Supplementary Information for

Decarbonization pathways and energy investment needs for developing Asia in line with well below 2 °C

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## Description of models and methods

### 1.1 MESSAGE modeling framework

The energy systems component of the IAM framework employed in this study, MESSAGEix (Model for Energy Supply Strategy Alternatives and their General Environmental Impact), is a linear programming (LP) energy-economy-environment-engineering (4E) model with global coverage (Fricko et al., 2017; Huppmann et al., 2018; Krey et al., 2016). As a whole-systems optimization model, MESSAGE is primarily used for medium- to long-term energy system planning, energy policy analysis, and scenario development. In addition, the version of MESSAGE employed in this study includes a reduced-form emulator of GLOBIOM (the GLObal BIOsphere Model) to consistently assess the implications of utilizing bioenergy of different types and to integrate the GHG emissions from energy and land use. This model is then linked to the aggregated macro-economic model MACRO to assess economic implications and to capture economic feedbacks.

This study presents the results from four climate policy scenarios consistent with the Shared Socioeconomic Pathway SSP2, a ‘middle-of-the-road’ narrative for future socio-economic development. A full documentation of the SSP storylines and the database can be found in the SSP database (https://tntcat.iiasa.ac.at/SspWorkDb). Each SSP has been implemented by multiple IAM models. There are thus alternative interpretations from different IAM models for each of the SSPs. For each SSP, a so-called Marker Scenario was selected from the available model interpretations. MESSAGEix-GLOBIOM, the model we employed in this study, was used to generate the SSP2 marker scenarios. The marker scenarios can be interpreted as representatives of the different storylines. The elaborations of the different markers provide a consistent story across the different SSPs. In addition, other IAM elaborations for specific SSPs can be used as an indication of the SSP uncertainty space.

The modeling framework is now open-source and publicly available at the git-hub repository (<https://github.com/iiasa/message_ix>), and the detailed documentation can be found at (<https://message.iiasa.ac.at/en/stable>). Here we only introduce a succinct form of the objection function and a brief explanation of its paradigm, presented as below.

Objective function



Indices

Index of nodes (regions)

Index of years

Index of technologies

Index of commodities

Index of grades of energy resource

Index of modes of technology operation

Index of sub-annual time periods

Index of emission types

Index of land use scenarios

Parameters

Discount factor

Resource cost

Investment cost

Construction time factor

End of horizon factor

Fix cost

Variable cost

Emission scaling factor

Emissions tax rate

Land cost

Decision Variables

Extraction of non-renewable resources

Newly installed capacity

Maintained capacity

Activity of a technology

Auxiliary variable for aggregate emissions

Relative share of land-use scenario (for land-use model emulator)

The model is subject to a bunch of constraints, including constraints on resource extraction, energy commodity balance, technical and engineering constraints, emissions targets, and renewable integration etc. Take renewable integration for example, there are three types of constraint being taken into account, i.e., capacity reserve constraint, operating reserve (flexibility) constraint, and curtailment constraint. The constraint on capacity reserve requires sufficient firm generating capacity to meet peak load and contingencies. The operating reserve constraint requires some flexibility in system to ensure grid stability. The curtailment constraint represents curtailment that can only be addressed by storage or load management.







where the index is the rating of non-dispatchable technologies relative to aggregate commodity use, the auxiliary variable is firm generating capacity, the parameters and define the technology efficiency. The parameters *, , , , ,*  denote duration time, capacity factor, reliability factor, peak load factor, flexibility factor, and duration time relation respectively. Detailed description of the treatment of renewable energy reliability and variability in MESSAGE by using load, resource availability, and system dispatch data with high temporal resolution is presented in (Sullivan et al., 2013) and (Johnson et al., 2017).

As shown above, the model entails technology-rich basis for representing energy dynamics over a multi-period time horizon. The core function aims to minimize the global cost of supplying energy services over a given time horizon (in this study from 1990 to 2110). The mode is calibrated to the past situations, and the future costs of all nodes (regions) and all years are discounted to present value. With parameterization of the existing stocks of energy related equipment in all sectors, the characteristics of available future technologies, as well as present and future sources of primary energy supply and their potentials, the model decides the investment and operation of technologies, primary energy supply, and energy trade among nodes. The reporting years are the final years of periods which implies that investments that lead to the capacities in the reporting year are the average annual investments over the entire period the reporting year belongs to. MESSAGE can both operate perfect foresight over the entire time horizon, limited foresight (e.g., two or three periods into the future) or myopically, optimizing one period at a time (Keppo and Strubegger, 2010).

