0.0
WEU	3.5	4.7	8.8	12.9	10.3	0.9
World	40.4	61.5	79.4	60.5	30.3	14.8

Table 10: Capacity factor by region and wind class for offshore wind (Johnson et al. in review [1])

	Wind Class					
	3	4	5	6	7	8+
AFR	0.24	0.28	0.32	0.36	0.41	0.47
CPA	0.24	0.28	0.32	0.36	0.40	0.42
EEU	0.24	0.29	0.32	0.34	0.40	0.42
FSU	0.25	0.28	0.32	0.35	0.39	0.43
LAM	0.24	0.28	0.32	0.36	0.40	0.49
MEA	0.24	0.28	0.32	0.36	0.40	0.45
NAM	0.25	0.28	0.32	0.36	0.40	0.43
PAO	0.24	0.28	0.32	0.36	0.40	0.47
PAS	0.24	0.28	0.32	0.35	0.39	0.42
SAS	0.24	0.27	0.32	0.36	0.40	0.42
WEU	0.24	0.28	0.32	0.36	0.40	0.42

4.2) Energy conversion - MESSAGE-GLOBIOM

Energy technologies are characterized by numerical model inputs describing their economic (e.g., investment costs, fixed and variable operation and maintenance costs), technical (e.g., conversion efficiencies), ecological (e.g., GHG and pollutant emissions), and sociopolitical characteristics. An example for the sociopolitical situation in a world region would be the decision by a country or world region to ban certain types of power plants (e.g., nuclear plants). Model input data reflecting this situation would be upper bounds of zero for these technologies or, equivalently, their omission from the data set for this region altogether.

Each energy conversion technology is characterized in MESSAGE by the following data:

- Energy inputs and outputs together with the respective conversion efficiencies. Most energy conversion technologies have one energy input and one output and thereby one associated efficiency. But technologies may also use different fuels (either jointly or alternatively), may have different operation modes and different outputs, which also may have varying shares. An example of different operation modes would be a passout turbine, which can generate electricity and heat at the same time when operated in co-generation mode or which can produce electricity only. For each technology, one output and one input are defined as main output and main input respectively. The activity variables of technologies are given in the units of the main input consumed by the technology or, if there is no explicit input (as for solar-energy conversion technologies), in units of the main output.
- Specific investment costs (e. g., per kilowatt, kW) and time of construction as well as distribution of capital costs over construction time.
- Fixed operating and maintenance costs (per unit of capacity, e.g., per kW).
- Variable operating costs (per unit of output, e.g. per kilowatt-hour, kWh, excluding fuel costs).
- Plant availability or maximum utilization time per year. This parameter also reflects maintenance periods and other technological limitations that prevent the continuous operation of the technology.
- Technical lifetime of the conversion technology in years.
- Year of first commercial availability and last year of commercial availability of the technology.
- Consumption or production of certain materials (e.g. emissions of kg of CO_2 or SO_2 per produced kWh).
- Limitations on the (annual) activity and on the installed capacity of a technology.
- Constraints on the rate of growth or decrease of the annually new installed capacity and on the growth or decrease of the activity of a technology.
- Technical application constraints, e.g., maximum possible shares of wind or solar power in an electricity network without storage capabilities.
- Inventory upon startup and shutdown, e.g., initial nuclear core needed at the startup of a nuclear power plant.
- Lag time between input and output of the technology.

- Minimum unit size, e.g. for nuclear power plants it does not make sense to build plants with a capacity of a few kilowatt power (optional, not used in current model version).
- Sociopolitical constraints, e.g., ban of nuclear power plants, or inconvenience costs of household cook stoves.
- Inconvenience costs which are specified only for end-use technologies (e.g. cook stoves)

The specific technologies represented in various parts of the energy conversion sector are discussed in the following sections on Electricity, Heat, Other conversion, and Grid, Infrastructure and System Reliability below.

4.2.1) Electricity - MESSAGE-GLOBIOM

MESSAGE covers a large number of electricity generation options utilizing a wide range of primary energy sources. For fossil-based electricity generation technologies, typically a number of different technologies with different efficiencies, environmental characteristics and costs is represented. For example, in the case of coal, MESSAGE distinguishes subcritical and supercritical pulverized coal (PC) power plants where the subcritical variant is available with and without flue gas desulpherization/denox and one internal gasification combined cycle (IGCC) power plant. The superciritical PC and IGCC plants are also available with carbon capture and storage (CCS) which also can be retrofitted to some of the existing PC power plants. Table 11 below shows the different power plant types represented in MESSAGE.

Four different nuclear power plant types are represented in MESSAGE-GLOBIOM, i.e. two light water reactor types, a fast breeder reactor and a high temperature reactor, but only the two light water types are included in the majority of scenarios being developed with MESSAGE in the recent past. In addition, MESSAGE includes a representation of the nuclear fuel cycle, including reprocessing and the plutonium fuel cycle, and keeps track of the amounts of nuclear waste being produced.

The conversion of five renewable energy sources to electricity is represented in MESSAGE-GLOBIOM (see Table 11). For wind power, both on- and offshore electricity generation are covered and for solar energy, photovoltaics (PV) and solar thermal (concentrating solar power, CSP) electricity generation are included in MESSAGE (see also sections on Non-biomass renewables of MESSAGE-GLOBIOM and Grid, pipelines and other infrastructure of MESSAGE-GLOBIOM).

Most thermal power plants offer the option of coupled heat production (CHP, see Table 11). This option is modeled as a passout turbine via a penalty on the electricity generation efficiency. In addition to the main electricity generation technologies described in this section, also the co-generation of electricity in conversion technologies primarily devoted to producing non-electric energy carriers (e.g., synthetic liquid fuels) is included in MESSAGE (see sections on Liquid fuels of MESSAGE-GLOBIOM and Gaesous fuels of MESSAGE-GLOBIOM).

Table 11: List of electricity generation technologies represented in MESSAGE-GLOBIOM by energy source

Energy source	Technology	CHP option
Coal	subcritical PC power plant without desulphurization/denox	yes
	subcritical PC power plant with desulphurization/denox	yes
	supercritical PC power plant with desulphurization/denox	yes
	supercritical PC power plant with desulphurization/denox and CCS	yes
	IGCC power plant	yes
	IGCC power plant with CCS	yes
Oil	heavy fuel oil steam power plant	yes
	light fuel oil steam power plant	yes
	light fuel oil combined cycle power plant	yes
Gas	gas steam power plant	yes
	gas combustion turbine gas	yes
	combined cycle power plant	yes
Nuclear	nuclear light water reactor (Gen II)	yes
	nuclear light water reactor (Gen III+)	yes
	fast breeder reactor	
	high temperature reactor	
Biomass	biomass steam power plant	yes
	biomass IGCC power plant	yes
	biomass IGCC power plant with CCS	yes
Hydro	hydro power plant (2 cost categories)	no
Wind	onshore wind turbine	no
	offshore wind turbine	no
Solar	solar photovoltaics (PV)	no
	concentrating solar power (CSP)	
Geothermal	geothermal power plant	yes

Technological change in MESSAGE is generally treated exogenously, although pioneering work on the endogenization of technological change in energy-engineering type models has been done with MESSAGE (Messner, 1997 [21]). The current cost and performance parameters, including conversion efficiencies and emission coefficients is generally derived from the relevant engineering literature. For the future alternative cost and performance projections are usually developed to cover a relatively wide range of uncertainties that influences model results to a good extent. As an example, Figure 6 and Figure 7 below provide an overview of costs ranges for a set of key energy conversion technologies (Fricko et al., 2016 [1]).

[1]

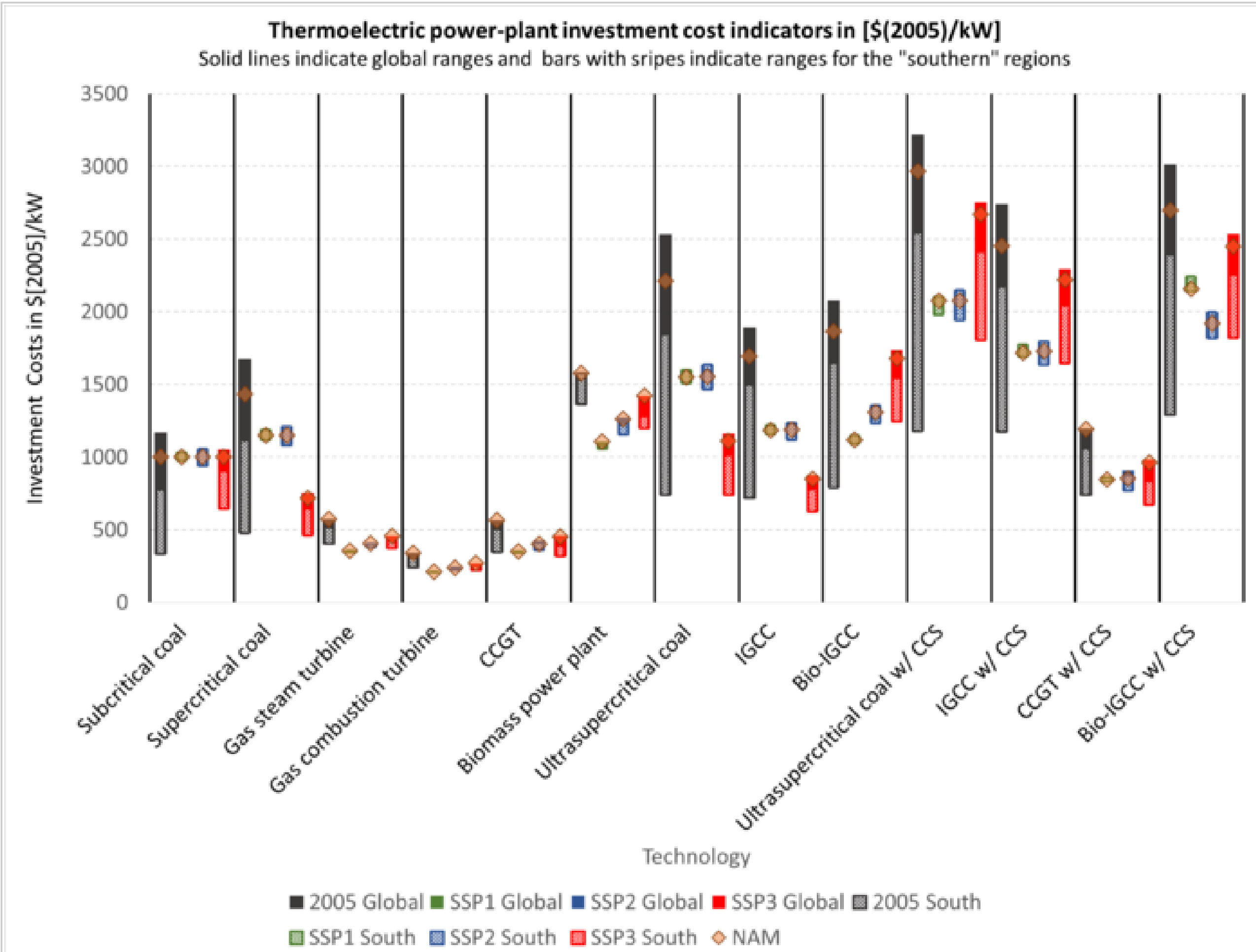


Figure 6: Cost indicators for thermoelectric power-plant investment (Fricko et al., 2016)

In Figure 6, the black ranges show historical cost ranges for 2005. Green, blue, and red ranges show cost ranges in 2100 for SSP1, SSP2, and SSP3, respectively (see descriptions of the SSP narratives in section ***ADD LINKS ONCE SSP INFO HAS BEEN ADDED***). Global values are represented by solid ranges. Values in the global South are represented by dashed ranges. The diamonds show the costs in the "North America" region. CCS – Carbon Capture and Storage; IGCC – Integrated gasification combined cycles; ST – Steam turbine; CT – Combustion turbine; CCGT – Combined cycle gas turbine (Fricko et al., 2016 [1]).

