message Documentation

Release 1.0

IIASA Energy Program

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These webpages document the IIASA Integrated Assessment Modeling (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. MESSAGE-GLOBIOM 1.0 was developed for the quantification of the so-called Shared Socio-economic Pathways (SSPs) which are the first application of the IAM framework.

This documentation is in part still under development and will be supplemented with additional information in certain sections.

When referring to MESSAGE-GLOBIOM 1.0 as described in this document, please use the following citations (Download ris, BibTeX):


The MESSAGE-GLOBIOM Integrated Assessment Model is based on the MESSAGEix framework, an open-source energy systems optimization modelling environment including macro-economic feedback using a stylized computable general equilibrium model. When referring to the software underpinning MESSAGE-GLOBIOM rather than the data or specific assessments, please use the following citation:


We thank Edward Byers, Jessica Jewell, Simon C. Parkinson, Narasimha D. Rao for their valuable comments that helped improving this manuscript.
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 central components. The five models provide input to and iterate between each other during a typical scenario development cycle. Below is a brief overview of how the models interact with each other, specifically in the context of developing the SSP scenarios.

MESSAGE (Huppmann et al., 2019 [44]) represents the core of the IIASA IAM framework (Fig. 1.1) 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, a single sector macro-economic model, which provides estimates of the macro-economic demand response that results from energy system and services costs computed by MESSAGE. For the six commercial end-use demand categories depicted in MESSAGE (see Energy demand), based on demand prices MACRO will adjust useful energy demands, until the two models have reached equilibrium (see Macro-economy (MACRO)). This iteration reflects price-induced energy efficiency adjustments that can occur when energy prices change.

GLOBIOM provides MESSAGE with information on land use and its implications, including the availability and cost of bioenergy, and availability and cost of emission mitigation in the AFOLU (Agriculture, Forestry and Other Land Use) sector (see Land-use (GLOBIOM)). To reduce computational costs, MESSAGE iteratively queries a GLOBIOM emulator which provides an approximation of land-use outcomes during the optimization process instead of requiring the GLOBIOM model to be rerun iteratively. Only once the iteration between MESSAGE and MACRO has converged, the resulting bioenergy demands along with corresponding carbon prices are used for a concluding analysis with the full-fledged GLOBIOM model. This ensures full consistency of the results from MESSAGE and GLOBIOM, and also allows producing a more extensive set of land-use related indicators, including spatially explicit information on land use.

Air pollution implications of the energy system are accounted for in MESSAGE by applying technology-specific air pollution coefficients derived from the GAINS model (see Air pollution). This approach has been applied to the SSP process (Rao et al., 2017 [96]). Alternatively, GAINS can be run ex-post based on MESSAGEix-GLOBIOM scenarios to estimate air pollution emissions, concentrations and the related health impacts. This approach allows analyzing different air pollution policy packages (e.g., current legislation, maximum feasible reduction), including the estimation of costs for air pollution control measures. Examples for applying this way of linking MESSAGEix-GLOBIOM and GAINS can be found in McCollum et al. (2018 [70]) and Grubler et al. (2018 [32]).
In general, cumulative global carbon emissions from all sectors are constrained at different levels, with equivalent pricing applied to other GHGs, to reach the desired radiative forcing levels (cf. right-hand side Fig. 1.1). 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 (MAGICC)), 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 – depending on the specific application – currently only partly 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 (Riahi et al., 2017 [107]).

The scientific software underlying the global MESSAGE-GLOBIOM model is called the MESSAGEix framework, an open-source, versatile implementation of a linear optimization problem, with the option of coupling to the computable general equilibrium (CGE) model MACRO to incorporate the effect of price changes on economic activity and demand for commodities and resources. MESSAGEix is integrated with the ix modeling platform (ixmp), a “data warehouse” for version control of reference timeseries, input data and model results. ixmp provides interfaces to the scientific programming languages Python and R for efficient, scripted workflows for data processing and visualisation of results (Huppmann et al., 2019 [44]).

Fig. 1.1: Overview of the IIASA IAM framework. Coloured boxes represent respective specialized disciplinary models which are integrated for generating internally consistent scenarios (Fricko et al., 2017 [27]).
1.1 Regions

The combined MESSAGE-GLOBIOM framework has global coverage and divides the world into 11 regions which are also the native regions of the MESSAGE model (see Fig. 1.2 and Table 1.1 below). GLOBIOM natively operates at the level of 30 regions which in the linkage to MESSAGE are aggregated to the 11 regions as listed in Table 1.2.

Fig. 1.2: Map of 11 MESSAGE-GLOBIOM regions including their aggregation to the four regions used in the Representative Concentration Pathways (RCPs).

The country definitions of the 11 MESSAGE regions are described in the table below (Table 1.1). In some scenarios, the MESSAGE region of FSU is disaggregated into four sub-regions resulting in a 14-region MESSAGE model.
Table 1.1: Listing of 11 regions used in MESSAGE-GLOBIOM, including their country definitions.

<table>
<thead>
<tr>
<th>Region</th>
<th>Definition</th>
<th>List of countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAM</td>
<td>North America</td>
<td>Canada, Guam, Puerto Rico, United States of America, Virgin Islands</td>
</tr>
<tr>
<td>WEU</td>
<td>Western Europe</td>
<td>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</td>
</tr>
<tr>
<td>PAO</td>
<td>Pacific OECD</td>
<td>Australia, Japan, New Zealand</td>
</tr>
<tr>
<td>EEU</td>
<td>Central and Eastern Europe</td>
<td>Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, The former Yugoslav Rep. of Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Yugoslavia, Estonia, Latvia, Lithuania</td>
</tr>
<tr>
<td>FSU</td>
<td>Former Soviet Union</td>
<td>Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan</td>
</tr>
<tr>
<td>CPA</td>
<td>Centrally Planned Asia and China</td>
<td>Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Viet Nam</td>
</tr>
<tr>
<td>SAS</td>
<td>South Asia</td>
<td>Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka</td>
</tr>
<tr>
<td>PAS</td>
<td>Other Pacific Asia</td>
<td>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</td>
</tr>
<tr>
<td>MEA</td>
<td>Middle East and North Africa</td>
<td>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</td>
</tr>
<tr>
<td>LAM</td>
<td>Latin America and the Caribbean</td>
<td>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</td>
</tr>
</tbody>
</table>
In addition to the 11 geographical regions, in MESSAGE there is a global trade region where market clearing of
global energy markets is happening and international shipping bunker fuel demand, uranium resource extraction and
the nuclear fuel cycle are represented.

Table 1.2: Listing of 30 regions used in GLOBIOM, including their
country definitions and the mapping to the 11 regions of the combined
MESSAGE-GLOBIOM model.

<table>
<thead>
<tr>
<th>11 MESSAGE regions</th>
<th>30 GLOBIOM regions</th>
<th>List of countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAM</td>
<td>Canada</td>
<td>Canada</td>
</tr>
<tr>
<td>USA</td>
<td>United States of America</td>
<td></td>
</tr>
<tr>
<td>WEU</td>
<td>EU_MidWest</td>
<td>Austria, Belgium, Germany, France, Luxembourg, Netherlands</td>
</tr>
<tr>
<td></td>
<td>EU_North</td>
<td>Denmark, Finland, Ireland, Sweden, United Kingdom</td>
</tr>
<tr>
<td></td>
<td>EU_South</td>
<td>Cyprus, Greece, Italy, Malta, Portugal, Spain</td>
</tr>
<tr>
<td>ROWE</td>
<td>Gibraltar, Iceland, Norway, Switzerland</td>
<td></td>
</tr>
<tr>
<td>Turkey</td>
<td>Turkey</td>
<td></td>
</tr>
<tr>
<td>PAO</td>
<td>ANZ</td>
<td>Australia, New Zealand</td>
</tr>
<tr>
<td></td>
<td>Japan</td>
<td>Japan</td>
</tr>
<tr>
<td>Pacific_Islands</td>
<td>Fiji Islands, Kiribati, Papua New Guinea, Samoa, Solomon Islands, Tonga, Vanuatu</td>
<td></td>
</tr>
<tr>
<td>EEU</td>
<td>EU_Baltic</td>
<td>Estonia, Latvia, Lithuania</td>
</tr>
<tr>
<td></td>
<td>EU_CentEast</td>
<td>Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia</td>
</tr>
<tr>
<td>RCEU</td>
<td>Albania, Bosnia and Herzegovina, Croatia, Macedonia, Serbia-Montenegro</td>
<td></td>
</tr>
<tr>
<td>FSU</td>
<td>Former_USSR</td>
<td>Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia</td>
</tr>
<tr>
<td>CPA</td>
<td>China</td>
<td>China</td>
</tr>
<tr>
<td></td>
<td>RSEA_PAC</td>
<td>Cambodia, Korea DPR, Laos, Mongolia, Viet Nam</td>
</tr>
<tr>
<td>SAS</td>
<td>India</td>
<td>India</td>
</tr>
<tr>
<td></td>
<td>RSAS</td>
<td>Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan, Sri Lanka</td>
</tr>
<tr>
<td>PAS</td>
<td>South_Korea</td>
<td>South Korea</td>
</tr>
<tr>
<td></td>
<td>RSEA_OPA</td>
<td>Brunei Daressalaam, Indonesia, Singapore, Malaysia, Myanmar, Philippines, Thailand</td>
</tr>
<tr>
<td>MEA</td>
<td>MidEastNAfr</td>
<td>Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Tunisia</td>
</tr>
<tr>
<td>LAM</td>
<td>Brazil</td>
<td>Brazil</td>
</tr>
<tr>
<td></td>
<td>Mexico</td>
<td>Mexico</td>
</tr>
<tr>
<td></td>
<td>RCAM</td>
<td>Bahamas, Barbados, Belize, Bermuda, Costa Rica, Cuba, Dominica, Dominican Republic</td>
</tr>
<tr>
<td></td>
<td>RSAM</td>
<td>Argentina, Bolivia, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname</td>
</tr>
<tr>
<td>AFR</td>
<td>Congo_Basin</td>
<td>Cameroon, Central African Republic, Congo Republic, Democratic Republic of Congo, Equatorial Guinea, Gabon, Congo (Kinshasa)</td>
</tr>
<tr>
<td></td>
<td>EasternAf</td>
<td>Burundi, Ethiopia, Kenya, Rwanda, Tanzania, Uganda</td>
</tr>
<tr>
<td></td>
<td>SouthAf</td>
<td>South Africa</td>
</tr>
<tr>
<td></td>
<td>RoSAfr</td>
<td>Angola, Botswana, Comoros, Lesotho, Madagascar, Malawi, Mauritius, Mozambique</td>
</tr>
<tr>
<td></td>
<td>WestCentAf</td>
<td>Benin, Burkina Faso, Cape Verde, Chad, Cote d’Ivoire, Djibouti, Eritrea, Gabon, Gambia</td>
</tr>
</tbody>
</table>

### 1.2 Time steps

MESSAGE models the time horizon 2010 to 2110 generally in 10-year periods (2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100, 2110), using 2010 as the base year. The 2020 period is partly calibrated so far, some recent trends are included in this time period, but some flexibility remains. 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. In some model versions, the model has been calibrated to 2015 running with 5-year modeling periods by the middle of the Century (2020, 2025, 2030, 2035, 2040, 2045, 2050, 2055, 2060) and 10-year periods between 2060 and 2110.

MESSAGE can both operate perfect foresight over the entire time horizon, limited foresight (e.g., two or three periods into the future) or myopically, optimizing one period at a time (Keppo and Strubegger, 2010 [57]) (see Mathematical...
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 [62]; O’Neill et al., 2010 [87]) limited foresight is used.

GLOBIOM models the time horizon 2000 to 2100 in 10 year time steps (2000, 2010, 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100) with the year 2000 being the base year of the model. The model is recursive-dynamic, i.e. it is solved for each period individually and then passes on results to the subsequent periods. The linkage between MESSAGE and GLOBIOM relies on the model results of the periods 2020 to 2100.
2.1 Behavioural change

With increasing affluence, consumers of final energy are more likely to demand technologies that are more convenient in their use, even if they cost more than less convenient energy forms. Examples of this empirically observed phenomenon are room heating with gas, electricity or district heat, which are more convenient than heating with coal. The affluent end-user does not like to fill up the coal furnace manually and is willing to pay more for a convenient technology. If MESSAGEix is to correctly reflect this phenomenon, the model’s cost-minimizing behavior must be modified accordingly. As a model feature to accomplish this task, the concept of inconvenience factors has been introduced in the definition of end-use technologies. The inconvenience factors are specified for each end-use technology, time period and world region. The cost entry in the objective function is calculated as the monetary costs, multiplied by the inconvenience factor. The inconvenience factors for a given world region increase with the level of affluence (GDP per capita) in this region. Flexible and grid-dependent energy technologies, such as electricity, gas and district heating have low inconvenience factors. A second mechanism for taking into account non-monetary decision criteria in the end-use sectors is the application of implicit discount rates which change perceived upfront investment costs by consumers. These two concepts are predominantly applied in the consumer dominated energy end-use sectors transportation (see Transport sector) and residential and commercial (see Residential and commercial sectors). Below, this is described in more detail for the MESSAGEix-Access model, an extension of MESSAGEix that focuses on residential energy services in developing countries which are characterized by high reliance on traditional fuels.

2.1.1 Behavioral change in MESSAGEix-Access

MESSAGEix-Access is a variant of the MESSAGEix model that provides a detailed representation of energy use for the residential sector in developing country regions. It is fully integrated with the MESSAGEix supply side model, but not in call scenarios is the the detailed demand-side representation used, but instead a more aggregated formulation with just seven demand categories is used (see Energy demand) which is parametrized off the detailed MESSAGEix-Access formulation. The objective function maximizes household utility by choosing an energy-equipment combination for an individual household group that meets a particular energy service demand at lowest cost. The model is calibrated with data on existing household energy use patterns, derived from national household surveys and energy statistics and balances for the base year 2005. Assumptions regarding urbanization, income growth and changes in income distributions over time drive the model outcomes in the future. In its current version the model is implemented
only for 3 of the 11 MESSAGEix regions (see Regions), SAS, PAS and AFR, that are developing regions where access to modern energy remains the most limited.

The model distinguishes between two primary energy end-uses in the residential sector – (1) thermal, largely cooking demand and (2) electricity demand for lighting and appliance use. Several alternative fuel and technology options can be specified in the model to meet each of these respective service demands. To reflect heterogeneity among consumers, the household or residential sector is further disaggregated into several sub-groups that distinguish among rural and urban households and five or more expenditure classes within the rural and urban sub-sectors (Figure 2.3).

The methodology for modeling energy choices in the residential sector of this model is described in detail in Ekholm et al. (2010) [19] and in the Supplementary Materials section of Pachauri et al. (2013) [88]. In addition to energy prices, technology costs and performance parameters, and income level of a household determining the least-cost energy-equipment combination that meets a specific energy need, two additional parameters determine choices in the model. The first is referred to as the “inconvenience cost”. An inconvenience cost is a cost related to the inconveniences associated with obtaining and using certain types of fuels. For example, gathering firewood involves an opportunity cost for the time spent in collecting it and a dis-utility to users from exposure to the smoke they inhale when it is combusted. This non-monetary cost is captured by estimating an inconvenience cost (see Ekholm et al. (2010) [19] for further details regarding the methodology) for each household group and fuel. This is considered an additional cost that must be taken into account by the household in making a decision regarding the choice of fuels. The second parameter that also determines energy choices for households is income dependent implicit discount rates that determine the annualized capital costs of equipment depending on their individual lifetimes.

![Figure 2.3: Split of residential energy demand into different spatial (urban/rural) and income (1-5) categories.](image)

### 2.2 SSP narratives

Narratives have been developed for the Shared Socioeconomic Pathways (SSPs) (O’Neill et al., 2015 [85]). These descriptions of alternative futures of societal development span a range of possible worlds that stretch along two climate-change-related dimensions: mitigation and adaptation challenges. The SSPs reflect five different developments of the world that are characterized by varying levels of global challenges (see Riahi et al., 2017 [107] for an overview). In the following, the three narratives that have been translated into quantitative scenarios with MESSAGE-GLOBIOM are presented (Fricko et al., 2017 [27]):
2.2.1 SSP1 Narrative: Sustainability — Taking the green road

“The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Increasing evidence of and accounting for the social, cultural, and economic costs of environmental degradation and inequality drive this shift. Management of the global commons slowly improves, facilitated by increasingly effective and persistent cooperation and collaboration of local, national, and international organizations and institutions, the private sector, and civil society. Educational and health investments accelerate the demographic transition, leading to a relatively low population. Beginning with current high-income countries, the emphasis on economic growth shifts toward a broader emphasis on human well-being, even at the expense of somewhat slower economic growth over the longer term. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Investment in environmental technology and changes in tax structures lead to improved resource efficiency, reducing overall energy and resource use and improving environmental conditions over the longer term. Increased investment, financial incentives and changing perceptions make renewable energy more attractive. Consumption is oriented toward low material growth and lower resource and energy intensity. The combination of directed development of environmentally friendly technologies, a favorable outlook for renewable energy, institutions that can facilitate international cooperation, and relatively low energy demand results in relatively low challenges to mitigation. At the same time, the improvements in human well-being, along with strong and flexible global, regional, and national institutions imply low challenges to adaptation.” (O’Neill et al., 2015 [85])

2.2.2 SSP2 Narrative: Middle of the Road

“The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceed unevenly, with some countries making relatively good progress while others fall short of expectations. Most economies are politically stable. Globally connected markets function imperfectly. Global and national institutions work toward but make slow progress in achieving sustainable development goals, including improved living conditions and access to education, safe water, and health care. Technological development proceeds apace, but without fundamental breakthroughs. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Even though fossil fuel dependency decreases slowly, there is no reluctance to use unconventional fossil resources. Global population growth is moderate and levels off in the second half of the century as a consequence of completion of the demographic transition. However, education investments are not high enough to accelerate the transition to low fertility rates in low-income countries and to rapidly slow population growth. This growth, along with income inequality that persists or improves only slowly, continuing societal stratification, and limited social cohesion, maintain challenges to reducing vulnerability to societal and environmental changes and constrain significant advances in sustainable development. These moderate development trends leave the world, on average, facing moderate challenges to mitigation and adaptation, but with significant heterogeneities across and within countries.” (O’Neill et al., 2015 [85])

2.2.3 SSP3 Narrative: Regional rivalry — A rocky road

“A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. This trend is reinforced by the limited number of comparatively weak global institutions, with uneven coordination and cooperation for addressing environmental and other global concerns. Policies shift over time to become increasingly oriented toward national and regional security issues, including barriers to trade, particularly in the energy resource and agricultural markets. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development, and in several regions move toward more authoritarian forms of government with highly regulated economies. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time, especially in developing countries. There are pockets of extreme poverty alongside pockets of moderate wealth, with many countries struggling to maintain living standards and provide access to safe water, improved sanitation, and health care for disadvantaged populations. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions. The combination of
impeded development and limited environmental concern results in poor progress toward sustainability. Population growth is low in industrialized and high in developing countries. Growing resource intensity and fossil fuel dependency along with difficulty in achieving international cooperation and slow technological change imply high challenges to mitigation. The limited progress on human development, slow income growth, and lack of effective institutions, especially those that can act across regions, implies high challenges to adaptation for many groups in all regions.” (O’Neill et al., 2015 [85])

2.3 Population and GDP

Population and economic developments have strong implications for the anticipated mitigation and adaptation challenges. For example, a larger, poorer and less educated population will have more difficulties to adapt to the detrimental effects of climate change (O’Neill et al., 2014 [86]). The primary drivers of future energy demand in MESSAGEix are projections of total population and GDP at purchasing power parity exchange rates, denoted as GDP (PPP). In addition to total population, the urban/rural split of population is relevant for the MESSAGEix-Access version of the model which distinguishes rural and urban population with different household incomes in developing country regions.

