The IIASA Energy - Multi Criteria Analysis (ENE-MCA) Policy Tool

Additional Documentation

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Description of the MESSAGE systems engineering global energy model

The MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) integrated assessment model (IAM) is a global systems engineering optimization model used for medium- to long-term energy system planning, energy policy analysis, and scenario development (Messner and Strubegger 1995). Developed at the International Institute for Applied Systems Analysis (IIASA) for more than two decades, MESSAGE is an evolving framework that, like other global IAMs in its class (e.g., AIM, EPPA, IMAGE, IPAC, and MiniCAM), has gained wide recognition over time through its repeated utilization in developing global energy and emissions scenarios, for example its use in previous IPCC reports (e.g., see Nakicenovic and Swart (Nakicenovic and Swart 2000)).

The MESSAGE model divides the world up into eleven (11) regions (Figure 1, Table 1) in an attempt to represent the global energy system in a simplified way, yet with many of its complex 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. Trade flows (imports and exports) between regions are monitored, capital investments and retirements are made, fuels are consumed, and emissions are generated. In addition to the energy system, the model includes also the other main greenhouse-gas emitting sectors, agriculture and forestry. MESSAGE tracks a full basket of greenhouse gases and other radiatively active gases – CO_2 , CH_4 , N_2O , NO_x , volatile organic compounds (VOCs), CO, SO_2, PM, BC, OC, NH_3, CF_4, C_2F_6, HFC125, HFC134a, HFC143a, HFC227ea, HFC245ca, and SF_6 – from both the energy and non-energy sectors (e.g., deforestation, livestock, municipal solid waste, manure management, rice cultivation, wastewater, and crop residue burning). In other words, all Kyoto gases plus several others are accounted for.

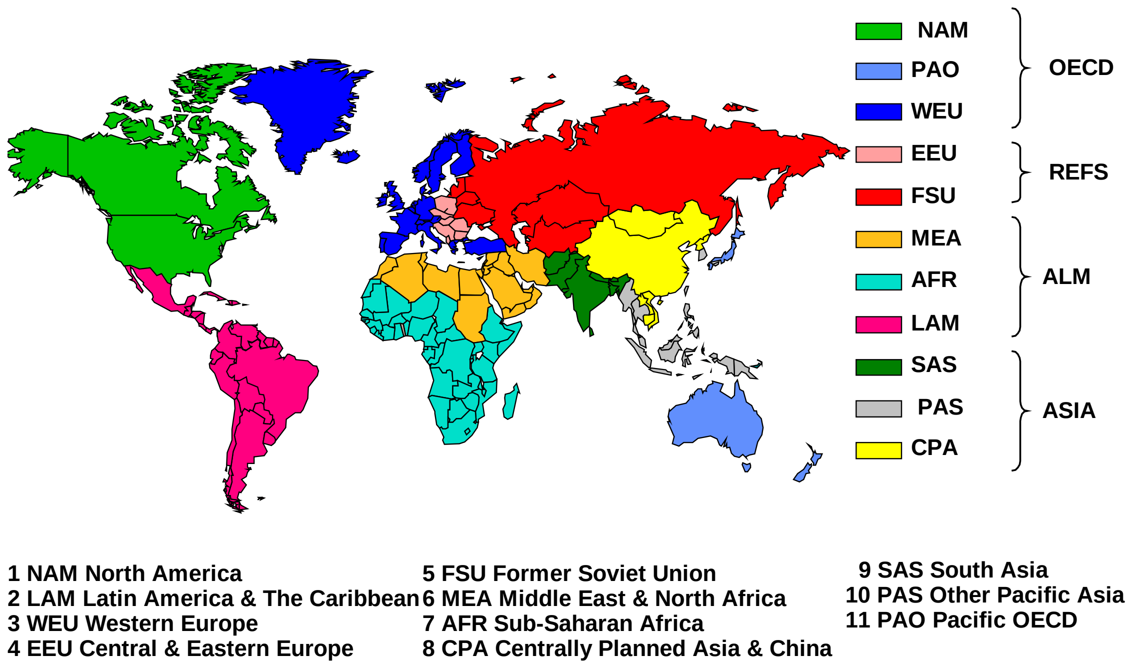

Figure 1 Map of 11 regions in MESSAGE model

Table 1 Listing 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), 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)
LAC	**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)