[1]

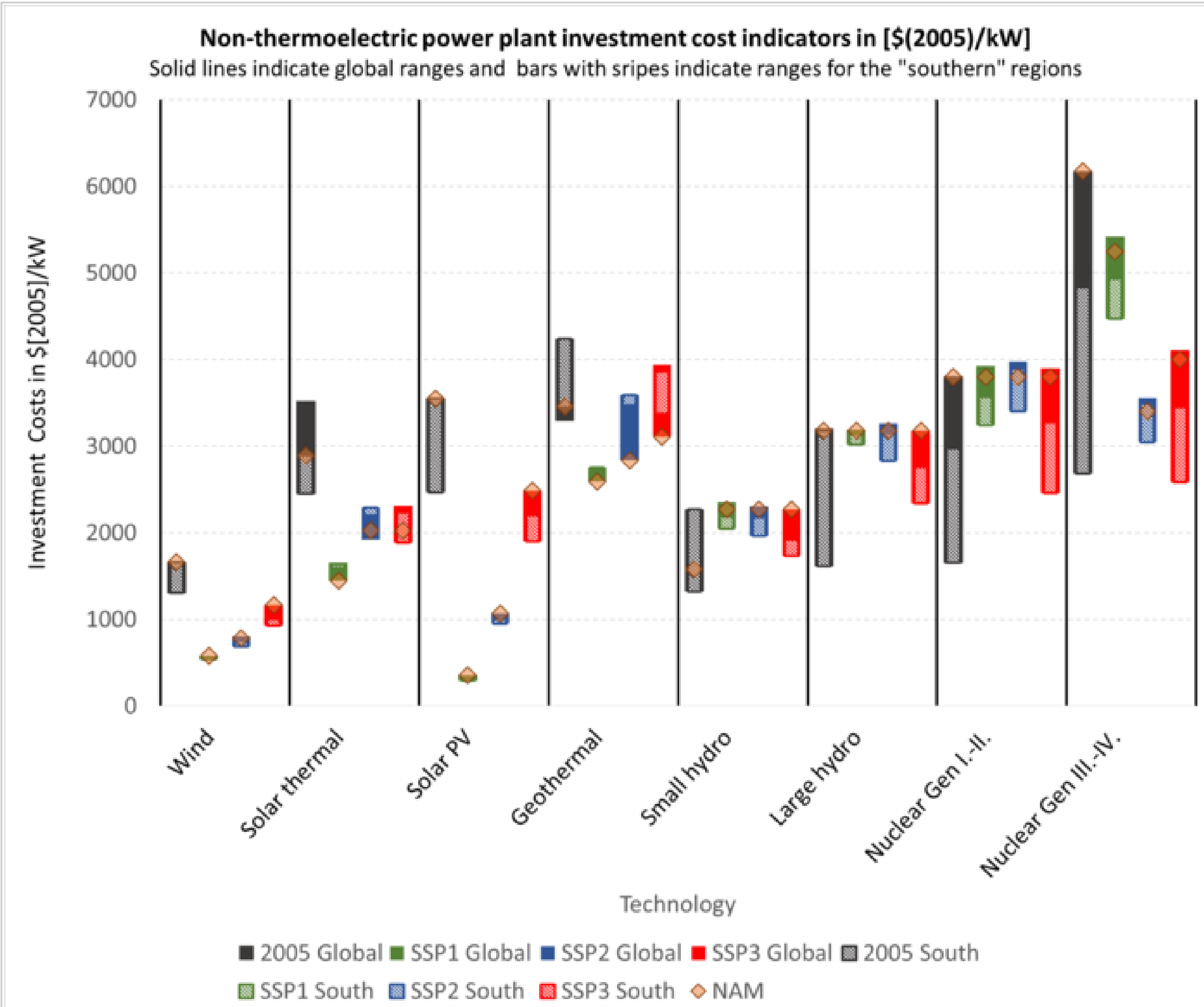


Figure 7: Cost indicators for non-thermoelectric power-plant investment (Fricko et al., 2016)

In Figure 7, the black ranges show historical cost ranges for 2005. Green, blue, and red ranges show cost ranges in 2100 for SSP1, SSP2, and SSP3, respectively. Global values are represented by solid ranges. Values in the global South are represented by dashed ranges. The diamonds show the costs in the “North America” region. PV – Photovoltaic (Fricko et al., 2016 [1]).

4.2.2) Heat - MESSAGE-GLOBIOM

A number centralized district heating technologies based on fossil and renewable energy sources are represented in MESSAGE (see Table 12). Similar to coupled heat and power (CHP) technologies that are described in the Electricity section of MESSAGE-GLOBIOM, these heating plants feed low temperature heat into the district heating system that is then used in the end-use sectors. In addition, there are (decentralized) heat generation options in Industrial sector of MESSAGE-GLOBIOM and Residential and commercial sectors of MESSAGE-GLOBIOM.

Table 12: List of centralized heat generation technologies represented in MESSAGE by energy source

Energy Source	Technology
coal	coal district heating plant
oil	light fuel oil district heating plant
gas	gas district heating plant
biomass	solid biomass district heating plant
geothermal	geothermal district heating plant

4.2.3) Gaseous fuels - MESSAGE-GLOBIOM

See Table 13 for a list of gaseous fuel production technologies in MESSAGE.

Table 13: Gaseous fuel production technologies in MESSAGE by energy source

Energy Source	Technology
Biomass	biomass gasification
	biomass gasification with CCS
Coal	coal
	coal gasification with CCS

Hydrogen Production

See Table 14 for a list of hydrogen production technologies in MESSAGE.

Table 14: Hydrogen production technologies in MESSAGE by energy source

Energy source	Technology	Electricity cogeneration
Gas	steam methane reforming	yes
	steam methane reforming with CCS	no
Electricity	electrolysis	no
Coal	coal gasification	yes
	coal gasification with CCS	yes
Biomass	biomass gasification	yes
	biomass gasification with CCS	yes

As already mentioned in the section for :ref:`electricity`, technological change in MESSAGE is generally treated exogenously, although pioneering work on the endogenization of technological change in energy-engineering type models has been done with MESSAGE (Messner, 1997 [21]). The current cost and performance parameters, including conversion efficiencies and emission coefficients is generally derived from the relevant engineering literature. For the future alternative cost and performance projections are usually developed to cover a relatively wide range of uncertainties that influences model results to a good extent. As an example, Figure 8 below provides an overview of costs ranges for a set of key energy conversion technologies (Fricko et al., 2016 [1]).

[1]

In Figure 8, the black ranges show historical cost ranges for 2005. Green, blue, and red ranges show cost ranges in 2100 for SSP1, SSP2, and SSP3, respectively. Global values are represented by solid ranges. Values in the global South are represented by dashed ranges. The diamonds show the costs in the “North America” region. CCS – Carbon capture and storage; CTL –

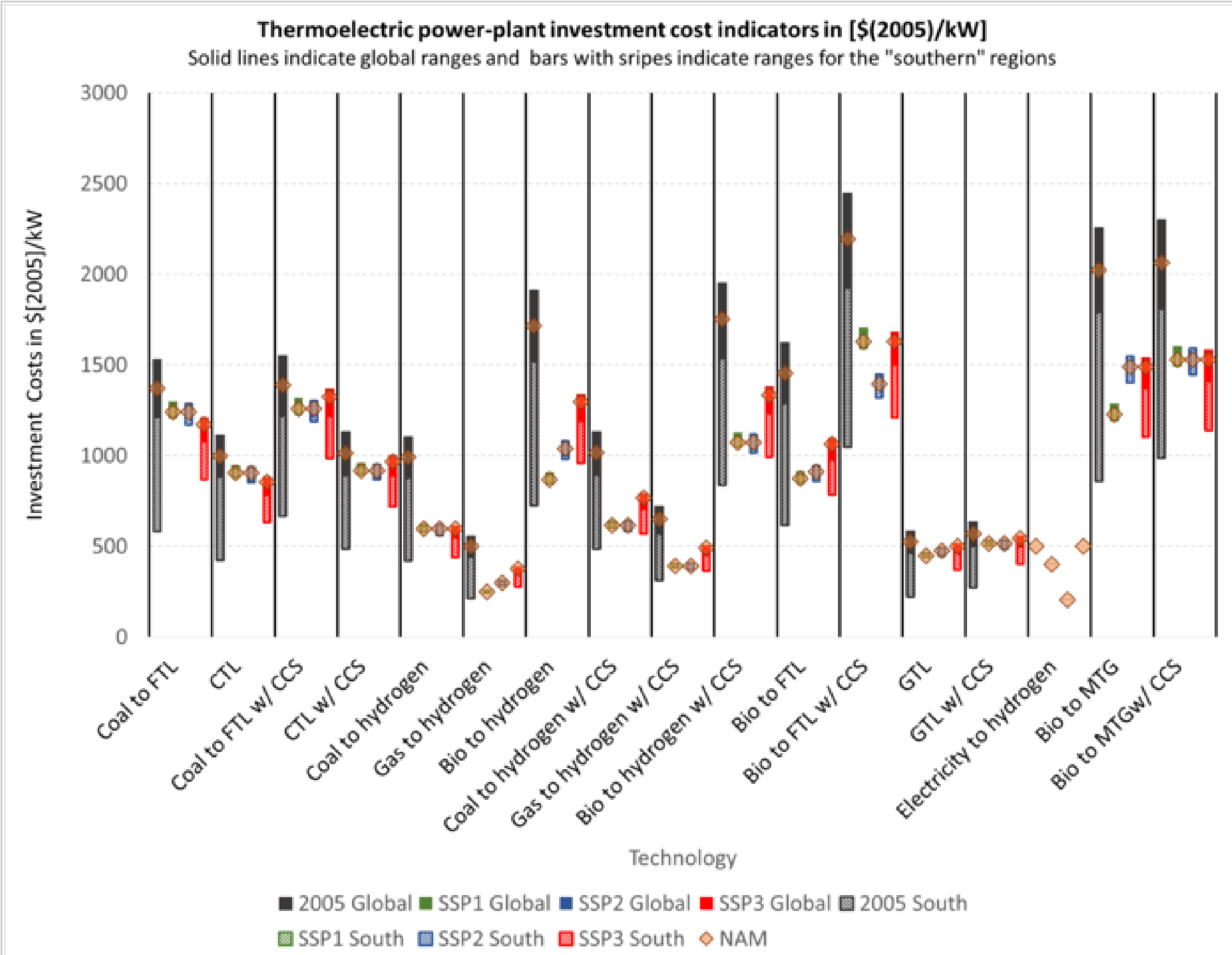


Figure 8: Cost indicators for other conversion technology investment (Fricko et al., 2016)

Coal to liquids; GTL – Gas to liquids; BTL – Biomass to liquids (Fricko et al., 2016 [1]).

4.2.4)

Liquid fuels - MESSAGE-GLOBIOM

Apart from oil refining as predominant supply technology for liquid fuels at present a number of alternative liquid fuel production routes from different feedstocks are represented in MESSAGE (see Table 15). Different processes for coal liquefaction, gas-to-liquids technologiesand biomass-to-liquids technologies both with and without CCS are covered. Some of these technologies include co-generation of electricity, for example, by burning unconverted syngas from a Fischer-Tropsch synthesis in a gas turbine (c.f. Larson et al., 2012 [22]). Technology costs for the synthetic liquid fuel production options are based on Larson et al. (2012) ([22]).

Table 15: Liquid fuel production technologies in MESSAGE by energy source

Energy Source	Technology	Electricity cogeneration
Biomass	Fischer-Tropsch biomass-to-liquids	yes
	Fischer-Tropsch biomass-to-liquids with CCS	yes
Coal	Fischer-Tropsch coal-to-liquids	yes
	Fischer-Tropsch coal-to-liquids with CCS	yes
	coal methanol-to-gasoline	yes
	coal methanol-to-gasoline with CCS	yes
Gas	Fischer-Tropsch gas-to-liquids	no
	Fischer-Tropsch gas-to-liquids with CCS	no
Oil	simple refinery	no
	complex refinery	no

4.2.6) Grid, pipelines and other infrastructure - MESSAGE-GLOBIOM

Energy transport and distribution infrastructure is included in MESSAGE at a level relevant to represent the associated costs. Within regions the capital stock of transmission and distribution infrastructure and its turnover is modeled for the following set of energy carriers:

- electricity
- district heat
- natural gas
- hydrogen

For all solid (coal, biomass) and liquid energy carriers (oil products, biofuels, fossil synfuels) a simpler approach is taken and only transmission and distribution losses and costs are taken into account.

Inter-regional energy transmission infrastructure, such as natural gas pipelines and high voltage electricity grids, are also represented between geographically adjacent regions. Solid and liquid fuel trade is, similar to the transmission and distribution within regions, modeled by taking into account distribution losses and costs. A special case are gases that can be traded in liquified form, i.e. liquified natural gas (LNG) and liquid hydrogen, where liquefaction and re-gasification infrastructure is represented in addition to the actual transport process.

Systems Integration and Reliability

The MESSAGE framework includes a single annual time period characterized by average annual load and 11 geographic regions that span the globe. Seasonal and diurnal load curves and spatial issues such as transmission constraints or renewable resource heterogeneity are treated in a stylized way in the model. The reliability extension described below elevates the stylization of temporal resolution by introducing two concepts, peak reserve capacity and general-timescale flexibility, to the model (Sullivan et al., 2013 [23]). To represent capacity reserves in MESSAGE, a requirement is defined that each region build sufficient firm generating capacity to maintain reliability through reasonable load and contingency events. As a proxy for complex system reliability metrics, a reserve margin-based metric was used, setting the capacity requirement at a multiple of average load, based on electric-system parameters. While many of the same issues apply to both electricity from wind and solar energy, the description below focuses on wind.

Toward meeting the firm capacity requirement, conventional generating technologies contribute their nameplate generation capacity while variable renewables contribute a capacity value that declines as the market share of the technology increases. This reflects the fact that wind and solar generators do not always generate when needed, and that their output is generally self-correlated. In order to adjust wind capacity values for different levels of penetration, it was necessary to introduce a stepwise-linear supply curve for wind power (shown in the Figure 9 below). Each bin covers a range of wind penetration levels as fraction of load and has discrete coefficients for the two constraints. The bins are predefined, and therefore are not able to allow, for example, resource diversification to increase capacity value at a given level of wind penetration.