Understanding how population and economic growth develops in the SSPs gives a first layer of understanding of the multiple mitigation and adaptation challenges. 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 [55]). Gross Domestic Product (GDP) follows regional historical trends (Dellink et al., 2015 [15]). In SSP2, 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. 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, both the population and GDP developments in SSP2 are designed to be situated in the middle of the road between SSP1 and SSP3, see KC and Lutz (2015) [55], Dellink et al. (2015) [15] and Fricko et al. (2017) [27] for more details.

The full quantitative data set of demographic and economic projections for the SSPs can be found in an online database (SSP database).
The MESSAGEix modeling framework, briefly known as 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 primarily used for medium- to long-term energy system planning, energy policy analysis, and scenario development (Huppmann et al., 2019 [huppmann_message_2019]; Messner and Strubegger, 1995 [80]). 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 (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 (MACRO)) 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 the model. MESSAGE is used in conjunction with MAGICC (Model for Greenhouse gas Induced Climate Change) version 6.8 (cf. Section Climate (MAGICC)) 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 policies as well as diffusion rates of 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 full set of available energy conversion technologies. In MESSAGE terms, energy conversion technology refers to all types of energy technologies from resource extraction to transforma-
tion, 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:

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

Technologies can take in energy commodities from one level and put out at another level (e.g., refineries produce refined oil products at secondary level from crude oil at the primary level) or at the same level (e.g., hydrogen electrolyzers produce hydrogen at the secondary energy level from electricity at the secondary 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. Technology characteristics generally vary over time period.

The mathematical formulation of MESSAGE ensures that the flows are consistent: demand is met, inflows equal outflows and constraints are not exceeded. In other words, MESSAGE itself is a partial equilibrium model. However, through its linkage to MACRO general equilibrium effects are taken into account (cf. Section Macro-economy (MACRO)).

### 3.1 Energy resource endowments

#### 3.1.1 Fossil Fuel Reserves and Resources

The availability and costs of fossil fuels influences the future development 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 important. Our fossil energy resource assumptions in MESSAGE are derived from various sources, including global databases such as The Federal Institute for Geosciences and Natural Resources (BGR) and The U.S. Geological Survey (USGS), as well as market reports and outlooks provided by different energy institutes and agencies. The availability of fossil energy resources in different regions under different socio-economic assumptions are then aligned with the storylines of the individual SSPs (Rogner, 1997 [113]; Riahi et al., 2012 [102]).

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 3.1, Fig. 3.1). However, driven by the 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 (Fig. 3.1, the middle panel).

Table 3.1 shows the assumed total quantities of fossil fuel resources in the MESSAGE model for 2005. Fig. 3.1 gives these resource estimates as cumulative resource supply curves. In addition, the assumptions are compared with estimates from the Global Energy Assessment (Rogner et al., 2012 [112]) and the databases mentioned earlier. 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 the 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) [112].

Table 3.1: Assumed global fossil fuel reserves and resources in the MES-SAGE model. Estimates from the Global Energy Assessment (Rogner et al., 2012 [rogner_chapter_2012]) also added for comparison.

<table>
<thead>
<tr>
<th>Source</th>
<th>MESSAGE (Rogner et al., 1997 [113])</th>
<th>Rogner et al., 2012 [112]</th>
<th>Rogner et al., 2012 [112]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reserves+Resources [ZJ]</td>
<td>Reserves [ZJ]</td>
<td>Resources [ZJ]</td>
</tr>
<tr>
<td>Coal</td>
<td>259</td>
<td>17.3 – 21.0</td>
<td>291 – 435</td>
</tr>
<tr>
<td>Conventional Oil</td>
<td>9.8</td>
<td>4.0 – 7.6</td>
<td>4.2 – 6.2</td>
</tr>
<tr>
<td>Unconventional Oil</td>
<td>23.0</td>
<td>3.8 – 5.6</td>
<td>11.3 – 14.9</td>
</tr>
<tr>
<td>Conventional Gas</td>
<td>16.8</td>
<td>5.0 – 7.1</td>
<td>7.2 – 8.9</td>
</tr>
<tr>
<td>Unconventional Gas</td>
<td>23.0</td>
<td>20.1 – 67.1</td>
<td>40.2 – 122</td>
</tr>
</tbody>
</table>

The following table (Table 3.2) presents the ultimate fossil resource availability for coal, oil and gas, for SSP1, SSP2 and SSP3, respectively.

Table 3.2: Fossil resource availability for SSP1, SSP2, and SSP3 (Fricko et al., 2017 [fricko_marker_2017]).

<table>
<thead>
<tr>
<th>Type</th>
<th>SSP1 [ZJ]</th>
<th>SSP2 [ZJ]</th>
<th>SSP3 [ZJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>93</td>
<td>92</td>
<td>243</td>
</tr>
<tr>
<td>Oil</td>
<td>17</td>
<td>40</td>
<td>17</td>
</tr>
<tr>
<td>Gas</td>
<td>39</td>
<td>37</td>
<td>24</td>
</tr>
</tbody>
</table>

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 fastest depleting fossil fuel with 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.

Fig. 3.1 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 the 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 baseline scenarios.

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 evenly 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.

3.1. Energy resource endowments
Fig. 3.1: Cumulative global resource supply curves for coal (top), oil (middle), and gas (bottom) in the IIASA IAM framework (Fricko et al., 2017 [27]).
3.1.2 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. Fig. 3.2 below shows the levels of uranium resources assumed available in the MESSAGE SSP scenarios, building upon earlier work developed in the Global Energy Assessment (see Riahi et al., 2012 [102]). 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 [112], Section 7.5.2 for a more detailed discussion of uranium resources). Nuclear resources and fuel cycle are modeled at the global level.

Fig. 3.2: Global uranium resources in the MESSAGE interpretation of the SSPs compared to seven supply curves from a literature review (Schneider and Sailor, 2008 [122]). 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 [149]). 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).

3.1.3 Non-Biomass Renewable Resources

Table 3.3 shows the assumed total potentials of non-biomass renewable energy deployment (by resource type) in the MESSAGE model. In addition, the technical potential estimates are based on different sources, such as the U.S.
National Renewable Energy Laboratory database as described in the Global Energy Assessment (Rogner et al., 2012 [112]). 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). These constraints may lead to a significant reduction of the technical potential.

Table 3.3: Assumed global non-biomass renewable energy deployment potentials in the MESSAGE model. Estimates from the Global Energy Assessment (Rogner et al., 2012 [rogner_chapter_2012]) also added for comparison.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro</td>
<td>38</td>
<td>50 - 60</td>
</tr>
<tr>
<td>Wind (on-/offshore)</td>
<td>689/287</td>
<td>1250 - 2250</td>
</tr>
<tr>
<td>Solar PV</td>
<td>6064</td>
<td>62,000 - 280,000</td>
</tr>
<tr>
<td>CSP</td>
<td>2132</td>
<td>same as Solar PV above</td>
</tr>
<tr>
<td>Geothermal</td>
<td>23</td>
<td>810 - 1400</td>
</tr>
</tbody>
</table>

Notes: MESSAGE renewable energy potentials are estimated based on the methods explained in Pietzcker et al., 2014 [92], Eurek et al., 2017 [21], Christiansson, 1995 [12], and Rogner et al., 2012 [112]. 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 [112] 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, [92]) and Eurek et al. (2017) [21]. Regional resource potentials as implemented into MESSAGE are provided by region and capacity factor for solar PV, concentrating solar power (CSP), and on-shore/offshore wind in Johnson et al. (2016, [52]). The physical potential of these sources is assumed to be the same across all SSPs. Table 3.4, Table 3.5, Table 3.6, Table 3.8 show the resource potential for solar PV, CSP (solar multiples (SM) of 1 & 3), on- and offshore wind respectively. For wind, Table 3.7 and Table 3.9 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 Electricity).
Table 3.4: Resource potential (EJ) by region and capacity factor for solar photovoltaic (PV) technology (Johnson et al., 2016 [johnson_vre_2016]). For a description of each of the regions represented in the table, see Regions.

<table>
<thead>
<tr>
<th>Capacity Factor (fraction of year)</th>
<th>0.28</th>
<th>0.21</th>
<th>0.20</th>
<th>0.19</th>
<th>0.18</th>
<th>0.17</th>
<th>0.15</th>
<th>0.14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Potential (EJ)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AFR</td>
<td>0.0</td>
<td>1.1</td>
<td>46.5</td>
<td>176.6</td>
<td>233.4</td>
<td>218.2</td>
<td>169.9</td>
<td>61.9</td>
</tr>
<tr>
<td>CPA</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>10.3</td>
<td>19.4</td>
<td>31.5</td>
<td>15.9</td>
<td>41.9</td>
</tr>
<tr>
<td>EEU</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>FSU</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
<td>2.8</td>
<td>23.6</td>
<td>94.9</td>
<td>116.6</td>
</tr>
<tr>
<td>LAM</td>
<td>0.1</td>
<td>4.9</td>
<td>49.4</td>
<td>165.6</td>
<td>157.5</td>
<td>167.4</td>
<td>81.4</td>
<td>48.5</td>
</tr>
<tr>
<td>MEA</td>
<td>0.2</td>
<td>3.1</td>
<td>100.8</td>
<td>533.6</td>
<td>621.8</td>
<td>310.1</td>
<td>75.3</td>
<td>14.5</td>
</tr>
<tr>
<td>NAM</td>
<td>0.0</td>
<td>0.3</td>
<td>24.3</td>
<td>140.4</td>
<td>131.0</td>
<td>116.3</td>
<td>155.7</td>
<td>106.4</td>
</tr>
<tr>
<td>PAO</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>2.2</td>
<td>53.1</td>
<td>226.4</td>
<td>311.2</td>
<td>158.9</td>
</tr>
<tr>
<td>PAS</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
<td>0.8</td>
<td>17.0</td>
<td>31.2</td>
<td>12.8</td>
<td></td>
</tr>
<tr>
<td>SAS</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>WEU</td>
<td>0.0</td>
<td>0.1</td>
<td>0.2</td>
<td>3.0</td>
<td>12.8</td>
<td>39.4</td>
<td>58.3</td>
<td>33.5</td>
</tr>
<tr>
<td>Global</td>
<td>0.3</td>
<td>9.6</td>
<td>227.4</td>
<td>1074.7</td>
<td>1474.6</td>
<td>1516.3</td>
<td>1160.9</td>
<td>600.0</td>
</tr>
</tbody>
</table>

Table 3.5: 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., 2016 [johnson_vre_2016]).

<table>
<thead>
<tr>
<th>Capacity Factor (fraction of year)</th>
<th>SM1</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Potential (EJ)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AFR</td>
<td>0.0</td>
<td>3.6</td>
<td>19.0</td>
<td>81.6</td>
<td>106.7</td>
<td>62.8</td>
<td>59.6</td>
<td>37.8</td>
</tr>
<tr>
<td>CPA</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.3</td>
<td>11.5</td>
<td>53.0</td>
</tr>
<tr>
<td>EEU</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>FSU</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.4</td>
<td>6.1</td>
</tr>
<tr>
<td>LAM</td>
<td>0.0</td>
<td>2.0</td>
<td>7.0</td>
<td>11.8</td>
<td>29.3</td>
<td>37.1</td>
<td>56.8</td>
<td>53.5</td>
</tr>
<tr>
<td>MEA</td>
<td>0.1</td>
<td>3.7</td>
<td>24.8</td>
<td>122.4</td>
<td>155.3</td>
<td>144.5</td>
<td>68.4</td>
<td>34.0</td>
</tr>
<tr>
<td>NAM</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>6.3</td>
<td>19.7</td>
<td>20.2</td>
<td>29.6</td>
<td>43.2</td>
</tr>
<tr>
<td>PAO</td>
<td>0.0</td>
<td>3.0</td>
<td>75.1</td>
<td>326.9</td>
<td>158.3</td>
<td>140.4</td>
<td>40.2</td>
<td>10.2</td>
</tr>
<tr>
<td>PAS</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.6</td>
</tr>
<tr>
<td>SAS</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>3.9</td>
<td>8.7</td>
<td>16.1</td>
<td>9.8</td>
</tr>
<tr>
<td>WEU</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
<td>0.7</td>
<td>2.4</td>
<td>3.0</td>
</tr>
<tr>
<td>Global</td>
<td>0.1</td>
<td>12.3</td>
<td>126.0</td>
<td>549.2</td>
<td>473.3</td>
<td>434.8</td>
<td>285.0</td>
<td>251.3</td>
</tr>
</tbody>
</table>

3.1. Energy resource endowments
Table 3.6: Resource potential (EJ) by region and wind class for onshore wind (Johnson et al., 2016 [johnson_vre_2016]).

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

Table 3.7: Capacity factor by region and wind class for onshore wind (Johnson et al., 2016 [johnson_vre_2016]).

<table>
<thead>
<tr>
<th>Wind Class</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8+</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFR</td>
<td>0.24</td>
<td>0.28</td>
<td>0.32</td>
<td>0.36</td>
<td>0.40</td>
<td>0.45</td>
</tr>
<tr>
<td>CPA</td>
<td>0.24</td>
<td>0.28</td>
<td>0.32</td>
<td>0.36</td>
<td>0.38</td>
<td>0.45</td>
</tr>
<tr>
<td>EEU</td>
<td>0.24</td>
<td>0.27</td>
<td>0.31</td>
<td>0.36</td>
<td>0.38</td>
<td>0.45</td>
</tr>
<tr>
<td>FSU</td>
<td>0.24</td>
<td>0.28</td>
<td>0.31</td>
<td>0.35</td>
<td>0.38</td>
<td>0.45</td>
</tr>
<tr>
<td>LAM</td>
<td>0.24</td>
<td>0.28</td>
<td>0.32</td>
<td>0.36</td>
<td>0.39</td>
<td>0.46</td>
</tr>
<tr>
<td>MEA</td>
<td>0.24</td>
<td>0.27</td>
<td>0.32</td>
<td>0.35</td>
<td>0.39</td>
<td>0.45</td>
</tr>
<tr>
<td>NAM</td>
<td>0.24</td>
<td>0.28</td>
<td>0.31</td>
<td>0.36</td>
<td>0.39</td>
<td>0.45</td>
</tr>
<tr>
<td>PAO</td>
<td>0.24</td>
<td>0.28</td>
<td>0.32</td>
<td>0.36</td>
<td>0.40</td>
<td>0.43</td>
</tr>
<tr>
<td>PAS</td>
<td>0.24</td>
<td>0.27</td>
<td>0.32</td>
<td>0.35</td>
<td>0.40</td>
<td>0.45</td>
</tr>
<tr>
<td>SAS</td>
<td>0.24</td>
<td>0.27</td>
<td>0.32</td>
<td>0.36</td>
<td>0.39</td>
<td>0.42</td>
</tr>
<tr>
<td>WEU</td>
<td>0.24</td>
<td>0.28</td>
<td>0.32</td>
<td>0.36</td>
<td>0.39</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Table 3.8: Resource potential (EJ) by region and wind class for offshore wind (Johnson et al., 2016 [johnson_vre_2016]).

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

Biomass energy is another potentially important renewable energy resource in the MESSAGE 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 are derived from the GLOBIOM model and 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 (Fig. 3.3). 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., 2017 [27])

3.2 Energy conversion

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 air 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 technologies (e.g., nuclear power plants). Model input data reflecting this situation would be constraining the use of 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).
Fig. 3.3: Global bioenergy potential. Availability of bioenergy at different price levels in the MESSAGE-GLOBIOM model for the three SSPs (Fricko et al., 2017 [27]). Typically non-commercial biomass is not traded or sold, however in some cases there is a market – prices range from 0.1-1.5$/GJ (Pachauri et al., 2013 [88]) ($ equals 2005 USD).
• 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 CO2 or SO2 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.
• 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.

3.2.1 Electricity

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 technology variants with different efficiencies, environmental characteristics and costs are 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 desulphurization/denox and one internal gasification combined cycle (IGCC) power plant. The supercritical 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 3.10 below shows the different power plant types represented in MESSAGE.

Four different nuclear power plant types are represented in MESSAGE, 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 (see Table 3.10). 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 Renewable Resources and Systems Integration and Reliability). Two CSP technologies are modeled: (1) a flexible plant with a solar multiple of one (SM1) and 6 h of thermal storage and (2) a baseload plant with a solar multiple of three (SM3) and 12 h of storage (Johnson et al. 2016, [52]).