MESSAGE solves based on a linear programming model, in which optimization is performed by minimizing total discounted energy system costs over the entire model time horizon (1990-2110). All primary energy resources are characterized by supply (cost) curves, and all energy technologies are characterized by investment, variable, and O&M costs. Energy prices are calculated endogenously, and investment decisions and fuel choices are made based on the least-cost decision-making principle, subject to constraints (both technical and policy), thus reflecting a perfectly functioning global energy market, to the extent possible. The model is able to choose between both conventional and non-conventional technologies and fuels (e.g., advanced fossil, nuclear fission, biomass, and renewables), and in this respect the portfolio of technologies/fuels available to the model obviously has an important effect on the model result. In the version of the model used in this study, we consider a portfolio of technologies whose components are either in the early demonstration or commercialization phase (e.g., coal, natural gas, oil, nuclear, biomass, solar, wind, hydro, geothermal, carbon capture and storage, hydrogen, biofuels, and electrified transport, to name just a subset). Notably, this portfolio includes bio-CCS, a technology that can potentially lead to negative emissions (i.e., permanent underground storage of CO_2 which was originally pulled out of the atmosphere by photosynthesis). Exceedingly futuristic technological options, such as nuclear fusion and geo-engineering, are, however, not included in the current version of the MESSAGE model.

Price-induced changes in energy demand (i.e., elastic demands) are also modeled in our version of MESSAGE. In short, we use an approach, similar to that described in Messner and Schrattenholzer (Messner and Schrattenholzer 2000) , which systematically assesses regional conservation costs for different levels of prices and demand. For each of the eleven MESSAGE regions, we estimate a conservation cost (i.e., demand response) curve for each of the six end-use demand categories in MESSAGE (relating to industrial, residential, commercial, and transportation demands). These curves are meant to represent the potential for energy conservation and efficiency improvements in each region, given policies that raise the price of energy services compared to the baseline scenario. Put more simply, a specified quantity of demand reduction can be achieved at a particular cost. The quantity and cost steps for each of these curves are generated via a multi-stage iterative solution process between MESSAGE and a top-down, macro-economic model of the global economy.[1] This integrated modeling framework is known as MESSAGE-MACRO (Messner and Schrattenholzer 2000) and must only be run once, since the five-step demand response curves that are generated can subsequently be used in all of our non-MACRO model runs. Such a procedure substantially reduces total computing time, when compared to the alternate method of solving MESSAGE-MACRO iteratively for every single scenario, and for this reason several recent studies have utilized this simplified demand response methodology (Keppo and Strubegger 2009; Krey and Riahi 2009; O'Neill, Riahi et al. 2010). Note that the demand-side conservation costs derive from the elasticities in the macro-economic model, and these costs represent both technological and behavioral measures for achieving energy efficiency and conservation, while considering the substitutability of capital, labor, and energy as inputs to the production function at the macro level. In this sense, demand reduction due to behavioral change is monetized in a way similar to technology-related costs. In essence, the conservation costs derived from the macro model represent the costs that society would be willing to bear to bring demand and prices into equilibrium. They do not, however, include macro-economic costs (e.g., GDP, welfare, and consumption losses).

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[1] Development of the conservation cost curves (CCCs) is relatively straightforward in practice. First, we run a baseline scenario and a set of five stabilization runs using the integrated MESSAGE-MACRO modeling framework. After several iterations of a given run, the two models reach convergence, and at that point the demand responses in each region are in equilibrium with the price increases resulting from a carbon constraint (or any other energy-related constraint that causes prices to increase or decrease, i.e., an energy security constraint). Once the six MESSAGE-MACRO runs have been completed (baseline + five stabilization runs), we obtain CCCs for each of the six end-use demands in each region. The equilibrium prices from the five stabilization runs are used directly as costs for the conservation steps, because these price levels trigger the demand response. The differentials between the six demand levels (for each of the six demands per region) represent the corresponding sizes of the steps.