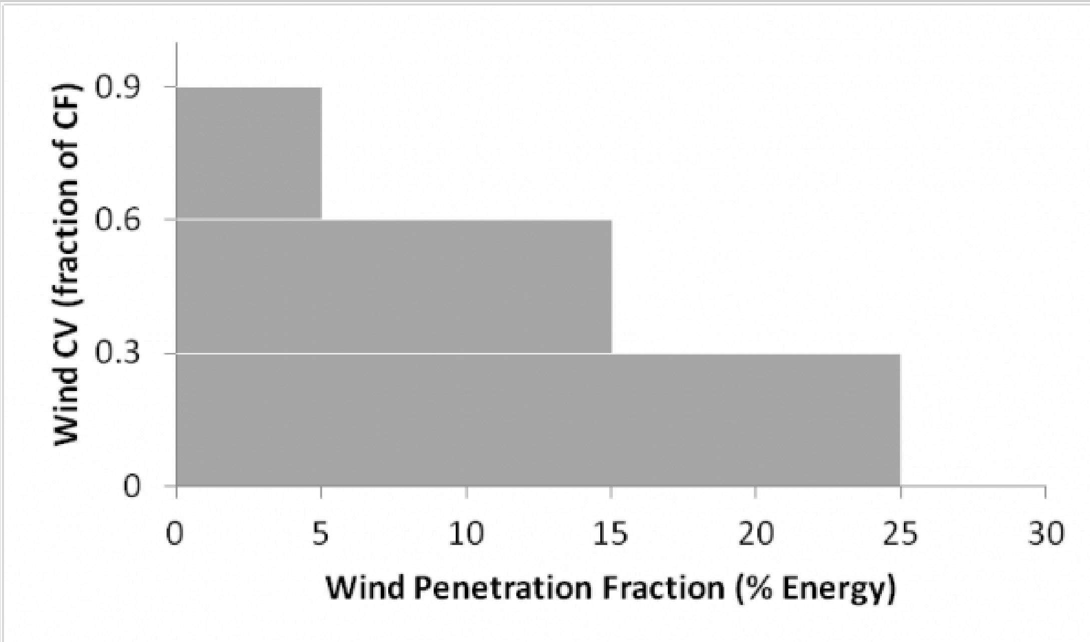


Figure 9: Parameterization of Wind Capacity Value

The capacity value bins are independent of the wind supply curve bins that already existed in MESSAGE, which are based on quality of the wind resource. That supply curve is defined by absolute wind capacity built, not fraction of load; and the bins differ based on their annual average capacity factor, not capacity value. Solar PV is treated in a similar way as wind with the parameters obviously being different ones. In contrast, concentrating solar power (CSP) is modeled very much like dispatchable power plants in MESSAGE, because it is assumed to come with several hours of thermal storage, making it almost capable of running in baseload mode.

In order to ensure adequate reserve dispatch, dynamic shadow prices are placed on capacity investments of intermittent technologies (e.g., wind and solar). The prices are a function of the cumulative installed capacity of the intermittent technologies, the ability for the convential power supply to act as reserve dispatch, and the demand-side reliability requirements. For instance, a large amount of storage capacity should, all else being equal, lower the shadow price for additional wind. Conversely, an inflexible, coal- or nuclear-heavy generating base should increase the cost of investment in wind by demanding additional expenditures in the form of natural gas or storage or improved demand-side management to maintain system reliability.

Starting from the energy metric used in MESSAGE (electricity is considered as annual average load; there are no time-slices or load-curves), the flexibility requirement uses MWh of generation as its unit of note. The metric is inherently limited because operating reserves are often characterized by energy not-generated: a natural gas combustion turbine (gas-CT) that is standing by, ready to start-up at a moment's notice; a combined-cycle plant operating below its peak output to enable ramping in the event of a surge in demand. Nevertheless, because there is generally a portion of generation associated with providing operating reserves (e.g. that on-call gas-CT plant will be called some fraction of the time), it is posited that using generated energy to gauge flexibility is a reasonable metric considering the simplifications that need to be made. Furthermore, ancillary services associated with ramping and peaking often do involve real energy generation, and variable renewable technologies generally increase the need for ramping.

Electric-sector flexibility in MESSAGE is represented as follows: each generating technology is assigned a coefficient between -1 and 1 representing (if positive) the fraction of generation from that technology that is considered to be flexible or (if negative) the additional flexible generation required for each unit of generation from that technology. Load also has a parameter (a negative one) representing the amount of flexible energy the system requires solely to meet changes and uncertainty in load. Table 16 below displays the parameters that were estimated using a unit-commitment model that commits and dispatches a fixed generation system at hourly resolution to meet load an ancilliary service requirements while hewing to generator and transmission operation limitations (Sullivan et al., 2013 [23]). Technologies that were not included in the unit-commitment model (nuclear, H2 electrolysis, solar PV) have estimated coefficients.

Table 16: Flexibility Coefficients by Technology (Sullivan et al., 2013 [1])

Technology	Flexibility Parameter
Load	-0.1
Wind	-0.08
Solar PV	-0.05
Geothermal	0
Nuclear	0
Coal	0.15
Biopower	0.3
Gas-CC	0.5
Hydropower	0.5
H2 Electrolysis	0.5
Oil/Gas Steam	1
Gas-CT	1
Electricity Storage	1

Thus, a technology like a simple-cycle natural gas plant, used almost exclusively for ancillary services, has a flexibility coefficient of 1, while a coal plant, which provides mostly bulk power but can supply some ancillary services, has a small, positive coefficient. Electric storage systems (e.g. pumped hydropower, compressed air storage, flow batteries) and flexible demand-side technologies like hydrogen-production contribute as well. Meanwhile, wind power and solar PV, which require additional system flexibility to smooth out fluctuations,

have negative flexibility coefficients.

4.3) Energy end-use - MESSAGE-GLOBIOM

4.3.1) Transport - MESSAGE-GLOBIOM

The most commonly applied MESSAGE transport sector representation is very stylized and essentially includes fuel switching and price-elastic demands (via MACRO linkage) as the main responses to energy and climate policy (see Figure 10).

In this stylized transport sector representation fuel switching is a main option, i.e. different final energy forms that provide energy for transportation can be chosen from. In addition to the alternative energy carriers that serve as input to these stylized transportation options, their relative efficiencies are also different. The useful energy demand in the transportation sector is specified as internal combustion engine (ICE) equivalent demands which therefore by definition has a conversion efficiency of final to useful energy of 1. Relative to that the conversion efficiency of alternative fuels is higher, for example, electricity in 2010 has about a factor of three higher final to useful efficiency than the regular oil-product based ICE. The overall efficiency improvements of the ICE in the transportation sector and modal switching over time is implicitly included in the demand specifications, coming from the scenario generator (see section on Energy demand of MESSAGE-GLOBIOM). Additional demand reduction in response to price increases in policy scenarios then occurs via the fuel switching option (due to the fuel-specific relative efficiencies) as well as via the linkage with the macro-economic model MACRO as illustrated in Figure 10 below.

Limitations of switching to alternative fuels may occur for example as a result of restricted infrastructure availability (e.g., rail network) or some energy carriers being unsuitable for certain transport modes (e.g., electrification of aviation). To reflect these limitations, share constraints of energy carriers (e.g., electricity) and energy carrier groups (e.g., liquid fuels) are used in the transport sector. In addition, the diffusion of speed of alternative fuels is limited to mimic bottlenecks in the supply chains, not explicitly represented in MESSAGE (e.g., non-energy related infrastructure). Both the share as well as the diffusion constraints are usually parametrized based on transport sector studies that analyze such developments and their feasibility in much greater detail.

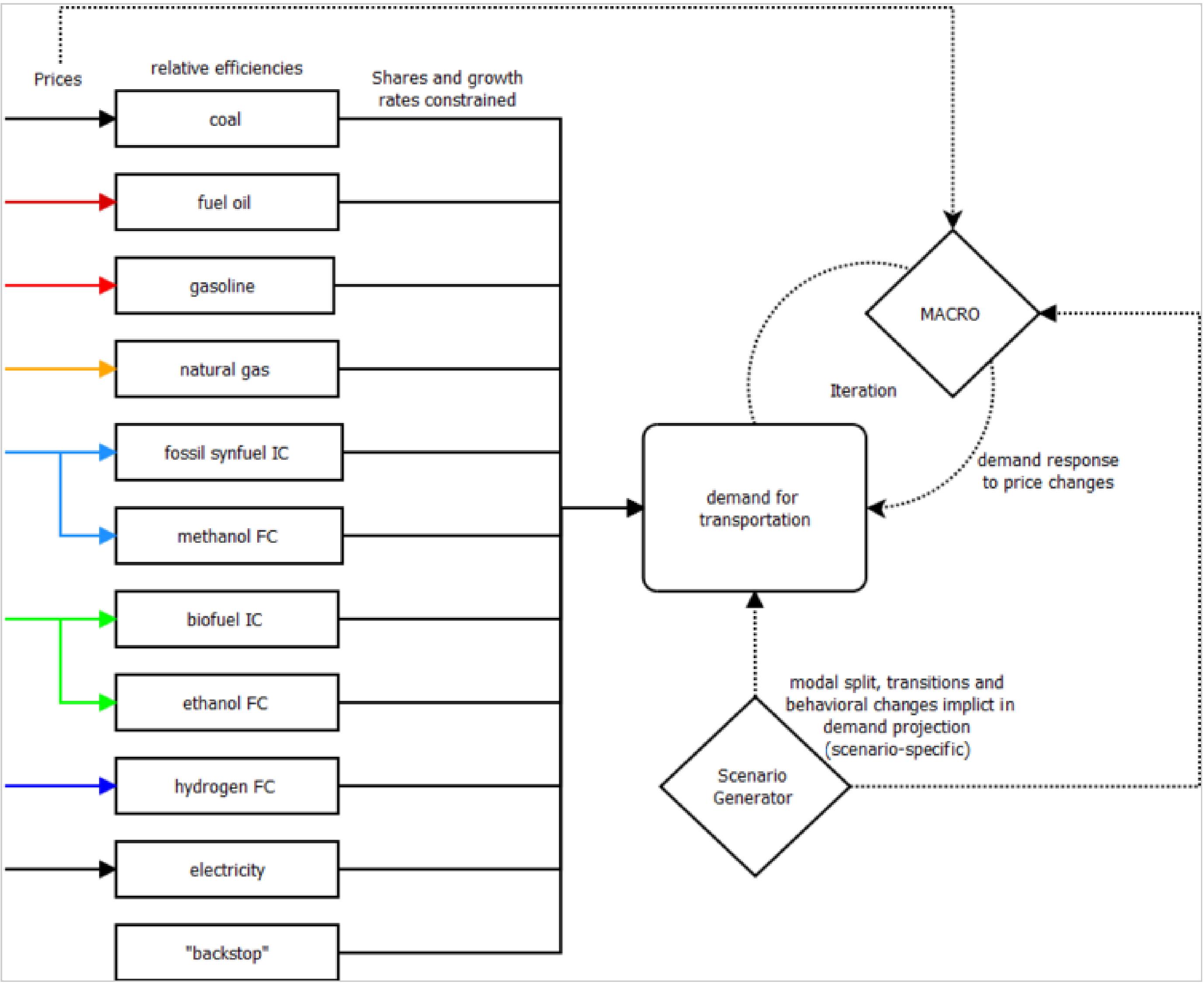


Figure 10: Schematic diagram of the stylized transport sector representation in MESSAGE

The demand for international shipping is modeled in a simplified way with a number of different energy carrier options (light and heavy fuel oil, biofuels, natural gas, and hydrogen). The demand for international shipping is coupled to global GDP development with an income elasticity, but to date no demand response in mitigation scenarios is implemented.

Table 17 presents the quantitative translation of the the storyline elements of SSP1, SSP2 and SSP3 in terms of electrification rate for transport (Fricko et al., 2016 [1]).

Table 17: Electrification rate within transport for SSP1, SSP2 and SSP3 (Fricko et al., 2016 [1]). The indicators apply to 2010-2100; Intensity improvements are presented in Final Energy (FE)/GDP annually

	SSP1	SSP2	SSP3
Transport	High electrification (max. 75% of total transport possible)	Medium electrification (max. 50% of total transport possible)	Low electrification (max 10% of total transport possible)

4.3.2) Residential and commercial sectors - MESSAGE-GLOBIOM

The residential and commercial sector in MESSAGE distinguishes two demand categories, thermal and specific. Thermal demand, i.e. low temperature heat, can be supplied by a variety of different energy carriers while specific demand requires electricity (or a decentralized technology to convert other energy carriers to electricity).

This stylized residential and commercial thermal energy demand includes fuel switching as the main option, i.e. different choices about final energy forms to provide thermal energy. In addition to the alternative energy carriers that serve as input to these thermal energy supply options, their relative efficiencies also vary. For example, solid fuels such as coal have lower conversion efficiencies than natural gas, direct electric heating or electric heat pumps. Additional demand reduction in response to price increases in policy scenarios is included via the fuel switching option (due to the fuel-specific relative efficiencies) as well as via the linkage with the macro-economic model MACRO (see Figure 11 below). The specific residential and commercial demand can be satisfied either by electricity from the grid or with decentralized electricity generation options such as fuel cells or CHP.

To reflect limitations of switching to alternative fuels, for example as a result of limited infrastructure availability (e.g., district heating network) or some energy carriers being unsuitable for certain applications, share constraints of energy carriers (e.g., electricity) and energy carrier groups (e.g., liquid fuels) are used in the residential and commercial sector. In addition, the diffusion of speed of alternative fuels is limited to mimic bottlenecks in the supply chains, not explicitly represented in MESSAGE (e.g., non-energy related infrastructure).

Table 18 presents the quantitative translation of the the storyline elements of SSP1, SSP2 and SSP3 in terms of electrification rate for the residential and commercial sectors. These indicators apply to 2010-2100; Intensity improvements are in FE/GDP annually (Fricko et al., 2016 [1]).

Table 18: Electrification rate within the residential and commercial sectors for SSP1, SSP2 and SSP3 (Fricko et al., 2016 [1])

	SSP1	SSP2	SSP3
Residential & Commercial	High electrification rate:1.44% (Regional range from 0.35% to 4%)	Medium electrification rate: 1.07% (Regional range from 0.23% to 3%)	Low electrification rate: 0.87% (Regional range from 0.37% to 2%)

4.3.3) Industrial sector - MESSAGE-GLOBIOM

The industrial sector in MESSAGE distinguishes two demand categories, thermal and specific. Thermal demand, i.e. heat at different temperature levels, can be supplied by a variety of different energy carriers while specific demand requires electricity (or a decentralized technology to convert other energy carriers to electricity).

This stylized industrial thermal energy demand includes fuel switching as the main option, i.e. different final energy forms that provide energy for thermal energy can be chosen from. In addition to the alternative energy carriers that serve as input to these thermal energy supply options, their relative efficiencies also vary. For example, solid fuels such as coal have lower conversion efficiencies than natural gas, direct electric heating or electric heat pumps. To account for the fact that some technologies cannot supply temperature at high temperature levels (e.g., electric heat pumps, district heat), the share of these technologies in the provision of industrial thermal demand is constrained. Additional demand reduction in response to price increases in policy scenarios is included via the fuel switching option (due to the fuel-specific relative efficiencies) as well as via the linkage with the macro-economic model MACRO (see Figure 12 below). The specific industrial demand can be satisfied either by electricity from the grid or with decentralized electricity generation options (including CHP) such as fuel cells.