The MESSAGE framework’s principal results comprise, among others, estimates of technology-specific multi-sector response strategies for specific climate stabilization targets, such as well below 2°C. In the case of decarbonization pathways, the model identifies the least-cost portfolio of mitigation technologies, with the choice of the individual mitigation options across regions, fuels and sectors driven by the relative economics of the abatement measures, assuming full temporal and spatial flexibility (i.e., emissions-reduction measures are allowed to occur when and where they are cheapest to implement). Non-energy related investments (e.g. air pollution controls and food security) are not directly considered in the MESSAGE cost functions but are rather captured externally.

The caveat exists as specific parameters are not known with the desired level of confidence. Nevertheless, parametrizing a model requires the researcher to carefully and deliberately choose values that are a best estimate at the time of conducting the analysis (Huppmann et al., 2019).

### 1.2 Calculation of energy efficiency investments

Demand-side energy efficiency investments across the end-use sectors (buildings, transport, industry) are calculated by using a methodology that was originally developed for the Global Energy Assessment (Riahi, 2012), then adapted in the LIMITS project (McCollum et al., 2013), and further refined in the CD-LINKS project (McCollum et al., 2018). The methodology makes use of two separate energy efficiency components, as denoted in Eqs. (5)-(7). The first component is the ‘base-year efficiency’ component. This is calculated by taking the level of energy efficiency investments estimated by the IEA for the year 2016 (IEA, 2017)[[1]](#footnote-1), and then scaling those efficiency investments with total final energy demand in the model’s scenarios (relative to 2015 final energy demand) to arrive at future estimates for those same values. The second component is ‘supply-side offset’, in which the final energy demand in the tightened policy scenarios (NDC, 2C and 1.5C) is compared to that in the reference case (CPol); it is then assumed that, in equilibrium, the investments made to reduce energy demand equal the investments that are simultaneously offset on the supply side.







where  is the total investment of energy efficiency in Scenario *s*,  and  are the first and second component in Scenario ‘*s*’ respectively.  is the investment of energy efficiency in the base year of 2015, for which we take the value of 63 billion US$ from the IEA estimation for 2016.  is the final energy consumption in Scenario *s* in year *t*.  is the final energy consumption in the base year of 2015.  is the supply-side investment in Scenario *s* in year *t*.  is the gross domestic product in Scenario *s* in year *t*.

The way of calculating energy efficiency investment in this study is a compromised way as the detailed demand-side energy efficiency technologies are not yet included in the modeling work. As a result, we had to follow this ‘top-down’ approach from previous studies for this approximation. This is a caveat of the current modeling work. And further modeling with detailed energy efficiency technologies via a real ‘bottom-up’ approach is expected.

### 1.3 Calculation of investments for other SDGs

* Air pollution

The GAINS model (Greenhouse Gas - Air Pollution Interactions and Synergies) is used to estimate the investments needed for air pollution control technologies that will limit air pollutant emissions to certain levels consistent with an extrapolation of current air quality legislation in cities or countries throughout the world. The GAINS model allows a systematic search for cost-effective combinations of emission control measures that meet user-supplied air quality and greenhouse gas targets, taking into account regional differences in emission control costs and atmospheric dispersion characteristics. There is a ‘soft link’ between MESSAGEix-GLOBIOM and GAINS for calculating the investment needs for air quality. That said, all the activity data from the four scenarios, i.e., projections for emissions and economic activities of different types—such as energy supply and demand, industrial production, transport and agriculture—are provided to GAINS from MESSAGEix-GLOBIOM. See Amann et al. (2011) for more details on the GAINS methodology, and Rafaj et al. (2018) on the assumptions, emission standards and control technologies applied to compute future emissions.

* Food security

Food security is interpreted in this study as avoiding any further increase in those at risk of hunger (over and above the baseline) due to energy and climate mitigation policies that promote a transformation of the global energy system. Unless appropriate safeguards are put in place, such policies can potentially have negative side-effects on food security by increasing agricultural prices, as a result of non-CO2 emissions abatement, greenhouse gas tax penalties on residual emissions, bioenergy expansion and afforestation (Hasegawa et al., 2018). Therefore, in this work we define food policy packages that prevent such negative side-effects. In other words, the ‘investments’ that we estimate for food security are actually the food policy expenditures needed to compensate the poor for any increases in food costs. These calculations are done externally to MESSAGEix-GLOBIOM. Carbon prices are taken from MESSAGEix-GLOBIOM, and then these are used to estimate the food policy expenditures (investments) required to limit those at risk of hunger.