Most thermal power plants offer the option of coupled heat production (CHP, see Table 3.10). 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 section on *Other conversion*).

Table 3.10: List of electricity generation technologies represented in MESSAGE-GLOBIOM by energy source.

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Technology</th>
<th>CHP option</th>
</tr>
</thead>
<tbody>
<tr>
<td>coal</td>
<td>subcritical PC power plant without desulphurization/denox</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>subcritical PC power plant with desulphurization/denox</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>supercritical PC power plant with desulphurization/denox</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>supercritical PC power plant with desulphurization/denox and CCS</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>IGCC power plant</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>IGCC power plant with CCS</td>
<td>yes</td>
</tr>
<tr>
<td>oil</td>
<td>heavy fuel oil steam power plant</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>light fuel oil steam power plant</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>light fuel oil combined cycle power plant</td>
<td>yes</td>
</tr>
<tr>
<td>gas</td>
<td>gas steam power plant</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>gas combustion turbine gas</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>combined cycle power plant</td>
<td>yes</td>
</tr>
<tr>
<td>nuclear</td>
<td>nuclear light water reactor (Gen II)</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>nuclear light water reactor (Gen III+)</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>fast breeder reactor</td>
<td></td>
</tr>
<tr>
<td></td>
<td>high temperature reactor</td>
<td></td>
</tr>
<tr>
<td>biomass</td>
<td>biomass steam power plant</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>biomass IGCC power plant</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>biomass IGCC power plant with CCS</td>
<td>yes</td>
</tr>
<tr>
<td>hydro</td>
<td>hydro power plant (2 cost categories)</td>
<td>no</td>
</tr>
<tr>
<td>wind</td>
<td>onshore wind turbine</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>offshore wind turbine</td>
<td>no</td>
</tr>
<tr>
<td>solar</td>
<td>solar photovoltaics (PV)</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>concentrating solar power (CSP) with a solar multiple of 1 (SM1)</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>concentrating solar power (CSP) with a solar multiple of 3 (SM3)</td>
<td>no</td>
</tr>
<tr>
<td>geothermal</td>
<td>geothermal power plant</td>
<td>yes</td>
</tr>
</tbody>
</table>

In Fig. 3.4, 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 description of the *SSP narratives*). 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 (Fricko et al., 2017 [27]).

In Fig. 3.5, 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., 2017 [27]).

### 3.2.2 Heat

A number centralized district heating technologies based on fossil and renewable energy sources are represented in MESSAGE (see Table 3.11). Similar to coupled heat and power (CHP) technologies that are described in the *Electricity* sector, 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 the *Industrial sector* and *Residential and commercial sectors*. 
Fig. 3.4: Cost indicators for thermoelectric power-plant investment (Fricko et al., 2017 [27]).
Fig. 3.5: Cost indicators for non-thermoelectric power-plant investment (Fricko et al., 2017 [27]). Abbreviations: CCS – Carbon Capture and Storage; IGCC – Integrated gasification combined cycles; ST – Steam turbine; CT – Combustion turbine; CCGT – Combined cycle gas turbine
### 3.2.3 Other conversion

Beyond electricity and centralized heat generation there are three further subsectors of the conversion sector represented in MESSAGE, liquid fuel production, gaseous fuel production and hydrogen production. Fig. 3.6 provides an overview of the investment cost ranges for these conversion technologies. The black bars show historical cost ranges for 2005. Green, blue, and red bars 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.

#### Liquid Fuel Production

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 3.12). Different processes for coal liquefaction, gas-to-liquids technologies and 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 [63]). Technology costs for the synthetic liquid fuel production options are based on Larson et al. (2012) [63].

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Technology</th>
<th>Electricity cogeneration</th>
</tr>
</thead>
<tbody>
<tr>
<td>biomass</td>
<td>Fischer-Tropsch biomass-to-liquids</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>Fischer-Tropsch biomass-to-liquids with CCS</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>Gasoline via the Methanol-to-Gasoline (MTG) Process</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>Gasoline via the Methanol-to-Gasoline (MTG) Process with CCS</td>
<td>yes</td>
</tr>
<tr>
<td>coal</td>
<td>Fischer-Tropsch coal-to-liquids</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>Fischer-Tropsch coal-to-liquids with CCS</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>coal methanol-to-gasoline</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>coal methanol-to-gasoline with CCS</td>
<td>yes</td>
</tr>
<tr>
<td>gas</td>
<td>Fischer-Tropsch gas-to-liquids</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>Fischer-Tropsch gas-to-liquids with CCS</td>
<td>no</td>
</tr>
<tr>
<td>oil</td>
<td>simple refinery</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>complex refinery</td>
<td>no</td>
</tr>
</tbody>
</table>

#### Gaseous Fuel Production

Gaseous fuel production technologies represented in MESSAGE are gasification of solids including coal and biomass. In both cases carbon capture and storage (CCS) can be combined with the gasification process to capture to a good part the carbon that is not included in the synthetically produced methane. Table 3.13 provides a listing of all gaseous fuel production technologies.

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gasification of solids including coal and biomass</td>
</tr>
<tr>
<td></td>
<td>In both cases carbon capture and storage (CCS) can be combined with the gasification process to capture to a good part the carbon that is not included in the synthetically produced methane. Table 3.13 provides a listing of all gaseous fuel production technologies.</td>
</tr>
</tbody>
</table>
Fig. 3.6: Cost indicators for other conversion technology investment (Fricko et al., 2017 [27]). Abbreviations: CCS – Carbon capture and storage; CTL – Coal to liquids; GTL – Gas to liquids; BTL – Biomass to liquids.
Table 3.13: Gaseous fuel production technologies in MESSAGE by energy source.

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>biomass</td>
<td>biomass gasification</td>
</tr>
<tr>
<td>coal</td>
<td>coal gasification</td>
</tr>
</tbody>
</table>

Hydrogen Production

A number of hydrogen production options are represented in MESSAGE. These include gasification processes for coal and biomass, steam methane reforming from natural gas and hydrogen electrolysis. The fossil fuel and biomass based options can be combined with CCS to reduce carbon emissions. Table 3.14 provides a full list of hydrogen production technologies.

Table 3.14: Hydrogen production technologies in MESSAGE by energy source.

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Technology</th>
<th>Electricity cogeneration</th>
</tr>
</thead>
<tbody>
<tr>
<td>coal</td>
<td>coal gasification</td>
<td>yes</td>
</tr>
<tr>
<td>coal</td>
<td>coal gasification with CCS</td>
<td>yes</td>
</tr>
<tr>
<td>biomass</td>
<td>biomass gasification</td>
<td>yes</td>
</tr>
<tr>
<td>biomass</td>
<td>biomass gasification with CCS</td>
<td>yes</td>
</tr>
<tr>
<td>gas</td>
<td>steam methane reforming</td>
<td>yes</td>
</tr>
<tr>
<td>gas</td>
<td>steam methane reforming with CCS</td>
<td>no</td>
</tr>
<tr>
<td>electricity</td>
<td>electrolysis</td>
<td>no</td>
</tr>
</tbody>
</table>

3.2.4 Grid, Infrastructure and System Reliability

Energy Transmission and Distribution Infrastructure

Energy transport and distribution infrastructure is included in MESSAGE at a level relevant to represent the associated costs as well as transmission and distribution losses. Within individual model 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 explicitly represented in addition to the actual transport process.
Systems Integration and Reliability

The global MESSAGE model includes a single annual time period within each modeling year characterized by average annual load and 11 geographic regions. 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 mechanism to represent power system reliability in MESSAGE is based on (Sullivan et al., 2013 [134]). This method elevates the stylization of temporal resolution by introducing two concepts, peak reserve capacity and general-timescale flexibility (for mathematical representation see this Section). 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 Fig. 3.7 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.

![Fig. 3.7: Parameterization of Wind Capacity Value.](image)

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 conventional 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 combustion turbines 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 3.15 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 and ancilliary service requirements while hewing to generator and transmission operation limitations (Sullivan et al., 2013 [134]). Technologies that were not included in the unit-commitment model (nuclear, hydrogen electrolysis, solar PV) have estimated coefficients.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Flexibility Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>-0.1</td>
</tr>
<tr>
<td>Wind</td>
<td>-0.08</td>
</tr>
<tr>
<td>Solar PV</td>
<td>-0.05</td>
</tr>
<tr>
<td>Geothermal</td>
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</tr>
<tr>
<td>Nuclear</td>
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</tr>
<tr>
<td>Coal</td>
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</tr>
<tr>
<td>Biopower</td>
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<tr>
<td>Gas CC</td>
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</tr>
<tr>
<td>Hydropower</td>
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<tr>
<td>H2 Electrolysis</td>
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<td>Oil/Gas Steam</td>
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<tr>
<td>Gas CT</td>
<td>1</td>
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<tr>
<td>Electricity Storage</td>
<td>1</td>
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</table>

Thus, a technology like a natural gas combustion turbine, 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.
3.3 Energy end-use

MESSAGEix distinguishes three energy end-use sectors, i.e. transport, residential/commercial (also referred to as the buildings sector) and industry. Given the long-term nature of the scenarios, the model version used for the SSPs, represents these end-use sectors in a stylized way. For more detailed short-term analysis, a model version with a more detailed transport sector module that distinguishes different transport modes, vehicle classes and consumer types exists (McCollum et al., 2016 [71]).

3.3.1 Transport sector

The most commonly applied MESSAGEix transport sector representation is stylized and essentially includes fuel switching and price-elastic demands (via MACRO linkage) as the main responses to energy and climate policy (see Fig. 3.8).

In this stylized transport sector representation fuel switching is a key option to reduce emissions, 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 demand). 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 Fig. 3.8 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 speed of alternative fuels is limited to mimic bottlenecks in the supply chains, not explicitly represented in MESSAGEix (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.

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.

\texttt{tab-trans} presents the quantitative translation of the storyline elements of SSP1, SSP2 and SSP3 in terms of electrification rate for transport (Fricko et al., 2017 [27]).

3.3.2 Residential and commercial sectors

The residential and commercial sector in MESSAGEix 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).

The 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 Fig. 3.9 below).
Fig. 3.8: Schematic diagram of the stylized transport sector representation in MESSAGEix.
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 and on-site 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, as in the transport sector, the diffusion speed of alternative fuels is limited to mimic bottlenecks in the supply chains, not explicitly represented in MESSAGEix (e.g., non-energy related infrastructure).

Table 3.16 presents the quantitative translation of 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., 2017 [27]).
Table 3.16: Electrification rate within the residential and commercial sectors for SSP1, SSP2 and SSP3 (Fricko et al., 2017 [fricko_marker_2017])

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<thead>
<tr>
<th></th>
<th>SSP1</th>
<th>SSP2</th>
<th>SSP3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential &amp; Com-</td>
<td>High electrification rate: 1.44% (Regional range from 0.35% to 4%)</td>
<td>Medium electrification rate: 1.07% (Regional range from 0.23% to 3%)</td>
<td>Low electrification rate: 0.87% (Regional range from 0.37% to 2%)</td>
</tr>
<tr>
<td>mercial</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3.3.3 Industrial sector

Similar to the residential and commercial sectors, the industrial sector in MESSAGEix 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 Fig. 3.10 below). The specific industrial demand can be satisfied either by electricity from the grid or with decentralized electricity generation options such as fuel cells and on-site CHP.

While cement production is not explicitly modeled at the process level in MESSAGEix, the amount of cement production is linked to industrial activity (more specifically the industrial thermal demand in MESSAGEix) and the associated CO2 emissions from the calcination process are accounted for explicitly. In addition, adding carbon capture and storage to mitigate these process-based CO2 emission is available.

Table 3.17 presents the quantitative translation of 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., 2017 [27]).

Table 3.17: Electrification rate within industry and feedstocks for SSP1, SSP2 and SSP3 (Fricko et al., 2017 [fricko_marker_2017])

<table>
<thead>
<tr>
<th></th>
<th>SSP1</th>
<th>SSP2</th>
<th>SSP3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industry</td>
<td>High electrification rate: 0.56% (Regional range from 0.2% to 1.2%)</td>
<td>Medium electrification rate: 0.47% (Regional range from 0.07% to 1.08%)</td>
<td>Low electrification rate: 0.12% (Regional range from -0.03% to 0.71%)</td>
</tr>
<tr>
<td>Feedstock</td>
<td>High feedstock reduction rate: -0.33% (Regional range from -0.51 to 0.59%)</td>
<td>Medium feedstock reduction rate: -0.27% (Regional range from -0.45 to 0.64%)</td>
<td>Low feedstock reduction rate: -0.24% (Regional range from -0.38 to 0.51%)</td>
</tr>
</tbody>
</table>

### 3.4 Technological change

Technological change in MESSAGE is generally treated exogenously, although pioneering works on the endogenization of technological change via learning curves in energy-engineering type models (Messner, 1997 [78]) and the dependence of technology costs on market structure have been done with MESSAGE (Leibowitz, 2015 [65]). The
Fig. 3.10: Schematic diagram of the industrial sector representation in MESSAGEix.
current cost and performance parameters, including conversion efficiencies and emission coefficients are generally
derived from the relevant engineering literature. For the future, alternative cost and performance projections are de-
veloped to cover a relatively wide range of uncertainties that influence model results to a good extent.

3.4.1 Technology cost

The quantitative assumptions about technology cost development are derived from the overarching qualitative SSP
narratives (cf. section SSP 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 renewable
energy technologies 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 (e.g., coal-
to-liquids). 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. The regional differentiation of technology costs for the initial modeling
periods are based on IEA data (IEA, 2014 [45]) with convergence of costs assumed over time driven by economic
development (GDP/cap). 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 [102]) and World Energy Outlook (IEA,
2014 [3]). A summary of these cost assumptions can be found in sections Electricity and Other conversion.

3.4.2 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 con-
straints. 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 [80], cf. section 2.2.2 Dynamic Constraints on Activity and
Construction Variables).

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 rapid 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 [57]). 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.

Fig. 3.11 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.

For a more detailed description of the implementation of technology diffusion constraints, see the Annex Section 2
Conversion Technologies.
Fig. 3.11: 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.
3.5 Fuel Blending

Fuel blending in the energy system is a common practice, which allows the shared use of infrastructure by fuels with similar chemical attributes and thus use at the secondary and final energy level, without requiring the consumer to adapt the power plant or enduse devices. Fuel blending in the global energy model is modelled for two distinct blending processes. The first relates to the blending of natural gas with other synthetic gases. The second is related to the blending of light oil with coal derived synthetic liquids. In order to ensure that emissions and energy flows are correctly accounted for, blended fuels types are nevertheless explicitly modelled.

3.5.1 Natural gas and synthetic gas

Natural gas can be blended with hydrogen or with synthetic gas derived from the gasification of biomass or coal (cf. Section Other conversion). Despite the fact that in the real world, hydrogen or other synthetic gases are physically injected into a natural gas network, it is important to be able to track the use of blended fuels in the energy model for two reasons. Not all blended fuels can be used equally within all natural gas applications. For example, hydrogen mixed into the natural gas network is restricted to use in non-CCS applications only. Secondly, it is essential to keep track of where which of the blended fuels is being used in order to correctly report emissions and also to potentially restrict the degree to which fuels can be blended for individual applications. For example, natural gas end-use appliances may only be able to cope with a certain share of hydrogen while still guaranteeing their safety and longevity. Similarly, for policy analysis, it could be required that a certain minimum share of a synthetic gas is used sector specifically.

![Excerpt of Reference Energy System](image)

Fig. 3.12: Reference Energy System excerpt depicting the modelling of fuel blending.

3.5.2 Synthetic liquids and lightoil

Synthetic fuel oil via coal liquefaction is blended into the light oil stream at the secondary energy level.
3.6 Add-on technologies

Add-on technologies in the global model refer to a distinct formulation in MESSAGEix. The formulation is used to represent two main types of technical extensions/options for technologies. Add-on technologies provide additional modes of operation for a single or multiple technologies. They can also be used to depict emission mitigation options.

3.6.1 General description of add-on technologies

Add-on technologies can be defined using all the same parameters as any other technology. What makes a technology an add-on technology, is the fact that their activity is bound to the activity of one or more other technologies, henceforth referred to as the parent technology. The mathematical formulation can be found here. One of the main benefits of the add-on technology formulation, over specifying an alternative mode, is that it allows a single add-on technology to be coupled to the activity of multiple parent technologies. Furthermore, multiple add-on technologies can be linked to the activity of a single parent technology.

3.6.2 Modelling Combined Heat Powerplants (CHPs)

In the global model, there are numerous electricity generation technologies (cf. Section Electricity). A separate technology, known as a pass out turbine, is represented in the model to provide select electricity generation technologies the option to reduce their electricity output in favor of generating electricity and heat. The pass out turbine, which is a steam turbine in which a certain amount of the pressurized steam is passed out of the turbine for the purpose of heat production, is restricted to a share of the activity of the selected electricity generation technologies. Technically, this means that the electricity output of the electricity generation technologies remains unaltered, yet each unit of heat generated by the pass out turbine, requires a certain electricity input. The figure below is an excerpt of the Reference Energy System (RES), showing how the pass-out turbine is modelled.

3.6.3 Modelling emission mitigation options using add-on technologies

CO2 emission mitigation options for electricity and synthetic fuel generation can be modelled either as green-field power plants with carbon, capture and storage capabilities (CCS), but there is also the possibility to retrofit existing fossil fuel based energy generation technologies with CCS units. The latter, which is less efficient than the greenfield option, but an effective transition option to minimize stranded assets in deep mitigation scenarios, is modelled using the add-on technology formulation. Analogue to the way in which CHPs are modelled, a separate CCS-retrofit unit is depicted in the model, which is constrained by the activity of the respective parent technologies. The CCS-retrofit option requires electricity as an input, therefore mimicking the efficiency reduction associated with the operation of the CCS-retrofit unit. Per unit of activity of the CCS-retrofit, CO2 emissions are reduced, which differ depending on the assumed capture rates. CCS-retrofits are available for: coal power plants including internal gasification combined cycle plants (IGCC), select gas power plants, biomass power plants, gas and coal fuel cells as well as for hydrogen and cement production.