The costs shown in the main text of the paper are calculated as the cumulative sum between 2010 and 2030 (discounted at 5% annually) of energy system investments (including supply and demand as well as climate change mitigation, energy security, and pollution control investments), operation and maintenance, fuel, and nonenergy mitigation costs.

Further and more detailed information on the MESSAGE modeling framework is available, including documentation of model set-up and mathematical formulation (Messner and Strubegger 1995) and the model’s representation of technological change and learning (Roehrl and Riahi 2000; Riahi, Rubin et al. 2004; Rao, Keppo et al. 2006).

Description of the MAGICC global climate model and the probabilistic assessment of climate system impacts

MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change), version 5.3, has been used in this study to estimate the climate system impacts of the varying greenhouse gas emission trajectories of the scenarios in the ensemble. MAGICC is a reduced complexity coupled global climate-carbon cycle model, in the form of a user-friendly software package that runs on a personal computer (Wigley 2008). In its standard form, MAGICC calculates internally consistent projections for atmospheric concentrations, radiative forcing, global annual-mean surface air temperature, ice melt, and sea level rise, given emissions trajectories of a range of gases (CO_2, CH_4, N_2O, CO, NO_x, VOCs, SO_2, and various halocarbons, including HCFCs, HFCs, PFCs, and SF_6). The time horizon of the model extends as far back as 1750 and can make projections as far forward as 2400. The climate model in MAGICC is an upwelling-diffusion, energy-balance model, which produces output for global- and hemispheric-mean temperature and for oceanic thermal expansion. 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. The primary developer of MAGICC is Dr. Tom Wigley at the National Center for Atmospheric Research in the United States. The modeling package has been used in all IPCC Assessment reports, dating back to 1990, and its strength lies in its ability to replicate the more complex global climate models, which run on supercomputers. For our analysis, we use a version of the software that is consistent with the IPCC Fourth Assessment Report, Working Group 1, except that the model has been slightly, though importantly, modified to permit the explicit treatment of black and organic carbon (BC and OC) and their impacts on the global climate.[2]

Moreover, in contrast to how MAGICC is typically used, we run the model stochastically in order to generate probabilistic estimates of climate system responses (e.g., temperature increase or atmospheric GHG concentrations), a methodology first described in Keppo et al. (Keppo, O'Neill et al. 2007). Whereas a typical user of MAGICC, who is interested in generating (deterministic) point estimates of climate system responses, would run the user-interface version of the model by feeding in a single set of

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[2] We gratefully acknowledge Dr. Steve Smith of the Pacific Northwest National Laboratory (USA) for sharing a modified version of MAGICC (v5.3), which explicitly takes user-specified trajectories of BC and OC as inputs.

emissions trajectories under a single set of assumptions for key climate system parameters (e.g., climate sensitivity, ocean diffusivity and aerosol forcing), we automate a process to integrate MAGICC's executable and configuration files into a Java code script, in order to run a single set of trajectories under 100 different sets of parameter assumptions. In other words, we explore the uncertainty in climate system responses for a single emissions trajectory (from MESSAGE scenario output) by using a probability density function (PDF) to describe the following parameters: climate sensitivity, ocean diffusivity, and aerosol forcing. Therefore, instead of simply saying that, for a given mitigation scenario and emissions trajectory, "the projected maximum global temperature increase over the course of the twenty-first century is estimated at X ^{o}C", we can say something like "the probability of staying below X ^{o}C maximum global temperature increase is Y%."

