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

User Manual

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The online tool is available at:
www.iiasa.ac.at/web-apps/ene/GeaMCA

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About the Global Energy Assessment

The Global Energy Assessment involves specialists from a range of disciplines, industry groups and policy areas in defining a new global energy policy agenda, one that is capable of transforming the way society thinks about, uses and delivers energy and to facilitate equitable and sustainable energy services for all, in particular the two billion people who currently lack access to clean, modern energy.

Coordinated by the International Institute for Applied Systems Analysis (IIASA), the GEA is led by some of the world's leading energy experts, in research, academia, business, industry and policy, representing both the developed and the developing world. GEA is the first ever fully integrated energy assessment analyzing energy challenges, opportunities and strategies for developing industrialized and emerging economies. It is supported by government and non-governmental organizations, the United Nations System and the private sector.

The Assessment is subject to rigorous and independent analysis and review. The final assessment is published by Cambridge University Press and is available online at www.globalenergyassessment.org.

Disclaimer

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1. Introduction

Researchers at the International Institute for Applied Systems Analysis (IIASA), building on work carried out within the framework of the Global Energy Assessment (GEA), have developed an interactive web-based scenario analysis tool that permits the concurrent assessment of synergies and trade-offs between multiple energy objectives at the global scale. This software, known as the IIASA Energy–Multi Criteria Analysis Policy Tool (ENE-MCA), is designed to assist national policy makers in their strategic policy planning processes. The tool extends work undertaken for the GEA and, as such, is built on the extensive set of global energy and environmental scenarios that have been generated as part of the GEA process. This document serves as an introduction to the ENE-MCA tool and as a brief manual for the typical user.

2. Motivation & Rationale

The energy challenges facing society are as varied as they are great, and in charting a path toward a truly sustainable energy future, a number of different objectives will need to be fulfilled. These include:

- Avoiding dangerous climate change
- Achieving near-universal energy access
- Improving energy security
- Reducing air and water pollution and the consequent impacts on human health and ecosystems
- Minimizing ancillary risks
- Maintaining the affordability and reliability of energy supplies for healthy socio-economic growth

Simultaneously achieving each of these important targets is a major challenge for all societies, current and future. However, it is already quite evident that not all stakeholders (governments, private industry, individual consumers) prioritize the multiple objectives in exactly the same way or to the same degree of importance. In fact, more often than not, the objectives seem to be competing for attention. This partly explains the uneven progress seen across the different fronts (McCollum et al., 2011).

The primary aims of the ENE-MCA Policy Tool are to add some analytical rigor and objectivity to the often subjective discussion surrounding the concept of energy sustainability and to do this in such a way that the specific needs and priorities of the decision maker are considered. Due to the enormous synergies and, to a lesser extent, trade-offs between the various sustainability objectives, the tool takes a broad, systems approach. By allowing a large number of alternate energy–environmental–economic futures to be compared within a common framework, analysts and decision makers are able to gain a quick understanding of how alternate worldviews can shape the future of the global energy system in dramatically different ways, in terms of technology deployment, funding requirements, greenhouse gas emissions and climate change, air pollution and health impacts, and energy security.

The ENE-MCA tool is operationally straightforward, giving users from diverse backgrounds and with varied interests the opportunity to quickly "manipulate" a subset of energy sustainability objectives (climate mitigation, air pollution and health, energy security, and affordability) by ranking/prioritizing them relative to each other via a user-friendly interface. This kind of multi-criteria approach to energy policy analysis is important, especially in the sustainability context, because the achievement of some energy objectives cannot be easily converted into financial metrics, meaning that a strictly economic comparison of them is neither simple nor advisable. An important limitation of the tool, however, is that the underlying scenarios and data have a global focus, rather than national.

An elaborated description of the ENE-MCA policy tool is found in Section 4 of this document. Before discussing these technicalities, however, a summary of the underlying data and scenarios is given.