In the global model, emission mitigation options are modelled using add-on technologies for several other emission sources. N2O emissions from nitric and adipic acid are driven by industrial GDP and CH4 landfill emissions are driven by population (Rao and Riahi, 2006 [99]). As both GDP and population are model inputs, the developments for these specific sources are therefore not endogenous to the model. Similarly, HFC and SF6 emissions are linked to specific useful energy demands, which are again a model input, and electricity transmission, respectively. In order to provide mitigation options for these emissions sources, depending on the source, one or several mitigation options are modelled. For each source, the combined activity and therefore the mitigation is coupled to the activity of the parent technology. The share of the total emissions which can be reduced is limited to the technical feasibility and the combination of which mitigation technologies are employed are economically driven.
3.7 Energy demand

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

These demands are generated using a so-called scenario generator which is implemented in the script language R. The scenario generator relates historical country-level GDP per capita (PPP) to final energy and, using projections of GDP (PPP) and population, 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 [150])
4. Projected GDP (PPP) – Dellink et al. (2015) [15], also see Shared Socio-Economic Pathways database (SSP scenarios)

5. Projected Population – KC and Lutz (2014) [55], also see Shared Socio-Economic Pathways database (SSP scenarios)

The scenario generator runs regressions on the historical datasets to establish the relationship for each of the eleven MESSAGE regions between the independent variable (GDP (PPP) per capita) and the following dependent variables:

1. Total final energy intensity (MJ/2005USD)
2. Shares of final energy among several energy end-use sectors (transport, residential/commercial and industry)
3. Shares of electricity use between the industrial and residential/commercial 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 Schafer (2005) [120].

In parallel, the same historical data are used, now globally, in quantile regressions to develop global trend lines that represent each percentile of the cumulative distribution function (CDF) of each dependent 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.

A basic assumption here is that the regional trends derived above will converge to certain quantiles of the global trend when each region reaches a certain income level. Hence, two key user-defined inputs allow users to tailor the extrapolations to individual socio-economic scenarios: convergence quantile and the corresponding income. 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 within the global trend) 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 3.18, Table 3.19, Table 3.20. 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, users 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, users 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 used in the MESSAGE model for each model region (Regions).
Table 3.18: Convergence quantile and income for each quantity and region for SSP1 (for region descriptions, see: Regions)

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<th>AFR</th>
<th>CPA</th>
<th>EEU</th>
<th>FSU</th>
<th>LAM</th>
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Table 3.19: Convergence quantile and income for each quantity and region for SSP2 (for region descriptions, see: Regions)

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### 3.8 Modelling policies

The global energy model distinguishes between eleven global regions (cf. Section Regions). It is nevertheless important to represent current and planned national policies - such as the nationally determined contributions (NDCs) as agreed upon in the Paris Agreement - at a lower geographical resolution, in order to be able to adequately account for future changes in the scenario development processes.

#### 3.8.1 Representation of single country Nationally Determined Contributions (NDCs)

The targets formulated in the NDCs come in many different flavors. This applies to the sectors and gases covered by these policies:

1. Emission targets
2. Energy shares
3. Capacity or generation targets
4. Macro-economic targets

A detailed description of the methodological implementation of the NDCs in the global energy model, along with an extensive list of the energy-related targets considered can be found in Rogelj et al. (2017) [108].

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| **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 | 59835 | 61426 | 61426 | 61426 | 61426 | 61426 | 61426 | 61426 |
| Share Industry | 5981 | 5981 | 5981 | 5981 | 5981 | 5981 | 5981 | 5981 | 5981 | 5981 | 5981 |
| Elec Share Res/Com | 80976 | 80976 | 80976 | 80976 | 80976 | 80976 | 80976 | 80976 | 80976 | 80976 | 80976 |
| Feedstock Share Industry | 19935 | 26294 | 80927 | 80980 | 80953 | 80953 | 80953 | 80953 | 80953 | 80953 | 80953 |
| Elec Share Industry | 200009 | 200033 | 200000 | 200044 | 199975 | 200027 | 200109 | 199995 | 199968 | 200002 | 199977 |
3.8.2 Emission targets

Country-specific emission reduction targets are specified either in relation to historical emissions (e.g. \(x\%\) reduction compared to 1990) or in relation to a reference emission trajectory (in the form of a baseline or business as usual scenario (BAU); e.g. \(x\%\) reduction compared to 2030 emission levels in the baseline). The targets themselves are expressed as either (1) absolute reduction, (2) a percentage reduction or (3) intensity reductions e.g. emissions per GDP or per capita. In order to account for these different reduction targets in the global energy model, the targets are translated so that a regionally specific upper bound on emissions can be formulated. If not further specified, emission constraints are assumed to apply to all sectors and all gases, i.e. total GHGs.

3.8.3 Energy shares

Energy share targets refer to any target which aims to provide a specific energy level (e.g. primary, secondary or final energy) through a specific sub-set of energy forms. The five different forms in which these are formulated in the NDCs are: (1) renewable energy as share of total primary energy, (2) non-fossil energy forms as share of total primary energy, (3) renewable energy as a share of total electricity generation, (4) non-fossil energy as a share of total electricity generation, (5) renewable energy as a form of final energy. All of these share constraint variants can be implemented in the model using the following mathematical formulation. In order to be able to implement these for aggregate regions, it is necessary to harmonize these to single type of share constraint, so that their effects are considered cumulatively within a region. All variants are therefore harmonized to either the share type specified by the largest country, in terms of share of energy within a region, or the most frequently specified type within a region. Separately biofuel shares are implemented specifically for the transport sector.

3.8.4 Capacity and generation targets

Some NDCs specify capacity installation targets, e.g. for planned power plants which will be operational by a certain year. Others specify that a given energy commodity will come from a specific source, for example a certain amount of electricity will stem form a specific intermittent renewable source or nuclear. These targets types are implemented in the model as lower bounds on generation.

3.8.5 Representation of taxes and subsidies

Another set of policies addressed as part of climate change analysis, are energy-related taxes and subsidies. Removing fossil fuel subsidies could help reduce emissions by discouraging the use of inefficient energy forms. In the global energy model, fossil fuel prices are endogenously derived based on underlying supply curves representing the technical costs associated with the extraction of the resources (cf. Section Fossil Fuel Reserves and Resources). Refining and processing as well as transmission and distribution costs will be added to the total fuel cost. In order to account for taxes, price adjustment factors are applied, based on the underlying data set as described in Jewell et al. (2018) [50].
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 [68]), a predecessor of the MERGE model. The reason for linking the two models is to consistently reflect the influence of energy supply costs, as calculated by MESSAGE, 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 [79]) can generate a consistent economic response to changes in energy prices and estimate overall economic consequences (e.g., changes in GDP or household consumption) 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 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. End-use service demands in the (commercial) demand categories of MESSAGE (see Energy demand) is determined within the MACRO model, and is consistent with energy supply from MESSAGE, which is an input to the MACRO. 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, i.e. the so-called autonomous energy efficiency improvement (AEEI) coefficients. The latter are 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, for example induced by energy or climate policies, 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 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 (of energy use and imports) and revenues (from 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, the data exchange from MESSAGE to MACRO may also include the revenues or costs of trade in GHG permits.

For a more elaborate description of MACRO’s system of equations please consult the MACRO section of the MESSAGEix documentation. Details on the implementation of MACRO, its parameterization and the calibration procedure can be found in the Implementation: MACRO.
Land-use dynamics are modelled with the GLOBIOM (GLobal BIOsphere Management) model, which is a partial-equilibrium model (Havlik et al., 2011 [36]; Havlik et al., 2014 [37]). GLOBIOM represents the competition between different land-use based activities. It includes a detailed 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. 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 [61]; Kindermann et al., 2008 [59]; Gusti, 2010 [33]). The spatially explicit G4M model compares the income of 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.

As a partial equilibrium model representing land-use based activities, including agriculture, forestry and bioenergy sectors (see Fig. 5.1), production adjusts to meet the demand at the level of 30 economic regions (see list of the regions in Section 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 [135]; Schneider, McCarl et al., 2007 [123]). 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 [69]). As in other partial equilibrium models, prices are endogenous. The model is run recursively dynamic with a 10 year time step, going from 2000 to 2100. The model is solved using a linear programming solver and can be run on a personal computer with the GAMS software.

### 5.1 Spatial resolution

Land resources and their characteristics are the fundamental elements of the GLOBIOM modelling approach. In order to enable global bio-physical process modelling of agricultural and forest production, a comprehensive database has been built (Skalsky et al., 2008 [127]), which contains geo-spatial data on soil, climate/weather, topography, land cover/use, and crop management (e.g. fertilization, irrigation). The data were compiled from various sources (FAO, ISRIC, USGS, NASA, CRU UEA, JRC, IFRPI, IFA, WISE, etc.) and significantly vary with respect to spatial, temporal, and attribute resolutions, thematic relevance, accuracy, and reliability. Therefore, data were harmonized
Fig. 5.1: GLOBIOM land use and product structure.
into several common spatial resolution layers including 5 and 30 Arcmin as well as country layers. Subsequently, Homogeneous Response Units (HRU) have been delineated by geographically clustering according to only those parameters of the landscape, which are generally not changing over time and are thus invariant with respect to land use and management or climate change. At the global scale, five altitude classes, seven slope classes, and five soil classes have been included.

In a second step, the HRU layer is intersected with a 0.5 x 0.5 degree grid and country boundaries to delineate Simulation Units (SimUs) which contain other relevant information such as global climate data, land category/use data, irrigation data, etc. In total, 212,707 SimUs are delineated by clustering 5 x 5 minutes of arc pixels according to five criteria: altitude, slope, and soil class, 0.5 x 0.5 degrees grid, and the country boundaries. The SimUs are the basis for estimation of land use/management parameters in all other supporting models as well. For each SimU a number of land management options are simulated using the bio-physical process model EPIC (Environmental Policy Integrated Climate) (Izaurralde et al., 2006 [49]; Williams and Singh, 1995 [144]). For the SSP application of GLOBIOM, in order to ease computation time, the input data sets and the model resolution were aggregated to 2 x 2 degree cells disaggregated only by country boundaries and by three agro-ecological zones used in the livestock production system classification: arid, humid, temperate and tropical highlands. This led to a total of 10,894 different Supply Units.

5.2 Crop production

GLOBIOM directly represents production from three major land cover types: cropland, managed forest, and areas suitable for short rotation tree plantations. Crop production accounts for more than 30 of the globally most important crops. The average yield level for each crop in each country is taken from FAOSTAT. Management related yield coefficients according to fertilizer and irrigation rates are explicitly simulated with the EPIC model (Williams and Singh, 1995 [144]) for 17 crops (barley, dry beans, cassava, chickpea, corn, cotton, ground nuts, millet, potatoes, rapeseed, rice, soybeans, sorghum, sugarcane, sunflower, sweet potatoes, and wheat). These 17 crops together represent nearly 80 % of the 2007 harvested area and 85% of the vegetal calorie supply as reported by FAOSTAT. Four management systems are considered (irrigated, high input - rainfed, low input - rainfed and subsistence management systems) corresponding to the International Food and Policy Research Institute (IFPRI) crop distribution data classification (You and Wood, 2006 [146]). Within each management system, input structure is fixed following a Leontieff production function. But crop yields can change in reaction to external socio-economic drivers through switch to another management system or reallocation of the production to a more or less productive Supply Unit. Besides the endogenous mechanisms, an exogenous component representing long-term technological change is also considered. Only two management systems are differentiated for the remaining crops (bananas, other dry beans, coconuts, coffee, lentils, mustard seed, olives, oil palm, plantains, peas, other pulses, sesame seed, sugar beet, and yams) – rainfed and irrigated. Rainfed and irrigated crop yield coefficients, and crop specific irrigation water requirements for crops not simulated with EPIC, and costs for four irrigation systems for all crops, are derived from a variety of sources as described in Sauer et al. (2008) [119]. Crop supply can enter one of three processing/demand channels: consumption, livestock production and biofuel production (see Fig. 5.1).

5.3 Livestock

5.3.1 Livestock population

The principal variable characterizing the livestock production in GLOBIOM is the number of animals by species, production system and production type in each Simulation Unit. GLOBIOM differentiates four species aggregates: cattle and buffaloes (bovines), sheep and goats (small ruminants), pigs, and poultry. Eight production systems are specified for ruminants: grazing systems in arid (LGA), humid (LGH) and temperate/highland areas (LGT); mixed systems in arid (MXA), humid (MXH) and temperate/highland areas (MXT); urban systems (URB); and other systems (OTH). Mixed systems are an aggregate of the more detailed original Sere and Steinfeld’s classes (Sere and Steinfeld, 1996 [126]) – mixed rainfed and mixed irrigated. Two production systems are specified for monogastrics: smallholders
(SMH) and industrial systems (IND). In terms of production type, dairy and meat herds are modeled separately for ruminants: dairy herd includes adult females and replacement heifers, whose diets are distinguished. Poultry in smallholder systems is considered as mixed producer of meat and eggs, and poultry in industrial systems is split into laying hens and broilers, with differentiated diet regimes. Overall livestock numbers at the country level are, where possible while respecting minimum herd dynamics rules, harmonized with FAOSTAT.

The spatial distribution of ruminants and their allocation between production systems follows an updated version of Wint and Robinson (Wint and Robinson, 2007 [145]). Since better information is not available, it is assumed that the share of dairy and meat herds within one region is the same in all production systems. The share is obtained from the FAO country level data about milk producing animals and total herd size. Monogastrics are not treated in a spatially explicit way since no reliable maps are currently available, and because monogastrics are not linked in the model to specific spatial features, like grasslands. The split between smallholder and industrial systems follows Herrero et al. (2013) [38].

5.3.2 Livestock products

Each livestock category is characterized by product yield, feed requirements, and a set of direct GHG emission coefficients. On the output side, seven products are defined: bovine meat and milk, small ruminant meat and milk, pig meat, poultry meat, and eggs. For each region, production type and production system, individual productivities are determined.

Bovine and small ruminant productivities are estimated through the RUMINANT model (Herrero et al., 2008 [39]; Herrero et al., 2013 [38]), in a three steps process which consists of first, specifying a plausible feed ration; second, calculating in RUMINANT the corresponding yield; and finally confronting at the region level with FAOSTAT (Supply Utilization Accounts) data on production. These three steps were repeated in a loop until a match with the statistical data was obtained. Monogastrics productivities were disaggregated from FAOSTAT based on assumptions about potential productivities and the relative differences in productivities between smallholder and industrial systems. The full detail of this procedure is provided in Herrero et al. (2013) [38].

Final livestock products are expressed in primary commodity equivalents. Each product is considered as a differentiated good with a specific market except for bovine and small ruminant milk that are merged in a single milk market. The two milk types are therefore treated as perfect substitutes.

5.3.3 Livestock feed

Feed requirements for ruminants are computed simultaneously with the yields (Herrero et al., 2013 [38]). Specific diets are defined for the adult dairy females, and for the other animals. The feed requirements are first calculated at the level of four aggregates – grains (concentrates), stover, grass, and other. When estimating the feed-yield couples, the RUMINANT model takes into account different qualities of these aggregates across regions and systems. Feed requirements for monogastrics are at this level determined through literature review presented in Herrero et al. (2013) [38]. In general, it is assumed that in industrial systems pigs and poultry consume 10 and 12 kg dry matter of concentrates per TLU and day, respectively, and concentrates are the only feed sources. Smallholder animals get only one quarter of the amount of grains fed in industrial systems, the rest is supposed to come from other sources, like household waste, not explicitly represented in GLOBIOM.

The aggregate GRAINS input group is harmonized with feed quantities as reported at the country level in Commodity Balances of FAOSTAT. The harmonization proceeds in two steps, where first, GRAINS in the feed rations are adjusted so that total feed requirements at the country level match with total feed quantity in Commodity Balances, and second, “Grains” is disaggregated into 11 feed groups: Barley, Corn, Pulses, Rice, Sorghum & Millet, Soybeans, Wheat, Cereal Other, Oilseed Other, Crops Other, Animal Products. The adjustment of total GRAINS quantities is first done through shifts between the GRAINS and OTHER categories in ruminant systems. Hence, if total GRAINS are lower than the statistics, a part or total feed from the OTHER category is moved to GRAINS. If this is not enough, all GRAINS requirements of ruminants are shifted up in the same proportions. If total GRAINS are higher than the statistics, then firstly a part of them must be reallocated to the OTHER category. If this is not enough, values are to be kept, which
then results in higher GRAINS demand than reported in FAOSTAT. This inconsistency is overcome in GLOBIOM, by creating a “reserve” of the missing GRAINS. This reserve is in simulations kept constant, thus it enables to reproduce the base year activity levels mostly consistent with FAOSTAT, but requires that all additional GRAINS demand arising over the simulation horizon is satisfied from real production. The decomposition of GRAINS into the 11 subcategories has to follow predefined minima and maxima of the shares of feedstuffs in a ration differentiated by species and region. At the same time, the shares of the feedstuffs corresponding to country level statistics need to be respected. This problem is solved as minimization of the square deviations from the prescribed minimum and maximum limits. In GLOBIOM, the balance between demand and supply of the crop products entering the GRAINS subcategories needs to be satisfied at regional level. Substitution ratios are defined for the byproducts of biofuel industry so that they can also enter the feed supply.

STOVER is supposed less mobile than GRAINS, therefore stover demand in GLOBIOM is forced to match supply at grid level. The demand is mostly far below the stover availability. In the cells where this is not the case, the same system of reserve is implemented as for the grains. No adjustments are done to the feed rations as such.

There are unfortunately no worldwide statistics available on either consumption or production of grass. Hence grass requirements were entirely based on the values calculated with RUMINANT, and were used to estimate the grassland extent and productivity. (This procedure is described in the next section.)

Finally, the feed aggregate OTHER is represented in a simplified way, where it is assumed that it is satisfied entirely from a reserve in the base year, and all additional demand needs to be satisfied by forage production on grasslands.