* Clean water

A specialized version of the MESSAGEix-GLOBIOM model is used for the analysis. The model is enhanced to include a reduced-form representation of the water supply sector. The approach accounts for the rapid expansion of piped water access and treatment in the developing world, as well as the maintenance and replacement of existing water infrastructure in developed economies. Wastewater recycling and desalination technologies are also enabled as approaches to reduce freshwater withdrawals from rivers and underground aquifers. Water infrastructure investment needs, as well as additional energy and emissions resulting from the water sector development, are accounted for.

## Regional definition

### 2.1 Regions in the original model

The combined MESSAGE framework has global coverage and divides the world into 11 regions, among which “Centrally Planned Asia and China” (CPA), ‘South Asia’ (SAS) and ‘Other Pacific Asia’ (PAS) cover all the developing Asian countries involved in this study. The detailed country definitions of the 11 MESSAGE regions can be found in the documentation of the model (Krey et al., 2016).

Table 1 List of 11 MESSAGE regions by country

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

### 2.2 Regions in this study

Developing Asia (or Asia in Supplementary Data) in this study includes most developing countries in Asia with the exception of the Middle East, Japan, South Korea and Former Soviet Union states. Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, China (incl. Hong Kong SAR, Macao SAR and Taiwan, hereafter China), Democratic People's Republic of Korea, East Timor, India, Indonesia, Lao People's Democratic Republic, Malaysia, Maldives, Mongolia, Myanmar, Nepal, Pakistan, Papua New Guinea, Philippines, Republic of Korea, Singapore, Sri Lanka, Thailand, Viet Nam. As the model searches the least-cost mitigation options among the 11 regions, the results presented in this study for the countries in developing Asia do not suggest any emissions reduction obligation or responsibility, rather they indicate a region-level situation where the least-cost requirement for satisfying the global carbon budget is met under the model’s myriad assumptions.

Three sub-regions in this study include China, India and SEAO (Southeast Asia and other countries), in which SEAO comprises Southeast Asia and other countries and regions except China and India in all countries of developing Asia defined in this study, including: Afghanistan, Bangladesh, Bhutan, Brunei Darussalam, Cambodia, Democratic People's Republic of Korea, East Timor, Indonesia, Lao People's Democratic Republic, Malaysia, Maldives, Mongolia, Myanmar, Nepal, Pakistan, Papua New Guinea, Philippines, Republic of Korea, Singapore, Sri Lanka, Taiwan (China), Thailand, Viet Nam.

In the modelled regions, a big economy may dominate some results of the respective region. For instance, China may account for approximately 80-90% of CO2 emissions in CPA over a long time horizon. In order to separate out the results of a single country, such as China and India, from their respective regions, we calculate the country’s contribution to the total of the region with respect to GDP per capita over the whole timeframe, and then we multiply these share numbers with the variables related to energy consumption, CO­2 emissions and investments of the model’s native region values. This is a compromised way given that the large differences in energy/CO2 intensity and economic composition of different regions. An ideal way is to perform such analysis on the country-level modeling results, which is still ongoing work.

In fact, downscaling the regions into specific counties is an ongoing work.

## Results for the three sub-regions

### 3.1 Primary energy

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Fig. 1. Projected primary energy of the three sub-regions from 2016 to 2050 under different scenarios.

### 3.2 Electricity generation mix

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|  |  |

Fig. 2. Projected electricity generation mix of the three sub-regions from 2016 to 2050 under different scenarios.

### 3.3 Final energy consumption



Fig. 3. Projected final energy consumption of the three sub-regions from 2016 to 2050 under different scenarios.

### 3.4 CO2 emissions



Fig. 4. Projected CO2 emissions of the three sub-regions under different scenarios.

### 3.5 CO2 emissions associated with final energy use



Fig. 5. Projected CO2 emissions associated with final energy use of the three sub-regions under different scenarios.

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1. Because the IEA published only a global number of energy efficiency investments for the year of 2015, and this number for China as of 2016, which is approximately 63 billion US$. We then use this number as the base year value. [↑](#footnote-ref-1)