While cement production is not explicitly modeled at the process level in MESSAGE, the amount of cement of cement production is linked to industrial activity (more specifically the industrial thermal demand in MESSAGE) and the associated CO_2 emissions from the calcination process are accounted for explicitly. In addition, adding carbon capture and storage to

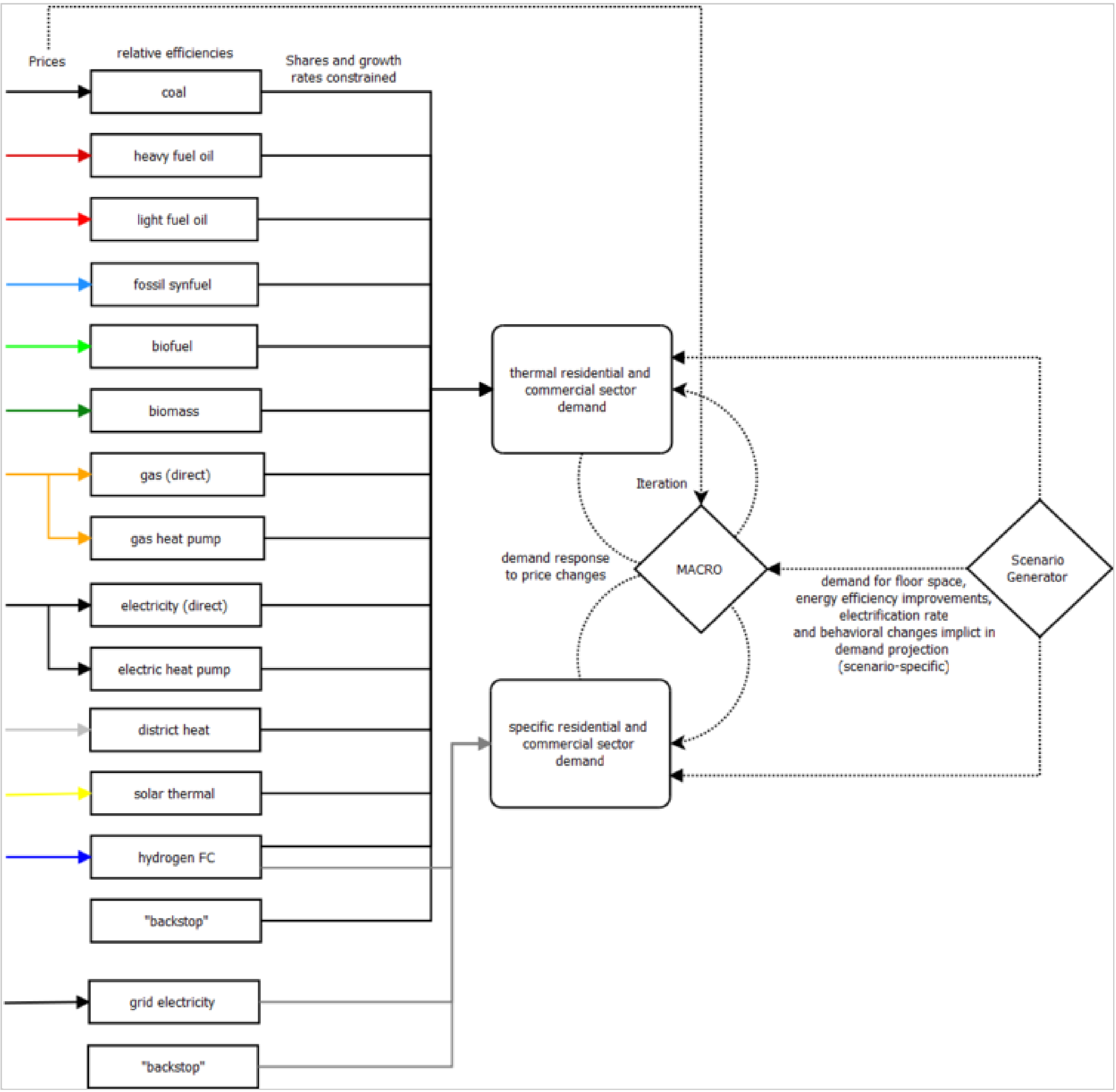


Figure 11: Schematic diagram of the residential and commercial sector representation in MESSAGE

mitigate these process-based CO2 emission is available.

??? presents the quantitative translation of the the storyline elements of SSP1, SSP2 and SSP3 in terms of electrification rate for industry and feedstocks. These indicators apply to 2010-2100; Intensity improvements are in FE/GDP annually (Fricko et al., 2016 [1]).

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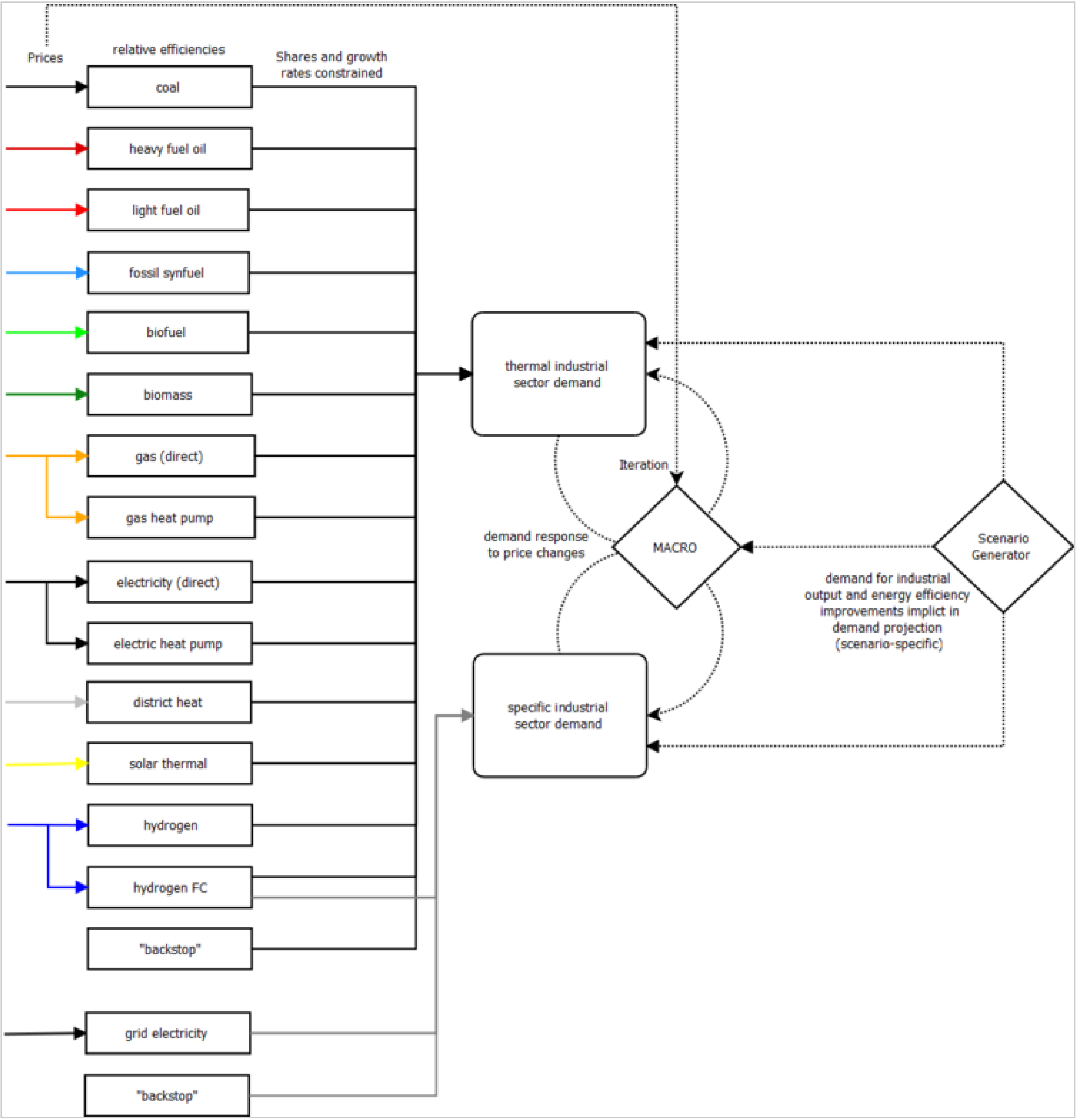

Figure 12: Schematic diagram of the industrial sector representation in MESSAGE

Electrification rate within industry and feedstocks for SSP1, SSP2 and SSP3 (Fricko et al., 2016 [1])

	SSP1	SSP2	SSP3
Industry and feedstocks	High electrification rate: 0.56% (Regional range from 0.2% to 1.2%) High feedstock reduction rate: -0.33% (Regional range from -0.51 to 0.59%)	Medium electrification rate: 0.47% (Regional range from 0.07% to 1.08%) Medium feedstock reduction rate: -0.27% (Regional range from -0.45% to 0.64%)	Low electrification rate: 0.12% (Regional range from -0.03% to 0.71%) Low feedstock reduction rate: -0.24% (Regional range from -0.38% to 0.51%)

4.4) Energy demand - MESSAGE-GLOBIOM

Baseline energy service demands are provided exogenously to MESSAGE, though they can be adjusted endogenously based on energy prices using the MESSAGE-MACRO link. There are seven energy service demands that are provided to MESSAGE, including:

1. Residential/commercial thermal
2. Residential/commercial specific
3. Industrial thermal
4. Industrial specific
5. Industrial feedstock (non-energy)
6. Transportation
7. Non-commercial biomass.

These demands are generated using a so-called scenario generator which is implemented in the script language [[1](https://www.r-project.org/%7CR)]. The scenario generator uses country-level historical data of GDP per capita (PPP) and final energy use as well as projections of GDP (PPP) and population to extrapolate the seven energy service demands into the future. The sources for the historical and projected datasets are the following:

1. Historical GDP (PPP) – World Bank (World Development Indicators 2012 [24])
2. Historical Population – UN Population Division (World Population Projection 2010 [25])
3. Historical Final Energy – International Energy Agency Energy Balances (IEA 2012 [26])
4. Projected GDP (PPP) – Dellink et al (2015 [7]), see Shared Socio-Economic Pathways database (scenarios (https://tntcat.iiasa.ac.at/SspDb/%7CSSP))
5. Projected Population – KC and Lutz (2014 [6]), see Shared Socio-Economic Pathways database(scenarios (https://tntcat.iiasa.ac.at/SspDb/%7CSSP))

The scenario generator runs regressions on the historical datasets to establish the relationship between the independent variable (GDP (PPP) per capita) and several dependent variables, including total final energy intensity (MJ/2005USD) and the shares of final energy in several energy sectors (%). In the case of final energy intensity, the relationship is best modeled by a power function so both variables are log-transformed. In the case of most sectoral shares, only the independent variable is log-transformed. The exception is the industrial share of final energy, which uses a hump-shaped function inspired by Schäfer (2005) [27]. This portion of the model provides the historical relationships between GDP per capita and the dependent variables for each of the eleven MESSAGE regions.

The historical data are also used in regressions (https://en.wikipedia.org/wiki/Quantile_regression%7Cquantile) to develop global trend lines that represent each percentile of the cumulative distribution function (CDF) of each regressed variable. Given the regional regressions and global trend lines, final energy intensity and sectoral shares can be extrapolated based on projected GDP per capita, or average income. Several user-defined inputs allow the user to tailor the extrapolations to individual socio-economic scenarios. In the case of final energy intensity (FEI), the extrapolation is produced for each region by defining the quantile at which FEI converges (e.g., the 20th percentile) and the income at which the convergence occurs. For example, while final energy intensity converges quickly to the lowest quantile (0.001) in SSP1, it converges more slowly to a larger quantile (0.5 to 0.7 depending on the region) in SSP3. Convergence quantiles and incomes are provided for each SSP and region in Table 19, Table 20 and Table 21. The convergence quantile allows one to identify the magnitude of FEI while the convergence income establishes the rate at which the quantile is approached. For the sectoral shares, the user can specify the global quantile at which the extrapolation should converge, the income at which the extrapolation diverges from the regional regression line and turns parallel to the specified convergence quantile (i.e., how long the sectoral share follows the historical trajectory), and the income at which the extrapolation converges to the quantile. Given these input parameters, the user can extrapolate both FEI and sectoral shares.

The total final energy in each region is then calculated by multiplying the extrapolated final energy intensity by the projected GDP (PPP) in each time period. Next, the extrapolated shares are multiplied by the total final energy to identify final energy demand for each of the seven energy service demands used in MESSAGE. Finally, final energy is converted to useful energy in each region by using the average final-to-useful energy efficiencies reported by the IEA for each country.