### 5.3.4 Grazing forage availability

The demand and supply of grass need to match at the level of Simulation Unit in GLOBIOM. But reliable information about grass forage supply is not available even at the country level. The forage supply is a product of the utilized grassland area and of forage productivity. However, at global scale, Ramankutty et al. (2008) [94] estimated that the extent of pastures spans in the 90% confidence interval between 2.36 and 3.00 billion hectares. The FAOSTAT estimate of 3.44 billion hectares itself falls outside of this interval which illustrates the level of uncertainty in the grassland extent. Similarly, with respect to forage productivity, different grassland production models perform better for different forage production systems and all are confronted with considerable uncertainty due to limited information about vegetation types, management practices, etc. (Conant and Paustian, 2004 [14]). These limitations precluded reliance on any single source of information or output from a single model. Therefore three different grass productivity sources were considered: CENTURY on native grasslands, CENTURY on native and managed grasslands, and EPIC on managed grasslands.

A systematic process was developed for selecting the suitable productivity source for each of GLOBIOM’s 30 regions. This process allowed reliance on sound productivity estimates that are consistent with other GLOBIOM datasets like spatial livestock distribution and feed requirements. Within this selection process, the area of utilized grasslands corresponding to the base year 2000 was determined simultaneously with the suitable forage productivity layer. Two selection criteria were used: livestock requirements for forage and area of permanent meadows and pastures from FAOSTAT. The selection process was based on simultaneous minimization of i) the difference between livestock demand for forage and the model-estimates of forage supply and ii) the difference between the utilized grassland area and FAOSTAT statistics on permanent meadows and pastures. Regional differentiation in grassland management intensity, ranging from dry grasslands with minimal inputs to mesic, planted pastures that are intensively managed with large external inputs – further informed the model selection by enabling constraints in the number of models for dry grasslands.

To calculate the utilized grassland area, the potential grassland area was first defined as the area belonging to one of the following GLC2000 land cover classes: 13 (Herbaceous Cover, closed-open), 16-18 (Cultivated and managed areas, Mosaic: Cropland / Tree Cover / Other natural vegetation, Mosaic: Cropland / Shrub and/or grass cover), excluding area identified as cropland according to the IFPRI crop distribution map (You and Wood, 2006 [146]), and 11, 12, 14 (Shrub Cover, closed-open, evergreen, Shrub Cover, closed-open, deciduous, Sparse herbaceous or sparse shrub cover). In each Simulation Unit the utilized area was calculated by dividing total forage requirements by forage productivity. In Simulation Units where utilized area was smaller than the potential grassland area, the difference would be allocated to either “Other Natural Land” or “Other Agricultural Land” depending on the underlying GLC2000 class.
In Simulation Units where the grassland area necessary to produce the forage required in the base year was larger than the potential grassland area, a “reserve” was created to ensure base year feasibility, but all the additional grass demand arising through future livestock production increases needed to be satisfied from grasslands.

Forage productivity was estimated using the CENTURY (Parton et al., 1987 [91]; Parton et al., 1993 [90]) and EPIC (Williams and Singh, 1995 [144]) models. The CENTURY model was run globally at 0.5 degree resolution to estimate native forage and browse and planted pastures productivity. It was initiated with 2000 year spin-ups using mean monthly climate from the Climate Research Unit (CRU) of the University of East Anglia with native vegetation for each grid cell, except cells dominated by rock, ice, and water, which were excluded. Information about native vegetation was derived from the Potsdam intermodal comparison study (Schloss et al., 1999 [121]). Plant community and land management (grazing) was based on growing-season grazing and 50 per cent forage removal. Areas under native vegetation that were grazed were identified using the map of native biomes subject to grazing and subtracting estimated crop area within those biomes in 2006 (Ramankutty et al., 2008 [94]). It is assumed 50 per cent grazing efficiency for
grass, and 25 per cent for browse for native grasslands. These CENTURY-based estimates of native grassland forage production (CENTURY_NAT) were used for most regions with low-productivity grasslands (Fig. 5.2).

Both the CENTURY and EPIC models were used to estimate forage production in mesic, more productive regions. For the CENTURY model, forage yield was simulated using a highly-productive, warm-season grass parameterization. Production was modeled in all cells and applied to areas of planted pasture, which were estimated based on biomes that were not native rangelands, but were under pasture in 2006 according to Ramankutty (Ramankutty et al., 2008 [94]). Pastures were replanted in the late winter every ten years, with grazing starting in the second year. Observed monthly precipitation and minimum and maximum temperatures between 1901 and 2006 were from the CRU Time Series data, CRU TS30 (Mitchell and Jones, 2005 [81]) Soils data were derived from the FAO Soil Map of the World, as modified by Reynolds et al. (2000) [101]. CENTURY model output for productive pastures (CENTURY_MGT) were the best-match for area/forage demand in much of the world with a mixture of mesic and drier pastures.

Fig. 5.3: Forage available for livestock in tonnes of dry matter per hectare as the result of combination of outputs from the CENTURY and EPIC models.

The EPIC model was the best fit for much of Europe and Eastern Asia, where most of the forage production is in intensively-managed grasslands. The EPIC simulations used the same soil and climatic drivers as the CENTURY runs plus topography data (high-resolution global Shuttle Radar Topography Mission digital elevation model (SRTM) and the Global 30 Arc Second Elevation Data (GTOPO30)). Warm and cold seasonal grasses were simulated in EPIC,
and the simulations included a range of management intensities represented by different levels of nitrogen fertilizer inputs and off-take rates. The most intensive management minimizing nitrogen stress and applying 80% off-take rates (EPIC_INT) was found to be the best match for South Korea. Highly fertilized grasslands but with an off-take rate of 50% only were identified in Western Europe, China and Japan (EPIC_MID), and finally extensive management, only partially satisfying the nitrogen requirements and considering 20% off-take rates corresponded best to Central and Northern Europe and South-East Asia (EPIC_EXT). The resulting hybrid forage availability map is represented in Fig. 5.3.

5.3.5 Livestock dynamics

In general, the number of animals of a given species and production type in a particular production system and Supply Unit is an endogenous variable. This means that it will decrease or increase in relation to changes in demand and the relative profitability with respect to competing activities.

Herd dynamics constraints need however to be respected. First, dairy herds are constituted of adult females and followers, and expansion therefore occurs in predefined proportions in the two groups. Moreover, for regions where the specialized meat herds are insignificant (no suckler cows), expansion of meat animals (surplus heifers and males) is also assumed proportional in size to the dairy herd. The ruminants in urban systems are not allowed to expand because this category is not well known and because it is fairly constrained by available space in growing cities. Finally, the decrease of animals per system and production type higher than 15 per cent per 10 years period are not considered, and no increase by more than 100 per cent on the same period. At the level of individual systems, the decrease can however be as deep as 50 per cent per system on a single period.

For monogastrics, the assumption is made that all additional supply will come from industrial systems and hence the number of animals in other systems is kept constant (Keyzer et al., 2005 [58]).

5.4 Forestry

The forestry sector is represented in GLOBIOM with five categories of primary products (pulp logs, saw logs, biomass for energy, traditional fuel wood, and other industrial logs) which are consumed by industrial energy, cooking fuel demand, or processed and sold on the market as final products (wood pulp and sawnwood). These products are supplied from managed forests and short rotation plantations. Harvesting cost and mean annual increments are informed by the G4M global forestry model (Kindermann et al., 2006 [61]) which in turn calculates them based on thinning strategies and length of the rotation period.

Primary forest production from traditional managed forests is characterized also at the level of SimUs. The most important parameters for the model are mean annual increment, maximum share of saw logs in the mean annual increment, and harvesting cost. These parameters are shared with the G4M model – a successor of the model described by Kindermann et al. (2006) [61]. More specifically, mean annual increment for the current management, is obtained by downscaling biomass stock data from the Global Forest Resources Assessment (FAO, 2006 [22]) from the country level to a 0.5 x 0.5 degree grid using the method described in Kindermann et al. (2008) [60]. The downscaled biomass stock data is subsequently used to parameterize increment curves. Finally, the saw logs share is estimated by the tree size, which in turn depends on yield and rotation time. Harvesting costs are adjusted for slope and tree size as well. Among the five primary forest products, saw logs, pulp logs and biomass for energy are further processed. Sawn wood and wood pulp production and demand parameters rely on the 4DSM model described in Rametsteiner et al. (2007) [95]. FAO data and other secondary sources have been used for quantities and prices of sawn wood and wood pulp. For processing cost estimates of these products an internal IIASA database and proprietary data (e.g. RISI database for locations of individual pulp and paper mills, with additional economic and technical information, http://www.risiinfo.com) were used. Biomass for energy can be converted in several processes: combined heat and power production, fermentation for ethanol, heat, power and gas production, and gasification for methanol and heat production. Processing cost and conversion coefficients are obtained from various sources (Biomass Technology Group, 2005 [31]; Hamelinck and Faaij, 2001 [34]; Leduc et al., 2008 [64]; Sorensen, 2005 [130]). Demand for woody bioenergy production is implemented through minimum quantity constraints, similar to demand for other industrial
logs and for firewood. Woody biomass for bioenergy can also be produced on short rotation tree plantations. To parameterize this land use type in terms of yields, an evaluation of the land availability and suitability was carried out. Calculated plantation costs involve the establishment cost and the harvesting cost. The establishment related capital cost includes only sapling cost for manual planting (Carpentieri et al., 1993 [11]; Herzogbaum GmbH, 2008 [40]). Labour requirements for plantation establishment are based on Jurvelius (1997) [54], and consider land preparation, saplings transport, planting and fertilization. These labour requirements are adjusted for temperate and boreal regions to take into account the different site conditions. The average wages for planting are obtained from ILO (2007) [46]. Harvesting cost includes logging and timber extraction. The unit cost of harvesting equipment and labour is derived from various datasets for Europe and North America (e.g. FPP, 1999 [26]; Jirousek et al., 2007 [51]; Stokes et al., 1986 [133]; Wang et al., 2004 [142]). Because the productivity of harvesting equipment depends on terrain conditions, a slope factor (Hartsough et al., 2001 [35]) was integrated to estimate total harvesting cost. The labour cost, as well as the cost of saplings, is regionally adjusted by the ratio of mean PPP (purchasing power parity over GDP), (Heston et al., 2006 [41]).

5.5 Land use change

The model optimizes over six land cover types: cropland, grassland, short rotation plantations, managed forests, unmanaged forests and other natural land. Economic activities are associated with the first four land cover types. There are three other land cover types represented in the model: other agricultural land, wetlands, and not relevant (bare areas, water bodies, snow and ice, and artificial surfaces). These three categories are currently kept constant. Each Simulation Unit can contain the nine land cover types. The base year spatial distribution of land cover is based on the Global Land Cover 2000 (GLC2000). However, as any other global dataset of this type, GLC2000 suffers from large uncertainty (Fritz et al., 2011 [29]). Therefore auxiliary datasets and procedures are used to transform this “raw” data into a consistent dataset corresponding to the model needs.

Land conversion over the simulation period is endogenously determined for each Supply Unit within the available land resources. Such conversion implies a conversion cost – increasing with the area of land converted - that is taken into account in the producer optimization behavior. Land conversion possibilities are further restricted through biophysical land suitability and production potentials, and through a matrix of potential land cover transitions (Fig. 5.4).

5.6 Food demand

Food demand is in GLOBIOM endogenous and depends on population, gross domestic product (GDP) and own product price. Population and GDP are exogenous variables while prices are endogenous. The simple demand system is presented in Eq. (5.1). First, for each product i in region r and period t, the prior demand quantity Q is calculated as a function of population POP, GDP per capita GDPc and adjusted by the income elasticity ϵ GDP, and the base year consumption level as reported in the Food Balance Sheets of FAOSTAT. If the prior demand quantity could be satisfied at the base year price P, this would be also the optimal demand quantity Q. However, usually the optimal quantity will be different from the prior quantity, and will depend on the optimal price P and the price elasticity ϵ price, the latter calculated from USDA (Seale et al., 2003 [124]), updated in Muhammad et al. (2011) [82] for the base year 2000. Because food demand in developed countries is more inelastic than in developing ones, the value of this elasticity is assumed to decrease with the level of GDP per capita. The rule applied is that the price elasticity of developing countries converges to the price elasticity of the USA in 2000 at the same pace as their GDP per capita reach the USA GDP per capita value of 2000. This allows capturing the effect of change in relative prices on food consumption taking into account heterogeneity of responses across regions, products and over time.

\[
\frac{Q_{i,r,t}}{Q_{i,r,2000}} = \left( \frac{P_{i,r,t}}{P_{i,r,2000}} \right)^{\epsilon_{price}}
\]

where

\[
Q_{i,r,t} = \frac{POP_{i,t}}{POP_{i,2000}} \times \left( \frac{GDP_{c}^{i,r,t}}{GDP_{c}^{i,r,2000}} \right)^{\epsilon_{GDP}} \times Q_{i,r,2000}
\]
Fig. 5.4: Land cover representation in GLOBIOM and the matrix of endogenous land cover change possibilities (Havlik et al., 2014 [37]).
This demand function has the virtue of being easy to linearize as GLOBIOM is solved as a linear program. This is currently necessary because of the size of the model and the performance of non-linear solvers. However, this demand function has although some limitations which need to be kept in mind when considering the results obtained with respect to climate change mitigation and food availability. One of them is that it does not consider direct substitution effects on the consumer side which could be captured through cross price demand elasticities. Such a demand representation could lead to increased consumption of some products like legumes or cereals when prices of GHG intensive products like rice or beef would go up as a consequence of a carbon price targeting emissions for the agricultural sector. Neglecting the direct substitution effects may lead to an overestimation of the negative impact of such mitigation policies on total food consumption. However, the effect on emissions would be only of second order, because consumption would increase for commodities the least affected by the carbon price, and hence the least emission intensive. Although direct substitution effects on the demand side are not represented, substitution can still occur due to changes in prices on the supply side and can in some cases lead to a partial compensation of the decreased demand for commodities affected the most by a mitigation policy.
The water withdrawal and return flows from energy technologies are calculated in MES-
SAGE following the approach described in Fricko et al., (2016) [28]. Each technology
is prescribed a water withdrawal and consumption intensity (e.g., m3 per kWh) that trans-
lates technology outputs optimized in MESSAGE into water requirements and return flows.

For power plant cooling technologies, the amount of water required and energy dissipated to water bodies
as heat is linked to the parameterized power plant fuel conversion efficiency (heat rate). Looking at a simple
thermal energy balance at the power plant (Fig. 6.1), total combustion energy \( E_{\text{comb}} \) is converted into elec-
tricity \( E_{\text{elec}} \), emissions \( E_{\text{emis}} \) and additional thermal energy that must be absorbed by the cooling sys-

\[
E_{\text{comb}} = E_{\text{elec}} + E_{\text{emis}} + E_{\text{cool}}
\]

Converting to per unit electricity, we can estimate the cooling required per unit of electricity generation
\( \phi_{\text{cool}} \) based on average heat-rate \( \phi_{\text{comb}} \) and heat lost to emissions \( \phi_{\text{emis}} \), and this data is identified from
the literature [28].

\[
\phi_{\text{cool}} = \phi_{\text{comb}} - \phi_{\text{emis}} - 1
\]

With time-varying heat-rates (i.e., \( t = 0, 1, 2, \ldots \)) and a constant share of energy to emissions and electricity:

\[
\phi_{\text{cool}}[t] = \phi_{\text{comb}}[t] \cdot \left( 1 - \frac{\phi_{\text{emis}}}{\phi_{\text{comb}}[0]} \right) - 1
\]

Increased fuel efficiency (lower heat-rate) reduces the cooling requirement per unit of electricity generated. This
enables heat rate improvements for power plants represented in MESSAGE to be translated into improvements in
water intensity. Water withdrawal and consumption intensities for power plant cooling technologies are calibrated to
the range reported in Meldrum et al., (2013) [77]. Additional parasitic electricity demands from recirculating and dry
A key feature of the implementation is the representation of power plant cooling technology options for individual power plant types (Fig. 6.2). Each power plant type that requires cooling in MESSAGE is connected to a corresponding cooling technology option (once-through, recirculating or air cooling), with the investment into and operation of the cooling technologies included in the optimization decision variables [89]. This enables MESSAGE to choose the type of cooling technology for each power plant type and track how the operation of the cooling technologies impact water withdrawals, return flows, thermal pollution and parasitic electricity use.

Costs and efficiency for cooling technologies are estimated following previous technology assessments [147][148][66]. The initial distribution of cooling technologies in each region and for each technology is estimated with the dataset described in Raptis and Pfister (2016) [100]. The shares estimated at the river basin-scale are depicted in Fig. 6.3.
Fig. 6.3: Average cooling technology shares across all power plant types at the river basin-scale.
CHAPTER 7

Emissions

7.1 Emission from energy (MESSAGE)

7.1.1 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 [105]; Riahi, Rubin et al., 2004 [106]; Rao and Riahi, 2006 [99]; Riahi et al., 2011 [104]). CO2 emission factors of fossil fuels and biomass are based on the 1996 version of the IPCC guidelines for national greenhouse gas inventories [47] (see Table 7.1). 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 (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 7.1: Carbon emission factors used in MESSAGE based on IPCC (1996, Table 1-2 [ipcc_revised_1996]). For convenience, emission factors are shown in three different units.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard coal</td>
<td>25.8</td>
<td>94.6</td>
<td>0.814</td>
</tr>
<tr>
<td>Lignite</td>
<td>27.6</td>
<td>101.2</td>
<td>0.870</td>
</tr>
<tr>
<td>Crude oil</td>
<td>20.0</td>
<td>73.3</td>
<td>0.631</td>
</tr>
<tr>
<td>Light fuel oil</td>
<td>20.0</td>
<td>73.3</td>
<td>0.631</td>
</tr>
<tr>
<td>Heavy fuel oil</td>
<td>21.1</td>
<td>77.4</td>
<td>0.665</td>
</tr>
<tr>
<td>Methanol</td>
<td>17.4</td>
<td>63.8</td>
<td>0.549</td>
</tr>
<tr>
<td>Natural gas</td>
<td>15.3</td>
<td>56.1</td>
<td>0.482</td>
</tr>
<tr>
<td>Solid biomass</td>
<td>29.9</td>
<td>109.6</td>
<td>0.942</td>
</tr>
</tbody>
</table>

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 7.1 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. A relevant feature of MESSAGE in this context is that CO2 emissions from the extraction process increase when moving from conventional to unconventional fossil fuel resources (McJeon et al., 2014 [72]).