The reason we estimate projections of climate system responses probabilistically is because of the large amount of uncertainty in key climate system parameters. Perhaps the most important among these, and one of the most uncertain, is climate sensitivity, which refers to the equilibrium global average warming expected if CO_2 concentrations were to be sustained at double their pre-industrial values. This value is estimated, by the IPCC Fourth Assessment Report (AR4) "as likely to be in the range 2 to 4.5 ^{o}C with a best estimate of about 3 ^{o}C" (IPCC 2007). Contributing to the IPCC AR4 were a number of studies that estimate PDFs for climate sensitivity (see Meinshausen et al. (Meinshausen, Meinshausen et al. 2009), and O'Neill, Riahi, et al. (O'Neill, Riahi et al. 2010) for good reviews). And as Figure 2 illustrates, the shape of these PDFs can be quite different. In our study, we have divided each of these PDFs into 100 steps between 0.1 and 10 ^{o}C. PDFs for ocean diffusivity and aerosol forcing, two other important though uncertain climate parameters, were then generated by correlating them with climate sensitivity at each step (Meinshausen 2006). Although there is the potential to use any of the PDFs shown in Figure 2, we focus on the Forest et al. (Forest, Stone et al. 2002) distribution with uniform priors (bold line in figure), since it is near the middle of the range found in the literature and also so that the results shown here are directly comparable to those of previous studies on this topic (e.g., O'Neill, Riahi, et al. (O'Neill, Riahi et al. 2010)). Note that a climate sensitivity value of 3 ^{o}C has a likelihood of 53.9% using the PDF from Forest et al. (Forest, Stone et al. 2002).

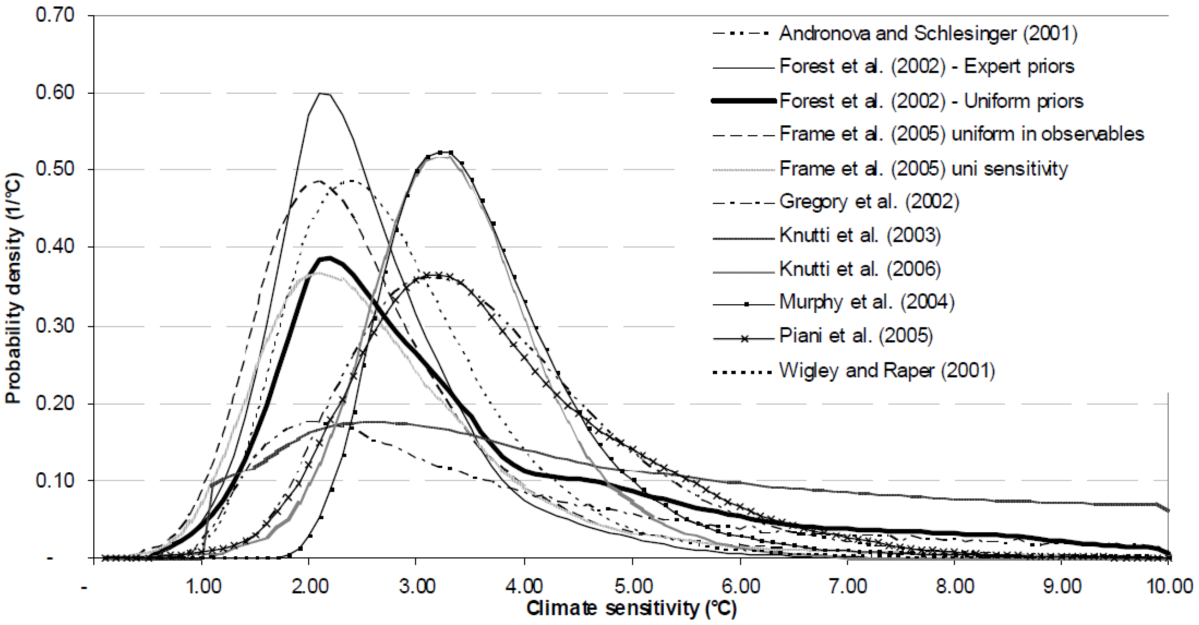

Figure 2 Probability density functions (PDF) for climate sensitivity (figure from O'Neill et al. (O'Neill, Riahi et al. 2010); reproduced with permission)

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