Table 19: Convergence quantile and income for each parameter and region for SSP1 (for region descriptions, see: Spatial dimension of MESSAGE-GLOBIOM)

SSP1	AFR	CPA	EEU	FSU	LAM	MEA	NAM	PAO	PAS	SAS	WEU
Convergence Quantile											
Final Energy Intensity (FEI)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Share NC Biomass	0.01	0.25	0.01	0.75	0.01	0.3	0.01	0.01	0.01	0.01	0.01
Share Transport	0.05	0.02	0.2	0.05	0.2	0.05	0.2	0.2	0.04	0.03	0.2
Share Res/Com	0.25	0.25	0.2	0.2	0.28	0.3	0.25	0.2	0.28	0.3	0.2
Share Industry	0.1	0.2	0.1	0.5	0.28	0.2	0.3	0.3	0.28	0.2	0.3
Elec Share Res/Com	0.45	0.45	0.45	0.45	0.63	0.62	0.4	0.63	0.62	0.64	0.43
Feedstock Share Industry	0.18	0.2	0.24	0.24	0.2	0.26	0.26	0.23	0.26	0.22	0.24
Elec Share Industry	0.4	0.4	0.42	0.36	0.4	0.33	0.36	0.36	0.4	0.4	0.4
Convergence Income											
Final Energy Intensity (FEI)	112295	98603	299177	112307	100188	113404	112356	112261	106323	112300	107636
Share NC Biomass	5981	46015	34405	40951	20038	34894	112356	112261	16357	11105	48153
Share Transport	99676	32868	112341	71664	112310	113404	123018	94337	112293	97169	141627
Share Res/Com	119611	112276	179506	153565	112310	112270	123018	157229	112293	112300	141627
Share Industry	39870	105177	164547	92139	40075	112270	123018	112261	126769	83288	127464
Elec Share Res/Com	112295	112276	112341	112307	112310	87234	131219	132072	112293	112300	112168
Feedstock Share Industry	112295	112276	112341	112307	112310	112270	123018	125783	112293	112300	112168
Elec Share Industry	112295	98603	299177	112307	100188	113404	112356	112261	106323	112300	107636

Table 20: Convergence quantile and income for each parameter and region for SSP2 (for region descriptions, see: Spatial dimension of MESSAGE-GLOBIOM)

SSP2	AFR	CPA	EEU	FSU	LAM	MEA	NAM	PAO	PAS	SAS	WEU
Convergence Quantile											
Final Energy Intensity (FEI)	0.03	0.03	0.03	0.04	0.04	0.04	0.05	0.02	0.03	0.03	0.02
Share NC Biomass	0.6	0.6	0.75	0.75	0.25	0.75	0.75	0.75	0.6	0.6	0.75
Share Transport	0.05	0.04	0.15	0.1	0.5	0.3	0.5	0.14	0.2	0.05	0.15
Share Res/Com	0.15	0.28	0.5	0.5	0.3	0.5	0.3	0.35	0.3	0.28	0.33
Share Industry	0.25	0.4	0.15	0.25	0.15	0.25	0.25	0.25	0.25	0.6	0.25
Elec Share Res/Com	0.42	0.4	0.35	0.22	0.58	0.6	0.14	0.57	0.6	0.51	0.18
Feedstock Share Industry	0.15	0.22	0.26	0.26	0.18	0.27	0.32	0.27	0.3	0.22	0.27
Elec Share Industry	0.39	0.38	0.4	0.45	0.35	0.4	0.4	0.4	0.4	0.43	0.35
Convergence Income											
Final Energy Intensity (FEI)	200009	200033	299177	266179	199975	139574	246036	141506	199968	200002	199977
Share NC Biomass	19935	26294	77786	40951	20038	94649	94724	132072	12268	18046	48153
Share Transport	49838	105177	94540	94596	80150	94649	94724	94652	81787	27763	99139
Share Res/Com	119611	65735	89753	71664	94577	69787	94724	110060	81787	83288	113301
Share Industry	31896	105177	44877	102377	100188	78511	94724	141506	98144	13881	94607
Elec Share Res/Com	69773	94593	94540	102377	94577	87234	123018	141506	94627	55525	113301
Feedstock Share Industry	19935	94593	94540	94596	94577	94649	94724	94652	94627	94615	94607
Elec Share Industry	200009	200033	299177	266179	199975	139574	246036	141506	199968	200002	199977

Table 21: Convergence quantile and income for each parameter and region for SSP3 (for region descriptions, see: Spatial dimension of MESSAGE-GLOBIOM)

SSP2	AFR	CPA	EEU	FSU	LAM	MEA	NAM	PAO	PAS	SAS	WEU
Convergence Quantile											
Final Energy Intensity (FEI)	0.6	0.55	0.5	0.7	0.7	0.5	0.7	0.5	0.5	0.7	0.6
Share NC Biomass	0.9	0.6	0.75	0.75	0.25	0.75	0.75	0.75	0.6	0.9	0.75
Share Transport	0.1	0.05	0.7	0.2	0.45	0.5	0.7	0.25	0.5	0.1	0.7
Share Res/Com	0.25	0.25	0.55	0.55	0.3	0.5	0.35	0.6	0.25	0.2	0.5
Share Industry	0.1	0.6	0.2	0.1	0.2	0.2	0.1	0.1	0.6	0.2	0.1
Elec Share Res/Com	0.4	0.6	0.45	0.4	0.9	0.9	0.25	0.65	0.9	0.6	0.33
Feedstock Share Industry	0.2	0.22	0.26	0.24	0.2	0.3	0.32	0.29	0.3	0.22	0.27
Elec Share Industry	0.3	0.43	0.37	0.45	0.3	0.4	0.35	0.45	0.4	0.35	0.4
Convergence Income											
Final Energy Intensity (FEI)	200009	200033	200000	200044	199975	200027	200109	199995	199968	200002	199977
Share NC Biomass	13955	26294	80927	40951	12023	80953	80782	132072	12268	12771	48153
Share Transport	13955	46015	59835	51188	70131	69787	80782	132072	32715	55525	81010
Share Res/Com	23922	65735	59835	61426	80952	52340	80782	80816	199968	80512	81010
Share Industry	5981	52588	200000	122852	18034	43617	200109	199995	81787	30539	198277
Elec Share Res/Com	80976	80986	80927	61426	80952	69787	80782	80816	80969	80956	81010
Feedstock Share Industry	19935	26294	80927	80980	80952	80953	80782	80816	80969	80956	81010
Elec Share Industry	200009	200033	200000	200044	199975	200027	200109	199995	199968	200002	199977

4.5) Technological change in energy - MESSAGE-GLOBIOM

Technological change in MESSAGE is generally treated exogenously, although pioneering work on the endogenization of technological change via learning curves in energy-engineering type models (Messner, 1997 [21]) and the dependence of technology costs on market structure has been done with MESSAGE (Leibowicz, 2015 [28]). The current cost and performance parameters, including conversion efficiencies and emission coefficients is generally derived from the relevant engineering literature. For the future alternative cost and performance projections are developed to cover a relatively wide range of uncertainties that influences model results to a good extent.

Technology cost

The quantitative assumptions about technology cost development are derived from the overarching qualitative SSP narratives (cf. section **narratives**). In SSP1, for instance, whose green-growth storyline is more consistent with a sustainable development paradigm, higher rates of technological progress and learning are assumed for renewables and other advanced technologies that may replace fossil fuels (e.g., the potential for electric mobility is assumed to be higher in SSP1 compared to SSP2 or SSP3). In contrast, SSP3 assumes limited progress across a host of advanced technologies, particularly for renewables and hydrogen; more optimistic assumptions are instead made for coal-based technologies, not only for power generation but also for liquid fuels production. Meanwhile, the middle-of-the-road SSP2 narrative is characterized by a fairly balanced view of progress for both conventional fossil and non-fossil technologies. In this sense, technological development in SSP2 is not biased toward any particular technology group.

Technological costs vary regionally in all SSPs, reflecting marked differences in engineering and construction costs across countries observed in the real world. Generally, costs start out lower in the developing world and are assumed to converge to those of present-day industrialized countries as the former becomes richer throughout the century (thus, the cost projections consider both labour and capital components). This catch-up in costs is assumed to be fastest in SSP1 and slowest in SSP3 (where differences remain, even in 2100); SSP2 is in between. Estimates for present-day and fully learned-out technology costs are from the Global Energy Assessment (Riahi et al., 2012 [12]) and World Energy Outlook (IEA, 2014 [29]). A summary of these cost assumptions can be found in sections Electricity of MESSAGE-GLOBIOM and Other conversion of MESSAGE-GLOBIOM.

Technology diffusion

MESSAGE tracks investments by vintage, an important feature to represent the inertia in the energy system due to its long-lived capital stock. In case of shocks (e.g., introduction of stringent climate policy), it is however possible to prematurely retire existing capital stock such as power plants or other energy conversion technologies and switch to more suitable alternatives.

An important factor in this context that influences technology adoption in MESSAGE are technology diffusion constraints. Technology diffusion in MESSAGE is determined by dynamic constraints that relate the construction of a technology added or the activity (level of production) of a technology in a period t to construction or the activity in the previous period t-1 (Messner and Strubegger, 1995 [10] **cf. section :ref:`upper_dynamic_constraint_capacity**).

While limiting the possibility of flip-flop behavior as is frequently observed in unconstrained Linear Programming (LP) models such as MESSAGE, a drawback of such hard growth constraints is that the relative advantage of some technology over another technology is not taken into account and therefore even for very competitive technologies, no acceleration of technology diffusion is possible. In response to this limitation, so called flexible or soft dynamic constraints have been introduced into MESSAGE (Keppo and Strubegger, 2010 [2]). These allow faster technology diffusion at additional costs and therefore generate additional model flexibility while still reducing the flip-flop behavior and sudden penetration of technologies.

Figure 13 below illustrates the maximum technology growth starting at a level of 1 in year t=0 for a set of five diffusion constraints which jointly lead to a soft constraint.

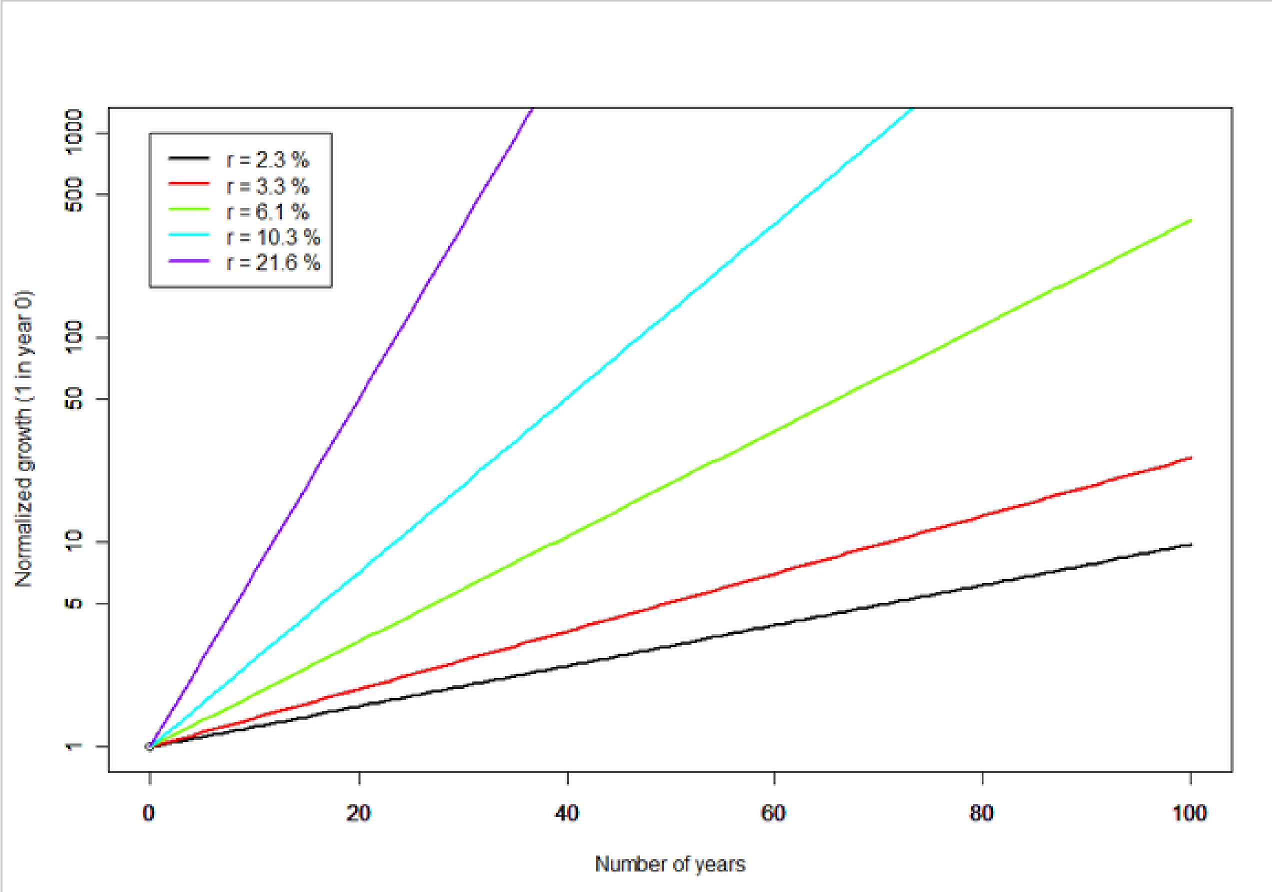

Figure 13: Illustration of maximum technology growth starting at a level of 1 in year t=0 for a set of soft diffusion constraints with effective growth rates r as shown in the legend

For a more detailed description of the implementation of technology diffusion constraints, see the Annex Section **ref:annex_convtech**.