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 (see Table 7.2).

<table>
<thead>
<tr>
<th>Conversion Process</th>
<th>Plant type</th>
<th>Capture rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity generation</td>
<td>supercritical PC power plant with desulphurization/denox and CCS</td>
<td>90%</td>
</tr>
<tr>
<td>Electricity generation</td>
<td>IGCC power plant with CCS</td>
<td>90%</td>
</tr>
<tr>
<td>Electricity generation</td>
<td>biomass IGCC power plant with CCS</td>
<td>86%</td>
</tr>
<tr>
<td>Liquid fuel production</td>
<td>Fischer-Tropsch coal-to-liquids with CCS</td>
<td>85%</td>
</tr>
<tr>
<td>Liquid fuel production</td>
<td>coal methanol-to-gasoline with CCS</td>
<td>85%</td>
</tr>
<tr>
<td>Liquid fuel production</td>
<td>Fischer-Tropsch gas-to-liquids with CCS</td>
<td>90%</td>
</tr>
<tr>
<td>Liquid fuel production</td>
<td>Fischer-Tropsch biomass-to-liquids with CCS</td>
<td>65%</td>
</tr>
<tr>
<td>Liquid fuel production</td>
<td>Biomass to Gasoline via the Methanol-to-Gasoline (MTG) Process with CCS</td>
<td>67%</td>
</tr>
<tr>
<td>Hydrogen production</td>
<td>coal gasification with CCS</td>
<td>92%</td>
</tr>
<tr>
<td>Hydrogen production</td>
<td>biomass gasification with CCS</td>
<td>85%</td>
</tr>
<tr>
<td>Hydrogen production</td>
<td>steam methane reforming with CCS</td>
<td>90%</td>
</tr>
</tbody>
</table>

### 7.1.2 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 [99]) 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 (see Section Emissions from land (GLOBIOM)).

### 7.1.3 Air pollution

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 [5]). 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 [13]; Amann et al., 2013 [7]). 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 [102]; Rao et al., 2013 [98]; Fricko et al., 2017 [27]).
7.2 Emissions from land (GLOBIOM)

7.2.1 Crop sector emissions

Crop emissions sources accounted in GLOBIOM are N2O fertilization emissions, from synthetic fertilizer and from organic fertilizers, as well as CH4 methane emissions from rice cultivation. Synthetic fertilizers are calculated on a Tier 1 approach, using the information provided by EPIC on the fertilizer use for each management system at the Simulation Unit level and applying the emission factor from IPCC AFOLU guidelines. Synthetic fertilizer use is therefore built in a bottom up approach, but upscaled to the International Fertilizer Association statics on total fertilizer use per crop at the national level for the case where calculated fertilizers are found too low at the aggregated level. This correction ensures a full consistency with observed fertilizer purchases. In the case of rice, only a Tier 1 approach was applied, with a simple formula where emissions are proportional to the area of rice cultivated. Emission factor is taken from EPA (2012) [20].

7.2.2 Livestock emissions

In GLOBIOM, the following emission accounts were assigned to livestock directly: CH4 from enteric fermentation, CH4 and N2O from manure management, and N2O from excreta on pasture (N2O from manure applied on cropland is reported in a separate account linked to crop production). In brief, CH4 from enteric fermentation is a simultaneous output of the feed-yield calculations done with the RUMINANT model, as well as nitrogen content of excreta and the amount of volatile solids. The assumptions about proportions of different manure management systems, manure uses, and emission coefficients are based on detailed literature review. A detailed description of how these coefficients have been determined including the literature review is provided in (Herrero et al., 2013 [38]).

7.2.3 Land use change emissions

Land use change emissions are computed based on the difference between initial and final land cover equilibrium carbon stock. For forest, above and below-ground living biomass carbon data are sourced from Kindermann et al. (2008) [59], where geographically explicit allocation of the carbon stocks is provided. The carbon stocks are consistent with the 2010 Forest Assessment Report (FAO, 2010 [23]). Therefore, the emission factors for deforestation are in line with those of FAO. Additionally, carbon stock from grasslands and other natural vegetation is also taken into account using the above and below ground carbon from the biomass map from (Ruesch and Gibbs, 2008 [115]). When forest or natural vegetation is converted into agricultural use, it is considered in this approach that all below and above ground biomass is released in the atmosphere. However, the following are not accounted for: litter, dead wood and soil organic carbon.

7.2.4 Comparison with other literature

In order to put the numbers in perspective with other sources they were compared with FAO (Tubiello et al., 2013 [137]) where a simple but transparent approach is used, largely relying on FAOSTAT activity numbers and IPCC Tier 1 emission coefficients (see Table 3.1).

The 2000 data for crops are overall about 11% higher than Tubiello et al., mainly because of rice where the data are closer to EPA (EPA 2012 [20]) which is higher than Tubiello et al. For livestock, it is by some 18% lower than Tubiello et al. So in total there is about 10% GHG emissions less in 2000 than the values reported. The year 2010 is already the result of simulations and hence may be interesting to compare with the data. In order to facilitate the comparison, the columns e), f) and g) in Table 1 are3 included. Columns e) and f) compare GLOBIOM data for 2000 and projections for 2010 respectively, with numbers reported by Tubiello et al. Column g) compares the relative change in emissions between 2000 and 2010 from these two sources (1.00 would indicate the same relative change in GLOBIOM and in Tubiello et al.). It is apparent that the relative change in total agricultural emissions in GLOBIOM is the same as the development reported by Tubiello et al. – an increase by 11%. The behavior of GLOBIOM is over this period very
close to the reported trends also at the level of individual accounts. The only exception is emissions from manure management where the relative change projected in GLOBIOM is by 13% higher than the relative change observed in Tubiello’s numbers.

Table 7.3: Comparison of agricultural GHG emissions from GLOBIOM and from FAO for the years 2000 and 2010

<table>
<thead>
<tr>
<th></th>
<th>GLOBIOM (a)</th>
<th>Tubiello et al. (b)</th>
<th>(c)</th>
<th>(d)</th>
<th>(e)</th>
<th>(f)</th>
<th>(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>1,239</td>
<td>1,114</td>
<td>1.11</td>
<td>1.05</td>
<td>0.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crops</td>
<td>1,365</td>
<td>1,298</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synthetic fertilizer</td>
<td>522</td>
<td>640</td>
<td>521</td>
<td>683</td>
<td>1.00</td>
<td>0.94</td>
<td>0.93</td>
</tr>
<tr>
<td>Manure applied</td>
<td>83</td>
<td>96</td>
<td>103</td>
<td>116</td>
<td>0.81</td>
<td>0.83</td>
<td>1.03</td>
</tr>
<tr>
<td>Rice</td>
<td>633</td>
<td>629</td>
<td>490</td>
<td>499</td>
<td>1.29</td>
<td>1.26</td>
<td>0.98</td>
</tr>
<tr>
<td>Livestock</td>
<td>2,362</td>
<td>2,625</td>
<td>2,893</td>
<td>3,135</td>
<td>0.82</td>
<td>0.84</td>
<td>1.03</td>
</tr>
<tr>
<td>Enteric fermentation</td>
<td>1,502</td>
<td>1,661</td>
<td>1,863</td>
<td>2,018</td>
<td>0.81</td>
<td>0.82</td>
<td>1.02</td>
</tr>
<tr>
<td>Manure on pastures</td>
<td>403</td>
<td>441</td>
<td>682</td>
<td>764</td>
<td>0.59</td>
<td>0.58</td>
<td>0.98</td>
</tr>
<tr>
<td>Manure management</td>
<td>457</td>
<td>524</td>
<td>348</td>
<td>353</td>
<td>1.31</td>
<td>1.48</td>
<td>1.13</td>
</tr>
<tr>
<td>Total Agriculture</td>
<td>3,601</td>
<td>3,991</td>
<td>4,007</td>
<td>4,433</td>
<td>0.90</td>
<td>0.90</td>
<td>1.00</td>
</tr>
</tbody>
</table>
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 [75]). 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 [76]), but also a probabilistic setup (Meinshausen et al., 2009 [74]) 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 [109]; Rogelj et al., 2013b [110]; Rogelj et al., 2015 [111]). 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., 2017 [27])

For more information about the model, see www.magicc.org.
CHAPTER 9

References
Annex: Mathematical formulation

This Annex provides a description of the mathematical formulation of MESSAGE-GLOBIOM and its modules.

10.1 Implementation: MACRO

MACRO is based on the macro-economic module of the global energy-economy-climate model Global 2100 [68], a predecessor of the MERGE model. The original soft-linkage between MACRO and MESSAGE has been described in [79], but several adjustments have been made compared to this original implementation. The description below builds to a certain degree on these two publications, but deviates in some places as discussed in the following paragraphs. It is worthwhile mentioning that MACRO as used with MESSAGE has similar origins as the MACRO module of MARKAL-MACRO [67] with the exception of being soft-linked rather than hard-linked to the energy systems part of the model.

On the one hand, while the version of MACRO described in [79] like the MACRO module of Global 2100 operated at the level of electric and non-electric energy demands in the production function, the present version of MACRO operates at the level of the six commercial useful energy demands represented in MESSAGE (Energy demand). This change was made in response to electrification becoming a tangible option for the transport sector with the introduction of electric cars over the past decade. Previously (and as described in [79]), the electric useful energy demands in MESSAGE had been mapped to electric demand in MACRO and the thermal useful energy demands, non-energy feedstock and transport demands in MESSAGE had been mapped to non-electric demand in MACRO.

On the other hand, as a result of switching the implementation of MESSAGE to GAMS, the iterative information exchange between the two models is now handled within GAMS. This accelerates the iteration process considerably, because the solution of the previous iteration is kept in memory and can serve as a starting point for the next iteration.

Finally, the parameterization of MACRO has changed in a specific way. As mentioned, the model’s most important input parameters are the projected growth rates of total labor, i.e., the combined effect of labor force and labor productivity growth (note that labor supply growth is also referred to as reference or potential GDP growth) and the annual rates of reference energy intensity reductions, i.e. the so-called autonomous energy efficiency improvement (AEEI) coefficients. In all recent applications of MACRO, including the Shared Socio-economic Pathways (SSPs), these are calibrated to be consistent with the developments in a MESSAGE scenario. In practice, this happens by running MACRO and adjusting the potential GDP growth rates and the AEEI coefficients on a sectoral basis until...
MACRO does not produce an energy demand response and GDP feedback compared to the MESSAGE scenario that it is calibrated to.

### 10.1.1 MACRO parameterization

#### Initial conditions

Total capital $K_{r,y=0}$ in the base year is derived by multiplying base year GDP with the capital-to-GDP ratio $kgdp$.

$$K_{y=0,r} = kgdp \cdot GDP_{r,y=0}$$

Similarly investments $I_{r,y=0}$ and consumption $C_{r,y=0}$ in the base year are derived from base year GDP, capital value share and depreciation rate.

$$I_{y=0,r} = K_{y=0,r} \cdot (grow_{r,y=0} + depr_r)$$

$$C_{y=0,r} = GDP_{r,y=0} - I_{y=0,r}$$

Total production $Y_{y=0,r}$ in the base year then follows as total GDP plus energy system costs (estimation based on MESSAGE):

$$Y_{y=0,r} = GDP_{r,y=0} + total\_cost_{r,y=0}$$

The production function coefficients for capital, labor $a_r$ and energy $b_{r,s}$ are calibrated from the first-order optimality condition, i.e. $b_{r,s}$ from

$$\frac{\partial Y}{\partial NEW\_ENE_{r,s}} = p_{r,s}^{ref}$$

and $a_r$ by inserting $b_r$ back into the production function, setting the labor force index in the base year to 1 (numeraire) and solving for $a_r$ [68].

$$b_{r,s} = p_{r,s}^{ref} \cdot \left( \frac{Y_{y=0,r}}{PHYS\_ENE_{r,s,y=0}} \right)^{\rho_{r}^{-1}}$$

$$a_r = Y_{y=0,r}^{\rho_r} - \sum_s b_{r,s} \cdot \frac{PHYS\_ENE_{r,s,y=0}^{\rho_r}}{K_{y=0,r}^{\rho_r} \cdot \alpha_r}$$

#### Macro-economic parameters

Given that MESSAGE includes (exogenous) energy efficiency improvements in end-use technologies as well as significant potential final-to-useful energy efficiency improvements via fuel switching (e.g., via electrification of thermal demands and transportation), for the elasticity of substitution between capital-labor and total energy demand $\epsilon_r$ in MACRO relatively low values in the range of 0.2 and 0.3 were chosen. The elasticities are region-dependent with developed regions $r \in \{NAM, PAO, WEU\}$ assumed to have higher elasticities of 0.3, economies in transition $r \in \{EEU, FSU\}$ intermediate values of 0.25 and developing regions $r \in \{AFR, CPA, LAM, MEA, PAS, SAS\}$ the lowest elasticities of 0.2.

The capital value share parameter $\alpha_r$ can be interpreted as the optimal share of capital in total value added [68] and is chosen region-dependent with lower values between 0.24 and 0.28 assumed for developed regions and slightly higher values of 0.3 assumed for economies in transition and developing country regions.

#### Calibration

Via a simple iterative algorithm, MACRO is typically calibrated to an exogenously specified set of regional GDP trajectories and useful energy demand projections from MESSAGE. To calibrate GDP, after each MACRO run the realized
GDP from MACRO and the GDP to be calibrated to are compared and the potential GDP growth rate $GROW_{y,r}$ used in MACRO is then adjusted according to the following formula.

$$GROW_{corr,y,r} = \left( \frac{GDP_{cal,y+1,r}}{GDP_{cal,y,r}} \right)^{\frac{1}{\text{duration}_{period}+1}} - \left( \frac{GDP_{MACRO_{y+1,r}}}{GDP_{MACRO_{y,r}}} \right)^{\frac{1}{\text{duration}_{period}+1}}$$

where $GDP_{cal,y,r,s}$ is the set of GDP values that MACRO should be calibrated to. In the next run of MACRO the potential GDP growth rate $GROW_{y,r}$ is chosen to be

$$GROW_{y,r} = GROW_{y,r} + GROW_{corr,y,r},$$

after which the procedure is repeated. Similarly, to calibrate the physical energy demands $PHYSEN_{r,y,s}$ to ones from MESSAGE, the demand level realized in MACRO and the desired demand level from a MESSAGE model run are compared and the autonomous energy efficiency improvements (AEEIs) are corrected according to the following equations.

$$aei_{corr,y,r,s} = \left( \frac{PHYSN_{y+1,r,s}}{DEMAND_{cal,y+1,r,s}} \right)^{\frac{1}{\text{duration}_{period}+1}} - 1$$

$$aei_{r,y,s} = aei_{r,y,s} + aei_{corr,y,r,s}$$

where $DEMAND_{cal,y,r,s}$ is the set of demand levels from MESSAGE that MACRO should be calibrated to.

Given that GDP and demand calibration interact with each other, in practice they are done in an alternating fashion, i.e. after the first MACRO model run, the potential GDP growth rates are adjusted and in the second run the AEEI coefficients are adjusted. This calibration loop is continued until the correction factors for both the potential GDP growth rates $GROW_{corr,y,r}$ and the AEEI coefficients $aei_{r,y,s}$ all stay below $10^{-5}$.

### 10.1.2 Iterating between MESSAGE and MACRO

#### Exchanged parameters

MESSAGE and MACRO exchange demand levels of the six commercial service demand categories represented in MESSAGE, their corresponding prices as well as total energy system costs including trade effects of energy commodities and carbon permits (if any explicit mitigation effort sharing regime is implemented).

#### Convergence criterion

The iteration between MESSAGE and MACRO is either stopped after a fixed number of iterations - in case of which the user needs to manually check convergence between the models - or once the maximum of changes across all energy demand categories and regions (i.e. the convergence criterion) is less than a specified threshold. In both cases the convergence criterion is typically set to around 1%.

#### Constraint on demand response

Demand responses from MACRO to MESSAGE can be large if the initial demands are far from the equilibrium demand levels of a specific scenario (e.g., when using demand from a non-climate policy scenario as the starting point for a stringent climate mitigation scenario that aims at limiting temperature change to 2 degrees C). To avoid oscillations of demands in subsequent MESSAGE-MACRO iterations, a constraint on the maximum permissible demand change between subsequent iterations has been introduced which is usually set to 20%. In practical terms this means that the demand response is capped at 20% for each type of Energy demand and for each of the MESSAGE Regions. However, under specific conditions - typically under stringent climate policy - when price responses to small demand adjustments are large, an oscillating behavior between two sets of demand levels can still occur. In such situations, the constraint on the demand response is reduced further until the changes in demand are less than the convergence criterion mentioned above.
10.2 Mathematical Formulation: MESSAGE V

10.2.1 1 Introduction

This part of the document contains the mathematical formulation of MESSAGE as used at IIASA. The so-called matrix generator produces equations according to this formulation, the input data determine the form these equations actually take. In its general formulation MESSAGE a dynamic linear programming model with a mixed integer option. This implies that all relations that define the structure of a model are given as linear constraints between continuous variables. The variables of such a model are called ‘Columns’, the equations ‘Rows’. This nomenclature is derived from the usual notation used to write down linear models: in the shape of a matrix. The variables (columns) of MESSAGE be grouped into three categories:

1. Energy flow variables representing an annual energy flow quantity. The unit is usually GWyr for larger regions,
2. Power variables representing the production capacity of a technology (usual unit: GW), and
3. Stock-piles representing the quantity of a fuel being cumulated at a certain point in time (usual unit: GWyr).

The constraints (rows) generated by MESSAGE can be grouped into the following categories:

1. Energy flow balances modelling the flow of energy in the energy chain from resource extraction via conversion, transport, distribution up to final utilization,
2. sum or relational constraints limiting aggregate activities on an annual or cumulative basis, either absolute or in relation to other activities,
3. dynamic constraints setting a relation between the activities of two consecutive periods, and
4. counters that are only used for accounting purposes.