5) Land-use - MESSAGE-GLOBIOM

Land-use dynamics are modelled with the GLOBIOM (GLobal BIOsphere Management) model, which is a recursive-dynamic partial-equilibrium model (Havlík et al., 2011 [30]; Havlík et al., 2014 [31]). GLOBIOM represents the competition between different land-use based activities. It includes a bottom-up representation of the agricultural, forestry and bio-energy sector, which allows for the inclusion of detailed grid-cell information on biophysical constraints and technological costs, as well as a rich set of environmental parameters, incl. comprehensive AFOLU (agriculture, forestry and other land use) GHG emission accounts and irrigation water use. Its spatial equilibrium modelling approach represents bilateral trade based on cost competitiveness. For spatially explicit projections of the change in afforestation, deforestation, forest management, and their related CO2 emissions, GLOBIOM is coupled with the G4M (Global FORest Model) model (Kindermann et al., 2006 [32]; Kindermann et al., 2008 [33]; Gusti, 2010 [34]). The spatially explicit G4M model compares the income of managed forest (difference of wood price and harvesting costs, income by storing carbon in forests) with income by alternative land use on the same place, and decides on afforestation, deforestation or alternative management options. As outputs, G4M provides estimates of forest area change, carbon uptake and release by forests, and supply of biomass for bioenergy and timber. (Fricko et al., 2016 [1])

As a partial equilibrium model representing land-use based activities, including agriculture, forestry and bioenergy sectors, GLOBIOM is built following a bottom-up setting based on detailed gridcell information, providing the biophysical and technical cost information. Production adjusts to meet the demand at the level of 30 economic regions. International trade representation is based on the spatial equilibrium modelling approach, where individual regions trade with each other based purely on cost competitiveness because goods are assumed to be homogenous (Takayama and Judge 1971 [35]; Schneider, McCarl et al. 2007 [36]). Market equilibrium is determined through mathematical optimization which allocates land and other resources to maximize the sum of consumer and producer surplus (McCarl and Spreen 1980 [37]). As in other partial equilibrium models, prices are endogenous. The model is run recursively dynamic with a 10 year time step, along a baseline going from 2000 to 2100. The model is solved using a linear programming simplex solver and can be run on a personal computer with the GAMS software.

For more information about the land-use part of MESSAGE-GLOBIOM, please visit IIASA's MESSAGE-GLOBIOM documentation (http://data.ene.iiasa.ac.at/message-globiom/message_globiom/land_use/index.html).

6) Emissions - MESSAGE-GLOBIOM

In the sub-sections of this chapter, the GHG and non-GHG emissions included in MESSAGE-GLOBIOM are presented.

6.1) GHGs - MESSAGE-GLOBIOM

Carbon-dioxide (CO2)

The MESSAGE model includes a detailed representation of energy-related and - via the link to GLOBIOM - land-use CO2 emissions (Riahi and Roehrl, 2000 [38]; Riahi, Rubin et al., 2004 [39]; Rao and Riahi, 2006 [40]; Riahi et al., 2011 [41]). CO2 emission factors of fossil fuels and biomass are based on the 1996 version of the IPCC guidelines for national greenhouse gas inventories [42] (see Table 22). It is important to note that biomass is generally treated as being carbon neutral in the energy system, because the effects on the terrestrial carbon stocks are accounted for on the land use side, i.e. in GLOBIOM (see section Land-Use of MESSAGE-GLOBIOM). The CO2 emission factor of biomass is, however, relevant in the application of carbon capture and storage (CCS) where the carbon content of the fuel and the capture efficiency of the applied process determine the amount of carbon captured per unit of energy.

Table 22: Carbon emission factors used in MESSAGE based on IPCC (1996, Table 1-2 [1]). For convenience, emission factors are shown in three different units.

Fuel	Emission factor [tC/TJ]	Emission factor [tCO2/TJ]	Emission factor [tC/kWyr]
Hard coal	25.8	94.6	0.814
Lignite	27.6	101.2	0.870
Crude oil	20.0	73.3	0.631
Light fuel oil	20.0	73.3	0.631
Heavy fuel oil	21.1	77.4	0.665
Methanol	17.4	63.8	0.549
Natural gas	15.3	56.1	0.482
Solid biomass	29.9	109.6	0.942

CO2 emissions of fossil fuels for the entire energy system are accounted for at the resource extraction level by applying the CO2 emission factors listed in Table 22 to the extracted fossil fuel quantities. In this economy-wide accounting, carbon emissions captured in CCS processes remove carbon from the balance equation, i.e. they contribute with a negative emission coefficient. In parallel, a sectoral accounting of CO2 emissions is performed which applies the same emission factors to fossil fuels used in individual conversion processes. In addition to conversion processes, also CO2 emissions from energy use in fossil fuel resource extraction are explicitly accounted for. An important feature of MESSAGE in this context is that CO2 emissions from the extraction process increase when moving from conventional to unconventional fossil fuel resources.

CO2 mitigation options in the energy system include technology and fuel shifts; efficiency improvements; and CCS. A large number of specific mitigation technologies are modeled bottom-up in MESSAGE with a dynamic representation of costs and efficiencies. As mentioned above, MESSAGE also includes a detailed representation of carbon capture and sequestration from both fossil fuel and biomass combustion.

Non-CO2 GHGs

MESSAGE includes a representation of non-CO2 GHGs (CH4, N2O, HFCs, SF6, PFCs) mandated by the Kyoto Protocol (Rao and Riahi, 2006 [40]) with the exception of NF3. Included is a representation of emissions and mitigation options from both energy related processes as well as non-energy sources like municipal solid waste disposal and wastewater. CH4 and N2O emissions from land are taken care of by the link to GLOBIOM.

6.2) Pollutants and non-GHG forcing agents - MESSAGE-GLOBIOM

Air pollution implications are derived with the help of the GAINS (Greenhouse gas–Air pollution INteractions and Synergies) model. GAINS allows for the development of cost-effective emission control strategies to meet environmental objectives on climate, human health and ecosystem impacts until 2030 (Amann et al., 2011 [43]). These impacts are considered in a multi-pollutant context, quantifying the contributions of sulfur dioxide (SO2), nitrogen oxides (NOx), ammonia (NH3), non-methane volatile organic compounds (VOC), and primary emissions of particulate matter (PM), including fine and coarse PM as well as carbonaceous particles (BC, OC). As a stand-alone model, it also tracks emissions of six greenhouse gases of the Kyoto basket with exception of NF3. The GAINS model has global coverage and holds essential information about key sources of emissions, environmental policies, and further mitigation opportunities for about 170 country-regions. The model relies on exogenous projections of energy use, industrial production, and agricultural activity for which it distinguishes all key emission sources and several hundred control measures. GAINS can develop finely resolved mid-term air pollutant emission trajectories with different levels of mitigation ambition (Cofala et al., 2007 [44]; Amann et al., 2013 [45]). The results of such scenarios are used as input to global IAM frameworks to characterize air pollution trajectories associated with various long-term energy developments (see further for example Riahi et al., 2012 [12]; Rao et al., 2013 [46]; Fricko et al., 2016 [1]).

7) Climate - MESSAGE-GLOBIOM

The response of the carbon-cycle and climate to anthropogenic climate drivers is modelled with the MAGICC model (Model for the Assessment of Greenhouse-gas Induced Climate Change). MAGICC is a reduced-complexity coupled global climate and carbon cycle model which calculates projections for atmospheric concentrations of GHGs and other atmospheric climate drivers like air pollutants, together with consistent projections of radiative forcing, global annual-mean surface air temperature, and ocean-heat uptake (Meinshausen et al., 2011a [47]). MAGICC is an upwelling-diffusion, energy-balance model, which produces outputs for global- and hemispheric-mean temperature. MAGICC is most commonly used in a deterministic setup (Meinshausen et al., 2011b [48]), but also a probabilistic setup (Meinshausen et al., 2009 [49]) is available which allows to estimate the probabilities of limiting warming to below specific temperature levels given a specified emissions path (Rogelj et al., 2013a [50]; Rogelj et al., 2013b [51]; Rogelj et al., 2015 [52]). Climate feedbacks on the global carbon cycle are accounted for through the interactive coupling of the climate model and a range of gas-cycle models. (Fricko et al., 2016 [1])

For more information about the model, see www.magicc.org (http://www.magicc.org/).

7.1) Modelling of climate indicators - MESSAGE-GLOBIOM

8) Non-climate sustainability dimension - MESSAGE-GLOBIOM

Even other non-climate sustainable development dimensions have been modeled with the MESSAGE-GLOBIOM model framework. These include air pollution, water use in the energy sector and energy access. These are presented in the subsections of this chapter.

8.1) Air pollution and health - MESSAGE-GLOBIOM

The different Shared Socioeconomic Pathways (SSPs) have varying impacts on air pollution emissions. SSP1 and SSP5 show the most rapid emissions reductions than the other SSPs due to more effective pollution control and lower intensity for fossil fuels. SSP3 shows a consistent decline throughout the century, which is however less sharp than the reduction presented by SSP1 and SSP5. SSP3, due to larger projected population growth and relatively more slow and heterogeneous economic growth, results in an increase in emissions until 2030, and through a slight post-2030 decline end in only slightly lower emissions levels than the current ones by 2100.

Mitigation scenarios bring co-benefits in terms of air pollutant emission reductions. The largest emissions reductions can be seen for the SSP3 scenario, which has the highest baseline emissions, and the lowest for SSP1/SSP5. In terms of pollutants, SO2 and NOx emissions result in the largest reductions, whereas BC emissions do not decline as much - this can mainly be attributed to assumptions on fuel-substitution in the residential sector. (Rao et al, 2016[53])

Figure 14 presents the differences of emissions reductions between the different SSPs for both a reference case as well as for mitigation scenarios.

[1]

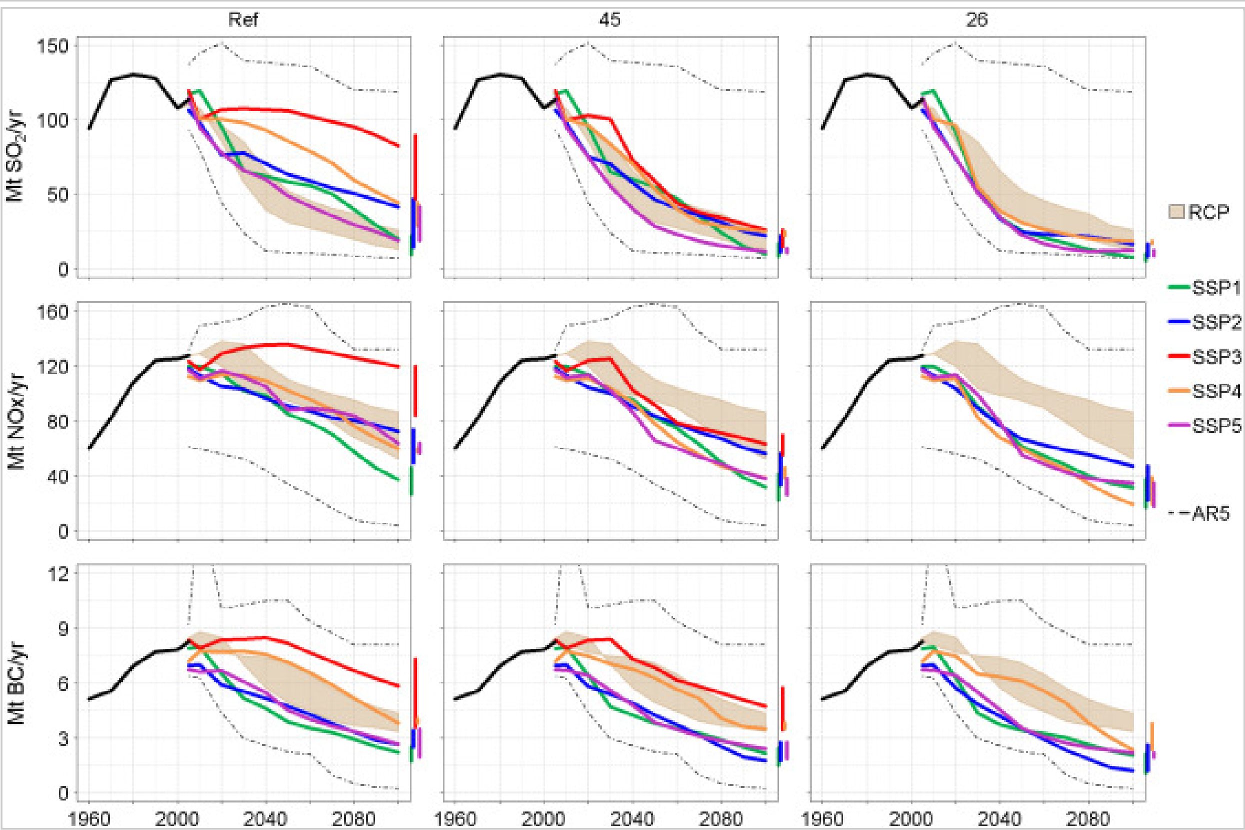

Figure 14: Emissions of SO2, NOX and BC in SSP marker baselines (Ref) and 4.5 (labeled as 45) and 2.6 (labeled as 26) W/m2 climate mitigation cases. Shaded area indicates range of total emissions from RCP scenario range from (van Vuuren et al., 2011a). Assessment Report (AR5) range refers to the full range of scenarios reviewed in the Fifth Assessment Report (AR5) (https://tntcat.iiasa.ac.at/AR5DB/) of Working Group III of the Intergovernmental Panel on Climate Change (IPCC); Historical values are derived from (Lamarque et al., 2010); Colored bars indicate the range of all models (markers and non-markers) in 2100. (Rao et al, 2016)

In terms of regional air pollution impacts of the different SSPs, the strong air pollution control scenarios (SSP1/SSP5) show significantly lower concentrations across all regions than the less stringent air pollution control scenarios (SSP3/SSP4). OECD countries are expected to enhance their air pollution situation by 2050 under all SSP scenarios. For Middle East and Africa, mineral dust is responsible for most of the higher concentration levels, and therefore, in this region, mitigation measures will not be as effective as elsewhere. For Asia the low air pollution control scenarios (SSP3/SSP4) would increase the amount of people exposed to high levels of air pollutants - however, mitigation measures have the potential for significant co-benefits in terms of air pollutants for the region. Figure 15 illustrates these regional impacts across the SSPs. (Rao et al, 2016[53])

[1]

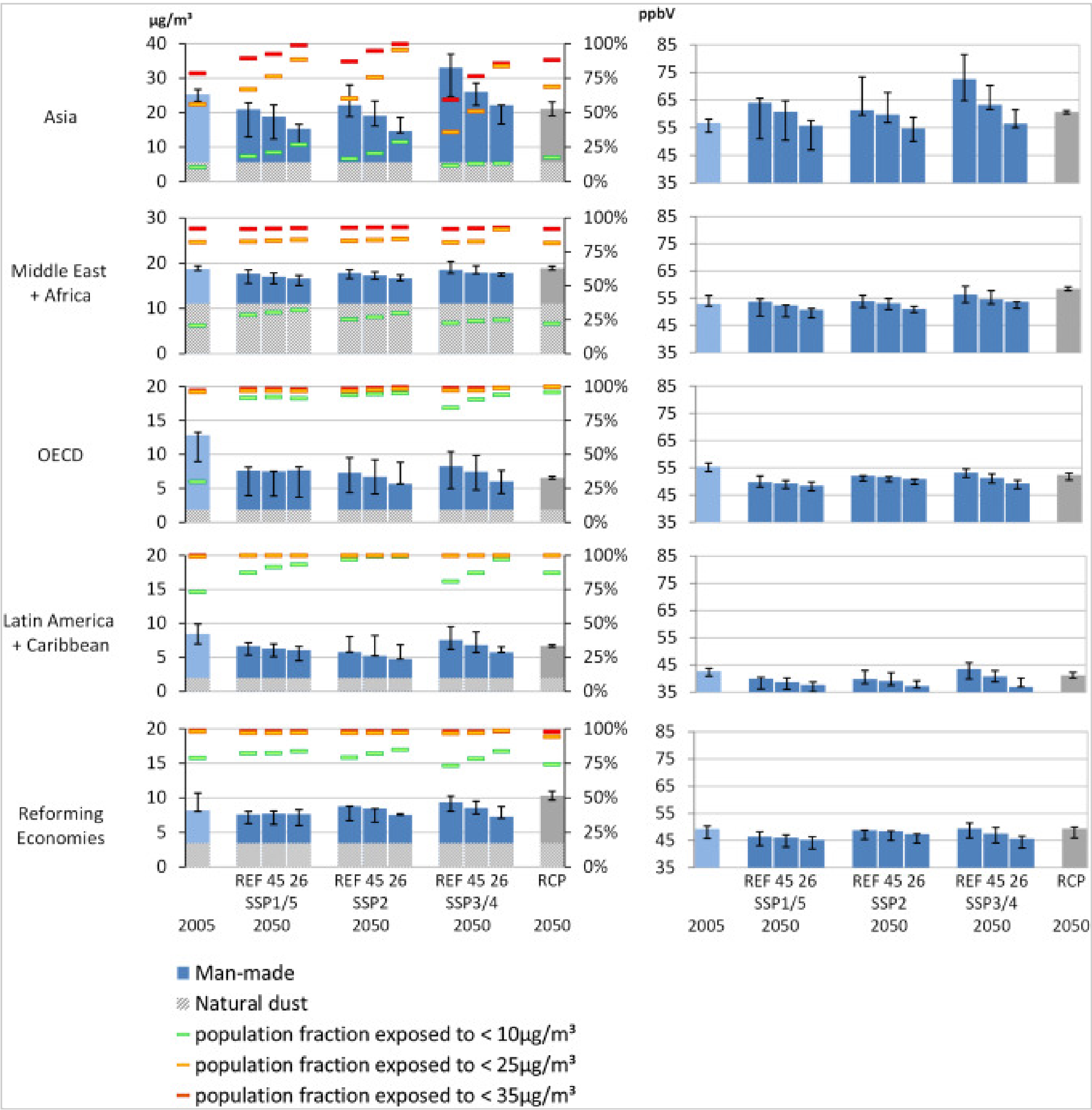

Figure 15: Left panel: region-population weighted mean PM2.5 in µg/m3 (left axis) from marker scenario (blue color bars) and average from the 3 RCP scenarios (grey bar), contribution of natural PM2.5 (hatched area) for the year 2005 (leftmost bar) and 2050. Green, orange and red colored markers indicate the fraction of the population exposed to <10, <25 and <35 µg/m3 respectively (right axis). Right panel: mean ozone concentration (maximal 6-monthly mean of daily maximum ozone). For the grouped scenarios SSP1/5 and SSP3/4 the concentration represents the mean of the respective marker scenarios. Error bars show the concentration range (min/max) of regional averages from all models in the (set of) SSP scenarios shown, including non-marker. For the RCP bars, the error bar indicates the min/max range within the set of 3 RCP2.6, RCP4.5 and RCP8.5 scenarios. (Rao et al, 2016)

8.2) Water - MESSAGE-GLOBIOM

Large amounts of water are currently being used in the energy sector. For assessing long-term freshwater sustainability, MESSAGE has been adapted to quantify the impact of energy system transformations on water.

The majority of energy sector freshwater withdrawal occurs in the steam-cycle and cooling systems related to thermoelectric power plants. The model distinguishes between two different water-cooling technologies, but also a technology only using air for cooling purposes, which provide an opportunity to reduce energy system reliance on water. The different technologies that are therefore distinguished in the model are:

- Once-through cooling technology: water is passed through the cooling system once and then returned to its source.
- Closed-loop cooling technology: water that is withdrawn is re-circulated.
- Air-cooling technology: instead of water, air is used for cooling purposes.

Further, the water source is distinguished across technologies between fresh or saline.

This choice of model formulation enables consistent representation of water use across power plant types and incorporates water impacts of heat-rate improvements due to anticipated long-term technological change. Moreover, the approach enables analysis of thermal water pollution from once-through cooled thermal power plants by allowing quantification of the heat energy embodied in cooling system effluents.

When applied to a broad range of climate mitigation scenarios that aim for 2 degrees Celsius, the results show a wide range of water implications across scenarios. Global demand of freshwater is expected to grow in all 2 degree scenarios due to rapidly growing electricity demand in many developing countries as a result of and the prevalence of freshwater-cooled thermal power generation. However, a shift to water-efficient cooling technologies can significantly reduce the use of water within the energy sector by reducing the freshwater withdrawals and thermal pollution related to thermoelectric power production. Further, controlling demand is another strategy that can reduce the water use, and further, it provides more flexibility in terms of cooling technology choices for thermoelectric power plants. Therefore, an integrated approach, using both technology adaptation and demand control, is seen as the most effective and flexible approach to reducing water demand in the energy sector. (Fricko et al, 2016[54])

Figure 16 presents the impact of water usage across different 2 degree scenarios from the Global Energy Assessment (GEA) (http://www.globalenergyassessment.org/), and how adopting technologies can help reduce the water demand.

[1]

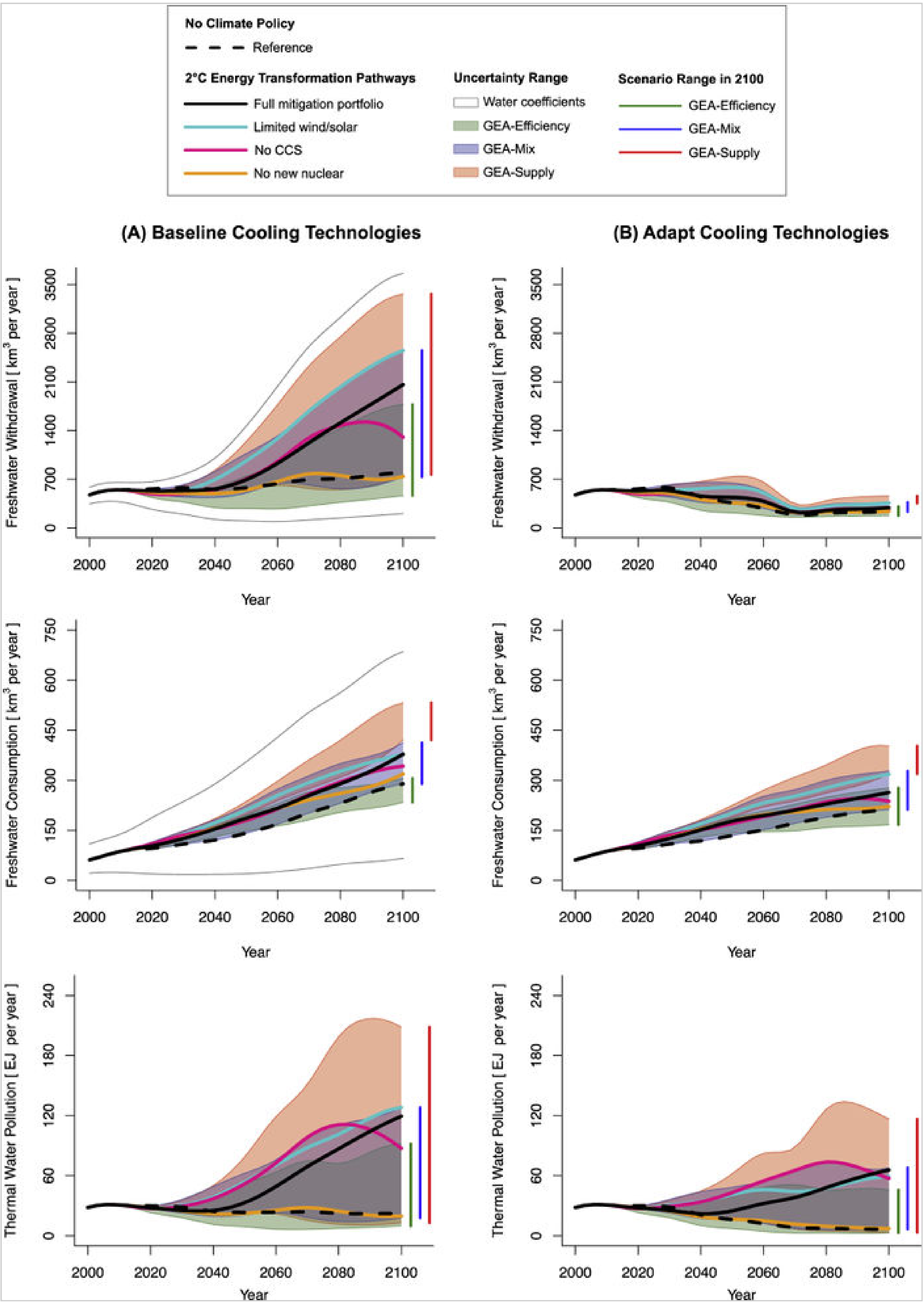

Figure 16: Global water impacts across the 2 °C and reference scenarios for the two thermal power plant cooling technology cases: (A) baseline cooling technologies; and (B) adapt cooling technologies. Individual scenario results are illustrated for a subset of climate change mitigation and reference scenarios with intermediate energy demand (GEA-Mix).

The full range of water impacts associated with all technology scenarios are illustrated for each energy demand assumption (GEA-Efficiency, GEA-Mix, and GEA-Supply). The additional range resulting from the maximum and minimum reported water intensity coefficients are indicated by gray lines. (Fricko et al., 2016)

Water consumption is responsive to the energy demand level, as depicted in Figure 16. Figure 17 explores the relationship between energy demand and water use by computing the water consumption intensity of the energy pathways (global water consumption divided by final energy demand). The intensity of water consumption increases over the simulation period regardless of the demand level. The GEA-Efficiency scenarios display the largest range of water since low demand levels permit a greater flexibility in supply side technologies for climate change mitigation. (Fricko et al, 2016[54])

[1]

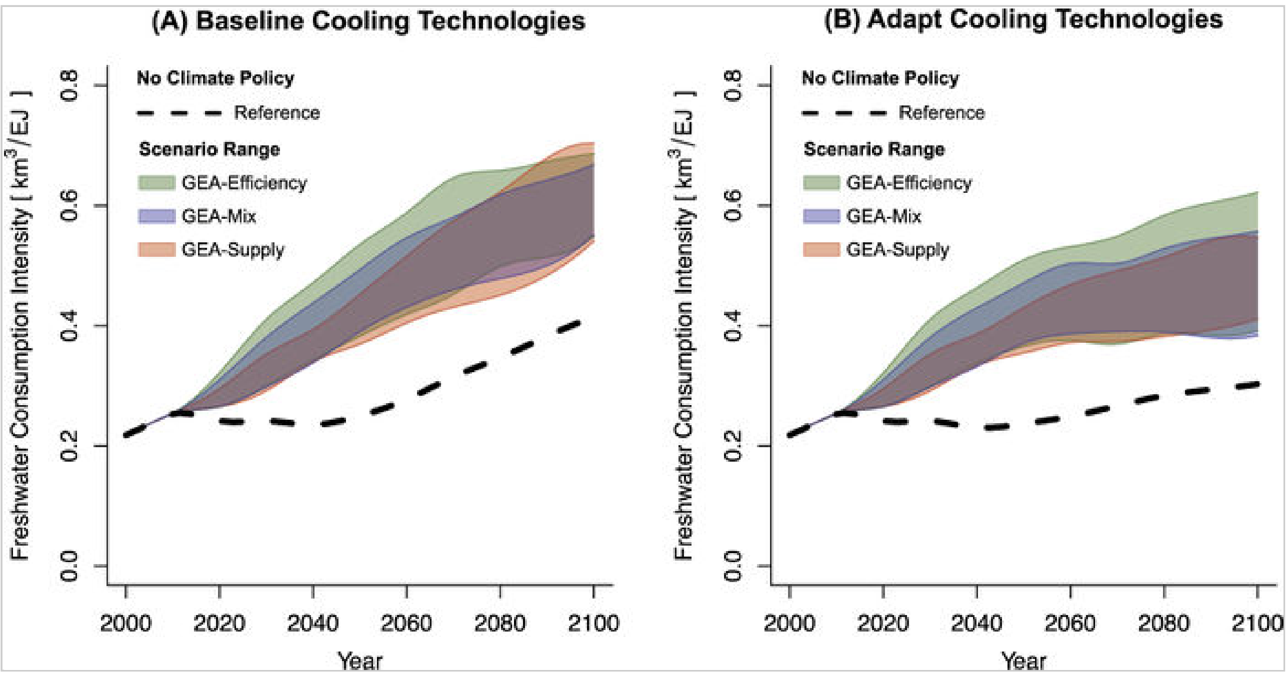

Figure 17: Water consumption intensity of the 2 °C and reference scenarios for the two thermoelectric cooling technology cases: (A) baseline cooling technologies; and (B) adapt cooling technologies. The consumption intensity is calculated as water consumption divided by final energy demand (in exajoules (EJ)). (Fricko et al., 2016)

8.4) Other sustainability dimensions - MESSAGE-GLOBIOM

Energy access

Three billion people globally depend on solid fuels for cooking and heating. According to Cameron et al (2016)[55], "household air pollution from the incomplete combustion of these fuels globally leads to 4.3 million premature deaths each year, with 1.7 million of those in South Asia". The Indian government is subsidizing petroleum-based fuels (such as kerosene and liquefied petroleum gas - LPG) to increase their uptake, however, still more than 72% of Indians mostly rely on solid fuels. Further, it is expected that more stringent climate policies will increase the cost of fuels making a switch to cleaner cooking more challenging.