This manual gives the mathematical formulation of MESSAGE. It contains a formalized description of all types of variables and equations that the matrix generator generates. The reader of this paper is assumed to be familiar with the theory of linear and mixed integer programming. Each of the building stones of MESSAGE handled in a separate chapter, which is again subdivided into sections on columns and rows. The notation used for the variable and equation names is the same as in the MPS-file. Uppercase letters are used to indicate predefined identifiers, while lowercase letters represent characters that are chosen by the user or varied over a set of characters. In order to keep the notation simple and the mathematical description as short as possible the more complex features are omitted from the description of the rows and described in an additional section (see _specialfeatures). Since practically all parameters of MESSAGE can be defined as time series (i.e. change over the planning horizon), the index for the period is often omitted in the formulation (e.g., for the efficiencies or the plant factors of conversion technologies).

The names of variables and equations used in this description follow the notation used in the mps and solution files of the problem. For variables and equations related to technologies this is generally name...rrlllttt, A...rrlllttt, or nameA...rrlllttt, where name is generated from main output level identifier, main input energy form identifier, a user given character, and the main output fuel identifier. A are indicators of related variables or rows like e.g. annual investments or market penetration. For used defined equations and variables the name is supplied by the user. rr denotes the region (’...’ for the main region of a multi-region model and for one-regional models). lll denotes the load region (usually this is season index, day index and hour index all indexed from a-Z). ttt is the model time period, calculated as year – int(year/100) * 100.

10.2.2 2 Conversion Technologies

2.1 Variables

Energy conversion technologies, both on the supply and demand side of the energy system, are modelled using two types of variables, that represent
• the amount of energy converted per year in a period (activity variables) and
• the annually installed capacity in a period (capacity variables).

### 2.1.1 Activities of Energy Conversion Technologies

\[
z_{zsvd...rrlltt}
\]

where

| \(z\) | level identifier of the main output of the technology. The demand level is handled differently to all other levels: Technologies with the main output on this level are defined without load regions. If defined, the input is split into the different load regions. |
| \(s\) | main energy input of the technology (supply). If the technology has no input \(s\) is set to ",", (e.g., solar technologies). |
| \(v\) | additional identifier of the conversion technology (used to distinguish technologies with the same main input and output). |
| \(d\) | main energy output of the technology. |
| \(rr\) | identifies the sub-region, \(rr\) as defined in file “regid” or \(rr = \_\_\_\), if the model has no sub-regions or if the technology is in the main region. |
| \(lll\) | identifies the load region, \(lll\) is \(sdp\) (season, day, part of day) or \(lll = \_\_\_), if the technology is not modelled with load regions, and |
| \(ttt\) | identifies the period, \(ttt = year - \text{int}(year_0/100) \times 100\). |

The activity variable of an energy conversion technology is an energy flow variable. It represents the annual consumption of this technology of the main input per period or load region. If a technology has no input, the variable represents the annual production of the main output divided by the efficiency.

If the main output is not on the demand level and at least one of the energy carriers consumed or supplied is defined with load regions the technology is defined with load regions. In this case the activity variables are generated separately for each load region, which is indicated by the additional identifier “\(lll\)”. However, this changes if the production of the technology over the load regions is predefined: one variable is generated for the time step, the distribution to the load regions is given by the definition of the user (e.g., production pattern of solar power-plants or consumption pattern of end-use devices).

### 2.1.2 Capacities of Energy Conversion Technologies

\[
y_{yzsvd...rr...ttt}
\]

where

| \(y\) | identifier for capacity variables. |
| \(z\) | identifies the level on that the main energy output of the technology is defined, |
| \(s\) | identifier of the main energy input of the technology, |
| \(v\) | additional identifier of the conversion technology, |
| \(d\) | identifier of the main energy output of the technology. |
| \(rr\) | identifier of the model region. |
| \(ttt\) | period in that the capacity is buildt. |
The capacity variables are power variables. Technologies can be modelled without capacity variables. In this case no capacity constraints and no dynamic constraints on construction can be included in the model. Capacity variables of energy conversion technologies can be defined as integer variables.

If a capacity variable is continuous it represents the annual new installations of the technology in period $t$, if it is integer it represents either the annual number of installations of a certain size or the number of installations of $1/\Delta t$ times the unit size (depending on the definition; $\Delta t$ is the length of period $t$ in years).

The capacity is defined in relation to the main output of the technology.

### 2.2 Constraints

These are equations used to calculate relations between timesteps or between different variables in the model. Partially they are generated automatically, partially they are entirely defined by the user.

- Utilization of a technology in relation to the capacity actually installed (capacity constraint),
- the activity or annual construction of a technology in a period in relation to the same variable in the previous period (dynamic constraints),
- limit on minimum or maximum total installed capacity of a technology,
- limit on minimum or maximum annual production of a technology modeled with load region, and
- user defined constraints on groups of technologies (activities or capacities).

#### 2.2.1 Capacity Constraints

The capacity is defined in relation to the main output of the technology.

$\epsilon_{zsvd...rrllltt} = \min(\tau, t_{zsvd}) \times \Delta(\tau - 1) \times \frac{i}{p} \times y_{zsvd...rr...\tau} \leq hc_{zsvd} \times \pi_{zsvd}$

where

- $c$ identifier for capacity constraints,
- $z$ identifies the level on that the main energy output of the technology is defined,
- $s$ identifier of the main energy input of the technology,
- $v$ additional identifier of the conversion technology,
- $d$ identifier of the main energy output of the technology,
- $rr$ identifier of the model region,
- $l$ identifier of the load region, and
- $t$ period in that the capacity is built.

For all conversion technologies modelled with capacity variables the capacity constraints will be generated automatically. If the activity variables exist for each load region separately there will be one capacity constraint per load region.

Additionally the activity variables of technologies with multiple operation modes (e.g., different fuels) can be linked to the same capacity variable, which allows the optimization to choose the activity variable used with a given capacity.

### Technologies without Load Regions

For technologies without load regions (i.e., technologies, where no input or output is modelled with load regions) the production is related to the total installed capacity by the plant factor. For these technologies the plant factor has to be given as the fraction they actually operate per year. All end-use technologies are modelled in this way.
Technologies with Varying Inputs and Outputs

Many types of energy conversion technologies do not have fixed relations between their inputs and outputs (e.g.: a power plant may use oil or gas as input or can produce electricity and/or heat as output). MESSAGE has the option to link several activity variables of a conversion technology into one capacity constraint. For the additional activities linked to a capacity variable a coefficient defines the maximum power available in relation to one power unit of the main activity.

\[
\sum_{z_{\sigma'\delta} \min(t, \tau_{z_{\sigma'\delta}})} \tau_{\sigma'\delta} \times \epsilon_{z_{\sigma'\delta}} \times z_{\sigma'\delta} \times \tau_{\sigma'\delta} \times y_{z_{\sigma'\delta}} \times \tau_{\sigma'\delta} \leq \lambda_{\sigma'\delta} \times \pi_{z_{\sigma'\delta}} \times \pi_{z_{\sigma'\delta}} \forall_{lll}
\]

The following notation is used in the above equations:

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(z_{\sigma'\delta} )</td>
<td>activity of conversion technology (z_{\sigma'\delta}) in region (rr), period (ttt) and, if defined so, load region (lll) (see section _activitiesECT),</td>
</tr>
<tr>
<td>(y_{z_{\sigma'\delta}})</td>
<td>capacity variable of conversion technology (z_{\sigma'\delta}) (see section _capacitiesECT).</td>
</tr>
<tr>
<td>(\epsilon_{z_{\sigma'\delta}})</td>
<td>efficiency of technology (z_{\sigma'\delta}) in converting the main energy input, (s), into the main energy output, (d),</td>
</tr>
<tr>
<td>(\kappa_{z_{\sigma'\delta}})</td>
<td>last period in that technology (z_{\sigma'\delta}) can be constructed,</td>
</tr>
<tr>
<td>(\pi_{z_{\sigma'\delta}})</td>
<td>“plant factor” of technology (z_{\sigma'\delta}), having different meaning depending on the type of capacity equation applied, in case the plant life does not coincide with the end of a period it also is adjusted time the technology can be operated in that period,</td>
</tr>
<tr>
<td>(\Delta \tau)</td>
<td>length of period (\tau) in years,</td>
</tr>
<tr>
<td>(\tau_{z_{\sigma'\delta}})</td>
<td>plant life of technology (z_{\sigma'\delta}) in periods,</td>
</tr>
<tr>
<td>(h_{\sigma'\delta})</td>
<td>represents the installations built before the time horizon under consideration, that are still in operation in the first year of period (t),</td>
</tr>
<tr>
<td>(f_i)</td>
<td>is 1. if the capacity variable is continuous, and represents the minimum installed capacity per year (unit size) if the variable is integer,</td>
</tr>
<tr>
<td>(f_p)</td>
<td>adjustment factor if the end of the plant life does not coincide with the end of a period ((\text{rest of plant life in period/period length})),</td>
</tr>
<tr>
<td>(\pi(l_m, svd))</td>
<td>share of output in the load region with maximum production,</td>
</tr>
<tr>
<td>(rel_{z_{\sigma'\delta}})</td>
<td>relative capacity of main output of technology (or operation mode) (svd) to the capacity of main output of the alternative technology (or operation mode) (\sigma'\delta), and</td>
</tr>
<tr>
<td>(\lambda_{l})</td>
<td>length of the load region (l) or the length of the load region with maximum capacity use if the production pattern over the year is fixed or the length of the load region with maximum capacity requirements as fraction of the year.</td>
</tr>
</tbody>
</table>

### 2.2.2 Dynamic Constraints on Activity and Construction Variables

\[
D_{z_{\sigma'\delta}} \times rlllttt
\]

The dynamic constraints relate the activity or annual new installations of a technology in a period to the activity or annual construction during the previous period.

\[
y_{z_{\sigma'\delta}} \times rtt - \gamma_{z_{\sigma'\delta},ttt} \times y_{z_{\sigma'\delta}} \times rtt \times (tti - 1) \sim g_{z_{\sigma'\delta},ttt}
\]

\[
\sum_{lll} z_{\sigma'\delta} \times rlllttt - \gamma_{z_{\sigma'\delta},ttt} \sum_{lll} z_{\sigma'\delta} \times rlll (tti - 1) \sim g_{z_{\sigma'\delta},ttt},
\]

where
As described in Keppo and Strubegger (2010 [57]) MESSAGE includes so called flexible or soft dynamic constraints to allow for faster diffusion in case of economically attractive technologies. To operationalize the concept of soft dynamic constraints, a set of $n$ dummy variables with index $i$, $B_{zs\_vd..ti}$, multiplied by a corresponding growth factor $(1 + \delta y_{zs\_vd..ti})$ are added to the upper dynamic constraint described above.

$$a_t = (1 + r)^T \times a_{t-1} + \sum_{i=1}^{n} (1 + r_i)^T \times b_{i,t-1} + S$$

The maximum value for these dummy variables $b^i$ is limited to the activity of the underlying technology $a$, i.e.

$$a_t \leq b^i_t \quad \forall i.$$ 

Therefore, this new formulation increases the highest allowed growth factor from

$$(1 + r)^T$$

to

$$(1 + r)^T + \sum_i (1 + r_i)^T$$

In addition, the objective function value for period $t$ is modified by the extra term

$$\cdots + \sum_{i=1}^{n} c_i \times b^i_t$$

which adds costs $c_i$ per additional growth factor utilized.

### 2.2.3 Contraints on total installed capacity

$I_{zs\_vd..rr..ttt}$

These constraints allow to set upper and/or lower limits on the total installed capacity of a technology at a given point in time.

$$\sum_{\tau=t-T}^{t} y_{zs\_vd..rr..\tau} \sim M_t$$

$T$ | plant life of the technology. 
---|---
$\sim$ | is $\leq$ or $\geq$ for lower and upper constraints respectively, 
$M_t$ | maximum or minimum allowed total installed capacity in time step $t$
2.2.4 User defined Constraints

\[ nname...rrllttt \]

- \( n \) may be ‘n’, ‘p’, or ‘c’ for three groups of user defined constraints,
- \( name \) is a user defined 4-character short name of the constraint.

Each technology may have entries related to their activity, new installed capacity, or total installed capacity into any of the defined constraints. In multi-region models the constraint is first searched in the region where the entry is defined and then, if not found, in the main-region. With this it is possible to create relations between technologies in different sub-regions. The main uses for such constraints are to put regional or global constraints on emissions or to relate the production from specific energy carrier to the total production, e.g.:

\[
\text{wind}_\text{electricity} + \text{solar}_\text{electricity} + \text{biomass}_\text{electricity} \geq \alpha \times \text{total}_\text{electricity}.
\]

where \( \text{total}_\text{electricity} \) can usually be taken from the input to the electricity transmission technology.

2.3 Bounds

Upper, lower, or fixed bounds may be put on activity or new installed capacity. This is usually very helpful at the beginning of the planning horizon to fit results to reality. In later time steps they may be used to avoid unrealistic behaviour like, e.g., too many new installations of a specific technology per year.

10.2.3 3 Domestic Resources

3.1 Variables

Extraction of domestic resources is modelled by variables that represent the quantity extracted per year in a period. A subdivision into cost categories (which are called “grades” in the model) can be modelled.

3.1.1 Resource Extraction Variables

\[ rzfg....rr...ttt \]

where

- \( r \) identifies resource extraction variables,
- \( z \) level on that the resource is defined (usually = \( r \)),
- \( f \) identifier of the resource being extracted,
- \( g \) grade (also called cost category) of resource \( r \), \( g \in \{a, b, c, ...\} \),
- \( rr \) identifies the region,
- \( ttt \) identifies the time period.

The resource variables are energy flow variables and represent the annual rate of extraction of resource \( f \). If several grades are defined, one variable per grade is generated (identifier \( g \) in position 4).
3.2 Constraints

The overall availability of a resource is limited in the availability constraint per grade, annual resource consumption can be constrained per grade and total. Additionally, resource depletion and dynamic resource extraction constraints can be modelled.

3.2.1 Total Resource Availability per Grade

\[ r_2^{fgg...rr} \]

Limits the domestic resource available from one cost category (grade) over the whole time horizon.

\[ \sum_p \sum_t \Delta t \times r_2^{fgg...rr...ttt} \leq r_2^{fgg...rr} - \Delta t_0 R_{rfg,0}, \]

where

| \( r_2^{fgg...rr} \) | total amount of resource \( f \), cost category \( g \), that is available for extraction in a given region \( rr \), |
| \( r_2^{fgg...rr...ttt} \) | annual extraction of resource \( f \), cost category (grade) \( g \) in region \( rr \) and period \( ttt \), |
| \( \Delta t \) | length of period \( t \), |
| \( \Delta t_0 \) | number of years between the base year and the first model year, and |
| \( R_{rfg,0} \) | extraction of resource \( r \), grade \( g \) in the base year. |

3.2.2 Resource Depletion Constraints

\[ r_2^{fgg...rr...ttt} \]

The extraction of a resource in a period can be constrained in relation to the total amount still existing at the beginning of the period.

\[ \Delta t \times r_2^{fgg...rr...ttt} \leq \delta_{fg} \left[ r_2^{fgg...rr} - \Delta t_0 R_{rfg,0} - \sum_{\tau=1}^{t-1} \Delta \tau \times r_2^{fgg...rr...\tau} \right] \]

where

| \( r_2^{fgg...rr} \) | total amount of resource \( f \), cost category \( g \), that is available for extraction, |
| \( r_2^{fgg...rr...ttt} \) | annual extraction of resource \( f \), cost category (grade) \( g \) and elasticity class \( p \) in period \( t \), |
| \( \delta_{fg} \) | maximum fraction of resource \( f \), cost category \( g \), that can be extracted in period \( ttt \), |
| \( \Delta t \) | length of period \( t \) in years, |
| \( \Delta t_0 \) | number of years between the base year and the first model year, and |
| \( R_{rfg,0} \) | extraction of resource \( r \), grade \( g \) in the base year. |
3.2.4 Maximum Annual Resource Extraction per Grade

Limits the domestic resource availability from one cost category per year.

\[ r_{zf}....rr...ttt \leq \text{value} \]

where

\[ r_{zf}....rr...ttt \] annual extraction of resource \( f \), cost category (grade) \( g \) in period \( ttt \).

3.2.5 Dynamic Resource Extraction Constraints per Grade

\[ mr_{zf}....rr...ttt \]

The annual extraction level of a resource in a period can be related to the previous one by a growth parameter and an increment of extraction activity resulting in upper dynamic extraction constraints. For the first period the extraction is related to the activity in the baseyear.

\[ r_{zf}....rr...ttt - \gamma_{fg} \times r_{zf}....rr...(ttt - 1) \leq g_{0f}^{tt}, \]

where

\[ m \] is \( m \) or \( l \), indicating upper and lower constraints respectively (lower limits are generally not used),

\[ \gamma_{fg}^{tt} \] maximum growth rate for the extraction of resource \( f \) between period \( ttt1 \) and \( ttt \),

\[ g_{0f}^{tt} \] annual increment of the extraction of resource \( f \) in period \( ttt \) (must be > 0 if the resource (grade) is not extracted in the base year), and

\[ r_{zf}....rr...ttt \] annual extraction of resource \( f \), cost category (grade) \( g \) in period \( ttt \).

10.2.4 4 Energy flows

4.1 Balance Equations

Energy flows are modelled by linking the activity variables of the different conversion, resource extraction technologies and demands in balance constraints. These constraints ensure that only the amounts of energy available are consumed. There are no further variables required to model energy flows.

Energy demands are also modelled as part of a balance constraint: the right hand side defines the amount to be supplied by the technologies in this constraint.

The description of the energy flow constraints in MESSAGE is given for the following set of level identifiers:

\[ u \] Useful energy (demand level),

\[ f \] Final energy (after transmission and distribution),

\[ x \] Secondary energy,

\[ a \] Primary energy, and

\[ r \] Energy resources.
The first level in the above list gives it a special meaning (see section _activitiesECT). Clearly any other combination of identifiers is also possible.

Another exception is a level labelled $q$, this letter is reserved for stock piles (see section _stockpiles).

**IMPORTANT:** Generally central production systems should not deliver to the first (demand) level. In this case the production of the system would be forced to follow the demand pattern.

### 4.1.1 Demand Constraints

\[
zd_{...rr...ttt} + \sum_{sv} \varepsilon_{zs\nu d} \times zs\nu d_{...rr...ttt} + \sum_{sv} \beta_{zs\nu \delta} \times zs\nu \delta_{...rr...ttt} \geq D_{drt}
\]

where

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$zd_{...rr...ttt}$</td>
<td>annual demand equation for $d$ in region $rr$ and period $ttt$,</td>
</tr>
<tr>
<td>$zs\nu d_{...rr...ttt}$</td>
<td>activity of end-use technology $zs\nu d$ in region $rr$ and period $ttt$ (see section _activitiesECT),</td>
</tr>
<tr>
<td>$\varepsilon_{zs\nu d}$</td>
<td>efficiency of end-use technology $zs\nu d$ in converting $s$ to $d$,</td>
</tr>
<tr>
<td>$\beta_{zs\nu \delta}$</td>
<td>efficiency of end-use technology $zs\nu d$ in producing by-product $d$ from $s$ ((\delta) is the main output of the technology), and</td>
</tr>
<tr>
<td>$D_{drt}$</td>
<td>annual demand for $d$ in region $rr$ and period $ttt$.</td>
</tr>
</tbody>
</table>

The first level, usually labelled ‘demand level’, has a special feature. This is related to the fact that useful energy is usually produced on-site, e.g., space heat is produced by a central heating system, and the load variations over the year are all covered by this one system. Thus, an allocation of production technologies to the different areas of the load curve, like the model would set it up according to the relation between investment and operating costs would ignore the fact that these systems are not located in the same place and are not connected to each other. MESSAGE represents the end-use technologies by one variable per period that produces the required useful energy in the load pattern needed and requires the inputs in the same pattern. For special technologies like, e.g., night storage heating systems, this pattern can be changed to represent the internal storage capability of the system.

Each energy form on any level can have an external demand. In this case the demand is given as right hand side to the balance equation (see section _enebal). If the energy carrier is modelled with load regions, the right hand sides are given for each load region. If no load region pattern is defined, the demand is assumed to be a base load demand.

### 4.1.2 Other Balances

These constraint match the consumption of a specific energy form with the production of this energy form on any of the defined energy levels. They are generated for each load region, if the energy form is modelled with load regions.

\[
\sum_{sv} \varepsilon_{zs\nu e} \times zs\nu e_{...rrllttt} + \sum_{sv} \beta_{zs\nu k} \times zs\nu k_{...rrllttt} - \\
\sum_{sv} zs\nu d_{...rrllttt} - \sum_{sv} \beta_{zs\nu d} \times zs\nu d_{...rrllttt} \geq 0
\]

where
activity of the technology producing energy form $e$ in regions $rr$, load region $lll$ and period $ttt$ (see section _activitiesECT),

$\epsilon_{zsv}$

efficiency of technology $zsv$ in producing $s$,

$zevd....rrlll$ttt

activity of the technology $zevd$ consuming energy form $e$ in region $rr$ and period $ttt$,

$\beta^e_{zsv}$

production of fuel $e$ relative to the main output $\kappa$ by technology $zsv$, and

$\beta^e_{zvvd}$

consumption of fuel $e$ relative to the main output $d$ by technology $zvvd$.

In case technologies are modeled with given production or consumption load curves, the variables are the annual variables multiplied by the share of the total energy flow in this load region $\eta_{zsv}$:

### 4.1.3 Resource Balance

The resources produced by the extraction technologies in a period can come from different cost categories (also called grades), which can, e.g., represent the different effort to reach certain resources. Short-term variations in price due to steeply increasing demand can be represented by an elasticity approach (see section 9.11).

$$\sum_{ttt} \sum_{g} rzfg....rr...ttt \leq rzfg....rr$$

where

$rzfg....rr...ttt$

annual extraction of resource $f$, cost category (grade) $g$ in region $rr$ and period $ttt$, and

$rzfg....rr$

total available amount of resource $f$, grade $g$ in region $rr$.

### 10.2.5 Stock-piles

#### 5 Variables

Generally MESSAGE does not generate any variables related to an energy carrier alone. However, in the case of man-made fuels, that are accumulated over time, a variable that shifts the quantities from one load region or period to the next is generated.

$qfb....rrlll$ttt

where

$q$

identifies stock-pile variables,

$f$

identifies the fuel with stock-pile,

$b$

distinguishes the variable from the equation, and

$rrlll$ttt

are the region, load region, and period identifiers respectively.

The stock-pile variables represent the amount of fuel $f$ that is transferred from period $t$ into period $t + 1$. Note that these variables do not, as usually, represent annual quantities, they refer to the period as a whole. These variables are a special type of storage, that just transfers the quantity of an energy carrier available in one period into the next period. Stock-piles are defined as a separate level. For all other energy carriers any overproduction that occurs in a period is lost.
5.2 Constraints

$q$ is a special level on that energy forms can be defined that are accumulated over time and may be consumed in later periods. One example is the accumulation of plutonium and later use in fast breeder reactors.

The general form of this constraint is:

\[
q_f \ldots rrlltttt - q_f \ldots rrllttt(\text{ttt} - 1) - \sum_v \left[ \Delta t \times (z_{svf} \ldots rrlltttt + \beta^f_{zsv} \times z_{svf} \ldots rrlltttt) - \epsilon_{zfv} \times z_{fv} \ldots rrlltttt \right. \\
- \beta^f_{z\phi v} \times z_{\phi v} \ldots rrlltttt + \Delta t \times \epsilon_{zfv} \times yzfv \ldots rr\ldots(\text{ttt}) - \Delta (t - \tau_{zfv} - 1) \times \rho_{zfv} \times yzfv \ldots rr\ldots(\text{ttt} - \tau_{zfv}) = 0
\]

where

<table>
<thead>
<tr>
<th>$f$</th>
<th>identifier of the man-made fuel (e.g. plutonium, U(_{233})).</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{zsv}$</td>
<td>plant life of technology $v$ in periods,</td>
</tr>
<tr>
<td>$t_{zsvf}$</td>
<td>&quot;first inventory&quot; of technology $zsvf$ of $f$ (relative to capacity of main output),</td>
</tr>
<tr>
<td>$\rho_{zfv}$</td>
<td>&quot;last core&quot; of $f$ in technology $zfv$, see also section _resourceextraction,</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>length of period $ttt$ in years,</td>
</tr>
<tr>
<td>$z_{fv} \ldots rrlltttt$</td>
<td>annual input of technology $zfv$ of fuel $f$ in load region $lll$ and period $ttt$ ($lll$ is &quot;...&quot; if $zfv$ does not have load regions), and</td>
</tr>
<tr>
<td>$yz_{fv} \ldots rr \ldots ttt$</td>
<td>annual new installation of technology $zfv$ in period $ttt$.</td>
</tr>
</tbody>
</table>

10.2.6 6 User-defined Relations

The user-defined relations allow the user to construct constraints that are not included in the basic set of constraints. For each technology the user can specify coefficients with that either the production variables (see section _activitiesECT), the annual new installation variables (see section _capacititesECT) or the total capacity in a year (like it is used in the capacity constraints, see section _capacityconstr) can be included in the relation. The relations can be defined with and without load regions, have a lower, upper or fix right hand side or remain free (non-binding) and may have an entry in the objective function, i.e., the objective function entries of all members of this relation are increased/decreased by this value. There are three types of user-defined constraints (denoted by $n$ for ‘relations1’, $p$ for ‘relations2’, or $C$ for ‘relationsc’ as first character). The entries to the objective function are (without discounting) summed up under the cost accounting rows $car1$ for ‘relations1’ and $car2$ for ‘relations2’ (see chapter _objectivecostcounters). For ‘relationsc’ no additional accounting rows exist, as they are already just single numbers containing the sum over all load regions and time steps.

The formulation of the user-defined relations is given for relations, that are related to the main output of the technologies. It is also possible (e.g., for greenhouse gas emissions) to relate the constraint to the main input of the technology, i.e. the amount of fuel used. In this case the efficiencies would be omitted from the formulation.

Relations without load regions sum up the activities (multiplied with the given coefficients) of all variables defined to be in this constraint. If a technology has load regions, the activity variables for all load regions of this technology are included. If the total capacity of a technology is included, all new capacities from previous periods still operating are
included, if new capacities are included, the annual new installation of the current period is taken.

\[
\sum_{z_{rs}} \left[ r_{mt} \times \sum_{ll} z_{rs} \times \ldots \times l_{ll} \times \epsilon_{z_{rs}} + r_{mt} \times z_{rs} \times \ldots \times \epsilon_{z_{rs}} + \right. \\
\left. \sum_{t} p_{t} \times r_{mt} \times y_{z_{rs}} \times \ldots \times \epsilon_{z_{rs}} \right] \sim r_{hs}^{l}
\]

where

- \(z_{rs}...\ldots l_{ll}l_{tt}l_{ttt}\): activity variables of technologies (lll if modelled with and ‘...’ without load regions),
- \(y_{z_{rs}}...\ldots l_{tttl}\): capacity variables of the technologies,
- \(\epsilon_{z_{rs}}\): efficiencies of the technologies; they are automatically included,
- \(r_{mt}\): relative factor per unit of output of technology \(z_{svd}\) (coefficient) for relational constraint \(m\),
- \(r_{mt}\): relative factor per unit of new built capacity,
- \(r_{mt}\): relative factor per unit of output of technology \(z_{svd}\) (coefficient) for relational constraint \(m\) and load region \(l\),
- \(r_{mt}\): relative factor per unit of new built capacity,
- \(p_{t}\): is 1 for relations with new construction and \(\Delta_{t}\) (period length) for relations with total capacity,
- \(ip\): is 1 for accounting during construction and the plant life in periods for accounting of total capacity,
- \(\sim\): \(\geq, \leq, =, or\ free\) indicating a lower, upper, equality, or free constraint, and
- \(r_{hs}^{l}\): is the right hand side of the constraint.

### 10.2.7 Objective and Cost Counters

#### 7.1 Cost Accounting Rows

The different types of costs (i.e. entries for the objective function) can be accumulated over all technologies in built-in accounting rows. These rows can be generated per load region or per period or for the whole time horizon and contain the sum of the undiscounted costs. They can also be limited. In case of \(func\) the entries are discounted as these are the entries into the objective function. The implemented types are:

<table>
<thead>
<tr>
<th>(func)</th>
<th>objective functions and discounted accounting rows,</th>
</tr>
</thead>
<tbody>
<tr>
<td>(cvar)</td>
<td>variable (related to the production) operation and maintenance costs,</td>
</tr>
<tr>
<td>(cfix)</td>
<td>fix (related to the installed capacity) operation and maintenance costs,</td>
</tr>
<tr>
<td>(ccap)</td>
<td>investment costs; if the investments of a technology are distributed over the previous periods, also the entries to this accounting rows are distributed,</td>
</tr>
<tr>
<td>(cres)</td>
<td>domestic fuel costs,</td>
</tr>
<tr>
<td>(car1)</td>
<td>costs related to the user defined relations of type 1 (see section 7),</td>
</tr>
<tr>
<td>(car2)</td>
<td>costs related to the user defined relations of type 2 (see section 7),</td>
</tr>
</tbody>
</table>

The cost accounting rows are further separated into the following schemes:
7.2 The Objective Function

\[ \text{func} \]

In its usual form, the objective function contains the sum of all discounted costs. All costs related to operation (i.e. resource use, operation costs, taxes on emissions, . . . ) are discounted from the middle of the current period to the first year. Costs related to construction are by default discounted from the first year of the period to the first year. By using the facility of distributing the investment related costs over the construction time these costs can be distributed over some years before or equal to the current one (see section _distributionsofinv).

The objective function has the following general form:

\[
\sum_r \sum_t \left[ \beta^t_m \Delta t \sum_{zsvd, lll} \left\{ \varepsilon_{zsvd} \times \text{ccur}(zsvd, t) + \sum_{i=1,2,c} \sum_{m} \rho_{zsvd}^{m\text{nl}} \times \text{cari}(ml, t) + \sum_{zsvd} \sum_{\tau=t-\tau_{zsvd}}^t \Delta \tau \times y_{zsvd..\tau} \times \text{cfi}(zsvd, \tau) + \sum_{g} \sum_{l} \sum_{p} \sum_{rzg,...,rrllllttt} \times \text{cres}(zrg, t) \right\} + \beta^t_b \Delta (t-1) \sum_{zsvd} \sum_{\tau=t}^{t+\Delta t} \left\{ y_{zsvd..\tau} \times \text{ccap}(svd, \tau) \times f_{ru_{zsvd,\tau}} \right\} \right] \rightarrow \text{min}
\]

with:

\[
\beta^t_b = \left[ \frac{1}{1 + \frac{dr}{100}} \right]^{t-t_0}, \quad \beta^t_m = \left[ \frac{1}{1 + \frac{dr}{100}} \right]^{t+\Delta t-t_0},
\]
Discounting of Costs

The whole time horizon of the calculations is divided into periods of optional length. All variables of MESSAGE are represented as average over the period they represent, resulting in a step-function. All entries in the objective function are discounted from the middle of the respective period to the first year, if they relate to energy flow variables and from the beginning of that period if they represent power variables. The function to discount the costs has the following form:

\[
c_t = \frac{C_r}{\prod_{k=1}^{t-1} \left(1 + \frac{d_r}{100}\right)^{\Delta k} \times f_i}
\]

where
### 8.2 Distributions of Investments

Investment costs can be distributed over the construction time. As these points in time are closer to the beginning of the time horizon, investments become more expensive, this represents interest during construction. MESSAGE allows for two options:

<table>
<thead>
<tr>
<th>Distribution Type</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>shifted</strong></td>
<td>all costs are paid in the time period(s) previous to the start of operation. This is usually used for models with short period lengths,</td>
</tr>
<tr>
<td><strong>half-half</strong></td>
<td>half of the investments are paid in the period before the start of operation, the other half is paid in the period when the technology goes into operation. With this, the period when the technology starts operating is the same as the construction period. This is usually used for models with long time periods.</td>
</tr>
</tbody>
</table>

Investment costs are spread evenly over the construction time. In reality the investment costs follow a bell-shape, but the resulting error after discounting and summing up over the construction time is very small. There still remains only one entry into the objective function, which is modified according to the sum over the distribution results.

### 8.3 The Contribution of Capacities Existing in the Base Year

The possible contribution of an installation that exists in the base year is kept track of over time. There are two possibilities to give the necessary information to MESSAGE.

1. Define the capacities that were built in the years \( iy_r, \ldots, iy_r \tau + 1 \), with \( iy_r = \) base year and \( \tau = \) plant life in years explicitly. These capacities are then distributed to historic periods of the length \( \nu \).

2. Define the total capacity, \( c_0 \), that exists in \( iy_r \) and the rate at which it grew in the last \( \tau \) years, \( \gamma \). This information is then converted to one similar to 1. by using the function:

\[
y_0 = c_0 \frac{\gamma^{-\nu} - 1}{\nu(\gamma^{-\tau} - 1)}, \quad y_t = y_0 \gamma^{-t \times \nu}, \quad t = 1(1) \frac{\tau}{\nu}
\]

where

- \( y_t \) is the annual construction in period \( t \), \((0 = \) base year)\,.
- \( \gamma \) is the annual growth of new installations before the base year,
- \( c_0 \) is the total capacity in the base year,
- \( \tau \) is the plant life, and
- \( \nu \) is the length of the periods in that the time before the base year is divided.

The right hand sides in the capacity constraints are derived by summing up all the old capacities that still exist in a certain period (according to the plant life). If the life of a technology expires within a period, MESSAGE takes
the average production capacity in this period as installed capacity (this represents a linear interpolation between the
starting points of this and the following period).
In case of formulation 2. one has to consider that some of the capacity goes out of operation between the base year
and the first year.

8.4 Capacities which Operate Longer than the Time Horizon

If a capacity of a technology is built in one of the last periods its life time can exceed the calculation horizon. This fact
is taken care of by reducing the investment costs by the following formula:

\[
C^*_t = C_t \times \frac{\sum_{k=1}^{\nu} \prod_{\tau=t}^{t+k-1} \frac{1}{1 + dr_{\tau}} \sum_{j=1}^{\tau_p} \prod_{\tau=t}^{t+j-1} 1}{\sum_{k=1}^{\nu} \prod_{\tau=t}^{t+k-1} \frac{1}{1 + dr_{\tau}}}
\]

where

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu )</td>
<td>the number of years the technology exists after the end of the calculation horizon,</td>
</tr>
<tr>
<td>( dr_{\tau} )</td>
<td>the discount rate for year ( \tau ),</td>
</tr>
<tr>
<td>( \tau_p )</td>
<td>the plant life in years,</td>
</tr>
<tr>
<td>( C_t )</td>
<td>the investment cost in year ( t ), and</td>
</tr>
<tr>
<td>( C^*_t )</td>
<td>the reduced investment.</td>
</tr>
</tbody>
</table>

8.5 The Mixed Integer Option

If the LP-package used to solve a problem formulated by MESSAGE has the capability to solve mixed integer prob-
lems, this can be used to improve the quality of the formulated problems, especially for applications to small regions.
The improvement consists in a definition of unit sizes for certain technologies that can only be built in large units.
This avoids for instance the installation of a 10 kW nuclear reactor in the model of the energy system of a city or small
region (it can only be built in units of e.g., 700 MW). Additionally this option allows to take care of the “economies
of scale” of certain technologies.

This option is implemented for a technology by simply defining the unit size for this technology (keyword cmix). The
according capacity variable is then generated as integer in the matrix, its value is the installation of one powerplant of
unit size.

If a problem is formulated as mixed integer it can be applied without this option by changing just one switch in the
general definition file (keyword mixsw). Then all capacity variables are generated as real variables.


[18] Bas Eickhout, Gert Jan van den Born, Jos Notenboom, M van Oorschot, JPM Ros, DP Van Vuuren, and HJ Westhoek. Local and global consequences of the EU renewable directive for biofuels: testing the sustainability criteria. *Local and global consequences of the EU renewable directive for biofuels: testing the sustainability criteria*, 2008.


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