For studying energy access issues, a household fuel-choice model, Access, is used in combination with MESSAGE. At the moment the MESSAGE Access runs have been developed for South Asia, which has the largest amount of solid-fuel users in the world. These two models are run iteratively until convergence: the Access model takes fuel prices from MESSAGE, selects optimal fuel choices for all household groups, and returns aggregate residential demand for the five cooking fuels

(LPG, piped gas, electricity, kerosene, and biomass). MESSAGE, in turn, determines the least-cost energy supply pathway to meet these demands and returns new prices. Climate policy is implemented from 2020 through 2100, with the implied carbon equivalent value rising at a discount rate of 5% per year over the time period.

The Access model reads in prices for five fuels from MESSAGE over the period from 2005 to 2100 and determines demand for each fuel in multiple heterogeneous population sub-groups. In this study, Access is implemented only for the MESSAGE South Asia region and represents only demand for cooking fuels. The Access model requires data inputs in three categories: 1) household characteristics and fuel preferences for each population sub-group calculated from nationally representative household surveys, 2) regional projections of population, GDP, urbanization, and electrification source and 3) cooking technology attribute data. When used in conjunction with MESSAGE, the two models iterate to account for the impact of changing household energy demands on fuel prices. MESSAGE-Access iterates until the output of the Access model from a given run is within 2% of its output from the previous run. This process is visualized in Figure 18. (Cameron et al, 2016 [55])

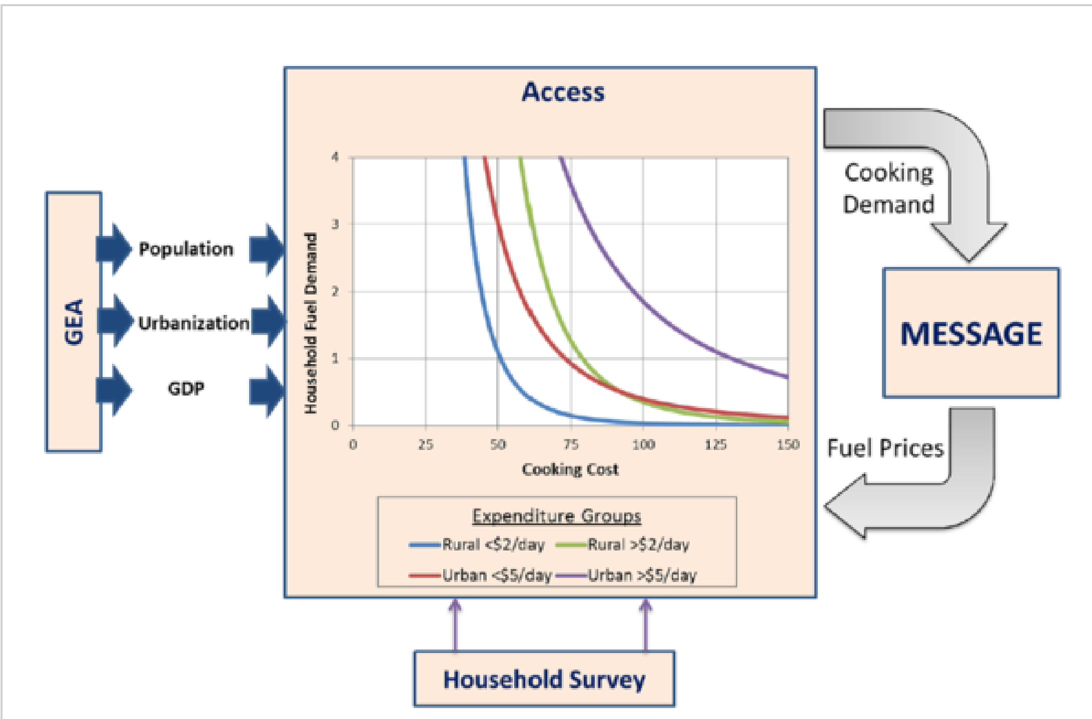

Figure 18: Overview of the MESSAGE-Access iteration process. Figure from Cameron et al. (2016).

When current trends are projected to the future, the GHG emissions of India are expected to rise sharply by 2050. At the same time, urbanization and high expected GDP growth would also enable 1 billion people (63% of the population) to transition to clean cooking fuels over the period from 2010 to 2050 (see Figure 19). However, climate mitigation scenarios, even though reducing total emissions, could have a negative effect on the transition to clean cooking fuels, due to increased prices of LPG. Figure 19 shows the effect of mitigation through the implementation carbon price if different stringency (US$10 (C10), US$20 (C20), US$30 (C30), and US$40 (C40) per ton CO2 equivalent in the year 2020) on GHG emissions versus solid-fuel reliance. (Cameron et al, 2016 [55])

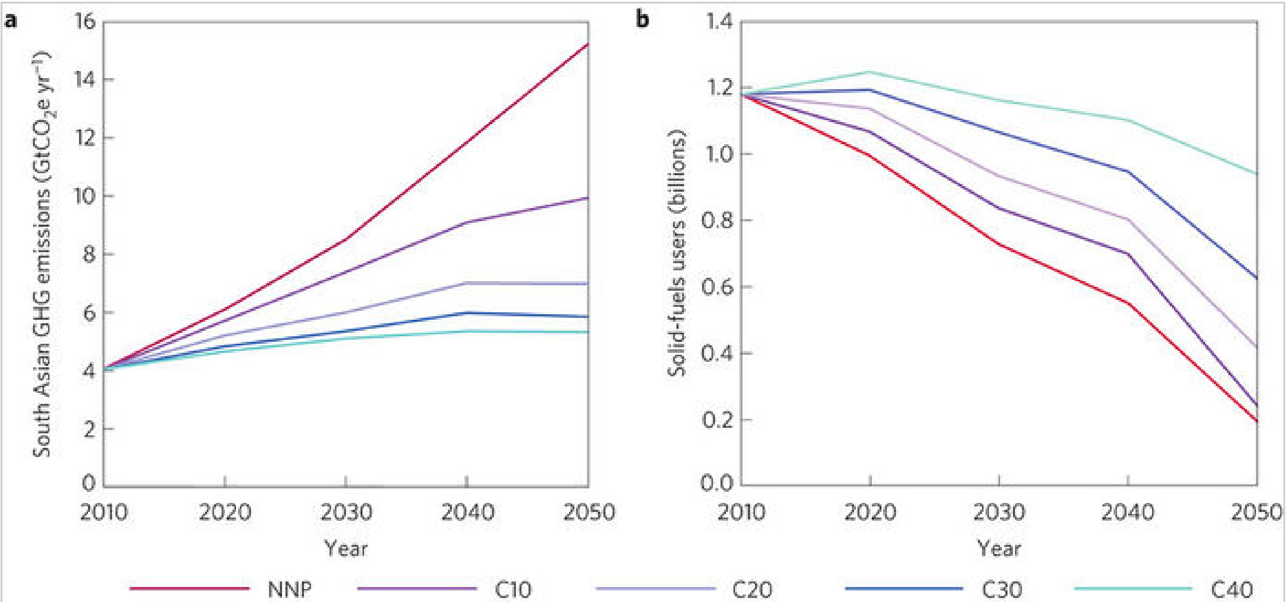

Figure 19: a, GHG emissions from the MESSAGE South Asia region. b, Solid-fuel users in billions from 2010 to 2050. Results are given for a baseline (NNP) and four increasingly stringent climate mitigation scenarios (C10, C20, C30, C40). Figure from Cameron et al. (2016).

The aforementioned negative impacts on energy access of mitigation policies can be counteracted by government policies. As is stated in Cameron et al (2016)[55], "Policies that reduce stove costs shift more households to clean fuels per dollar invested than policies to reduce fuel costs. This is because, although stoves represent only a small share of the actual (levelized) cost of cooking with clean fuels, the high upfront costs of clean stoves represent a larger barrier to clean cooking uptake than fuel prices for many poor households." Therefore, as Figure 20 shows, the most cost-effective measures are stove subsidies, and with different levels of support, different results in clean fuel uptake can be observed. For universal access, fuel price support would have to increase to 55 and 65%, respectively, with and without climate policy (at C30). (Cameron et al, 2016 [55])

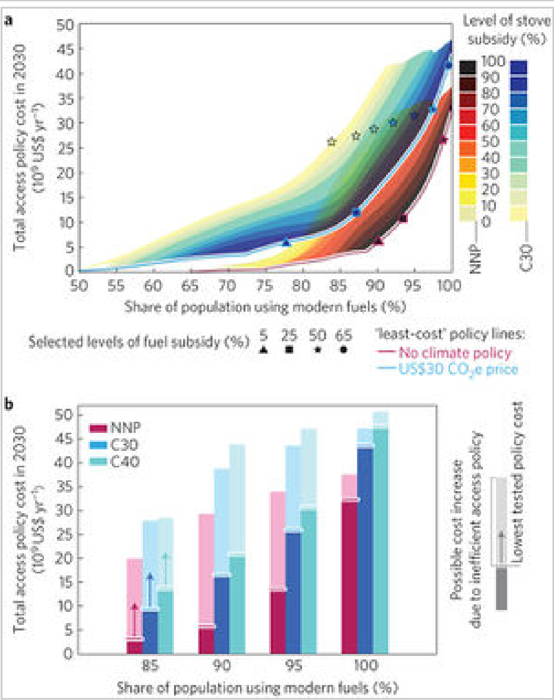

Figure 20: a, Fuel and stove price support combinations for the no climate policy (NNP) and US CO2e price (C30) scenario in 2030. Colours represent climate policy and stove price support level. Triangles, squares, stars and circles represent 5%, 25%, 50% and 65% fuel price support levels, respectively. An additional representation of fuel price support level can be viewed in Supplementary Fig. 11. 'Least-cost' policy lines are highlighted at the lower end of each of the areas by the cyan and magenta lines. b, Total access policy costs in 2030 for the achievement of an 85, 90, 95 and 100% share of population having access to modern fuels, respectively. Dark shaded bars show the lowest policy costs for the respective level of modern fuel access (corresponding to the level indicated by the 'least-cost' policy lines in a). Lighter shaded areas show the possible cost increase due to an inefficient access policy (illustrated by the arrows). Results are shown for the NNP, C30 and C40 scenarios. Figure from Cameron et al. (2016).

The impacts of climate and energy access policies will depend on the household income group. The urban poor and higher expenditure rural households (U1 and R2) are likely to be the most affected by climate policy, but they are also likely to benefit the most of access policies. See Figure 21 for more information. (Cameron et al, 2016 [55])

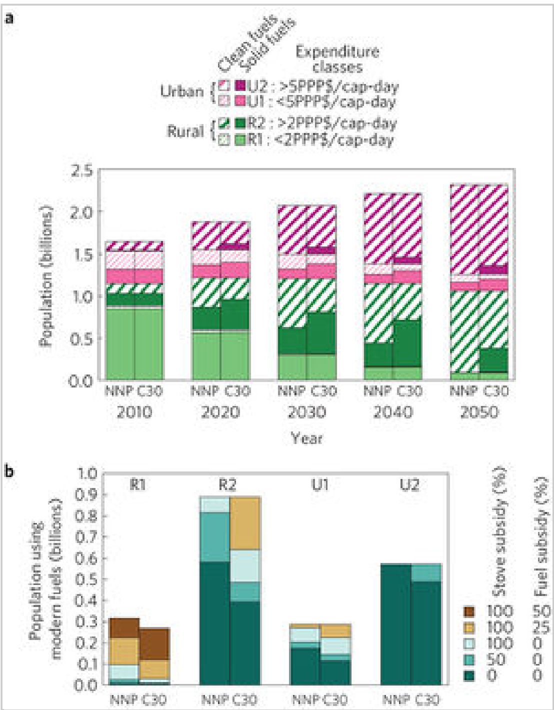

Figure 21: a, Solid and clean cooking in four population groups over time for the NNP and C30 scenarios in the absence of dedicated energy access policies such as fuel price or stove cost support. Population groups are divided according to rural and urban dwelling location and daily per-capita expenditure (under and over PPP per person per day for rural groups and PPP per person per day for urban groups). PPP, purchasing power parity. b, Impacts of selected stove cost and fuel price support polices on four expenditure groups in 2030 in the NNP and C30 scenarios. Figure from Cameron et al. (2016).

9) Appendices - MESSAGE-GLOBIOM

For information on the mathematical formulation of MESSAGE and MACRO, please visit IIASA's MESSAGE-GLOBIOM documentation (http://data.ene.iiasa.ac.at/message-globiom/message_globiom/annex/index.html).

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