3. Scenarios and Data Underlying the Tool

A thorough analysis of synergies and trade-offs among energy sustainability objectives demands a broad scenario space, stretching the potential development of the energy system in several dimensions. For this reason, the ENE-MCA tool is populated with more than six hundred energy scenarios, each of which meets the different objectives (particularly, climate mitigation, air pollution and health, energy security, and affordability)[1] in a unique way. For instance, some scenarios advance new climate policies but do not consider any new energy security and/or air pollution legislation, while other scenarios prioritize only security but at the same time ignore the other objectives. With this kind of set-up, the focus of the analysis is centered on the uncertainties related to future policy priorities rather than on exogenous technological or socio-economic uncertainties.

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[1] Note that achievement of the access objective is taken as given here. This simplification was made because achieving energy access, compared to other objectives, has relatively low impacts on energy use and GHG emissions.

All of the scenarios in the large ensemble spring from the illustrative GEA-*Mix* pathway of the Global Energy Assessment (Riahi et al., 2012). Assumptions about the future drivers of global change, namely population and gross domestic product (GDP) at national and regional levels, as well as the future availability of technologies, are the same as in GEA-*Mix*. The only major difference is that, because no baseline scenarios are developed in the GEA (rather, only pathways that meet a pre-defined set of societal targets for energy sustainability), it was necessary in this analysis to relax some of the constraints in the *GEA-Mix* pathway in order to create a "business-as-usual" baseline for energy system development. Then, from this baseline (for which global primary energy consumption is shown in Figure 1, simply for illustration), several hundred additional scenarios were generated by imposing varying combinations of policy constraints at varying levels of stringency across several different dimensions. In particular, for each scenario two types of constraints were imposed: one on the shape of the global annual GHG emissions trajectory over the course of the 21st century, and another on the maximum amount of energy that can be imported into each world region in a particular year, starting in 2030. On top of this, four different sets of air quality legislation packages are implemented, in order to stretch the scenario space in the air pollution and health dimension.

Figure 2 provides a simple graphical representation of how the multitude of scenarios in the ensemble is constructed. Notably, there are thirty-nine different greenhouse gas emissions trajectories represented, ranging from extremely high baseline futures (>1000 ppmv CO_2-eq in 2100) to low climate stabilization scenarios (<450 ppmv CO_2-eq in 2100) and many points in between (Figure 3). Similarly,

BOX 1 Models employed in the scenario development process

The MESSAGE integrated assessment modeling framework is used to generate the diverging alternate energy futures that comprise the large ensemble. MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) 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; Riahi et al., 2007). 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 (2000)).

The MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) model 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, which 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 (Wigley, 2008). MAGICC has been used in all previous IPCC Assessment reports, and its strength lies in its ability to replicate some of the more complex global climate models.

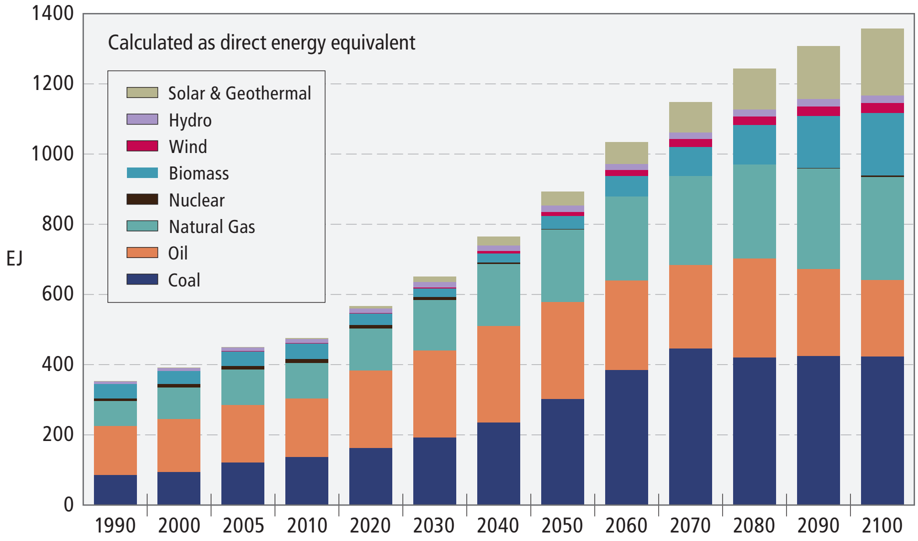

FIGURE 1
Global primary energy consumption by fuel type in the baseline scenario

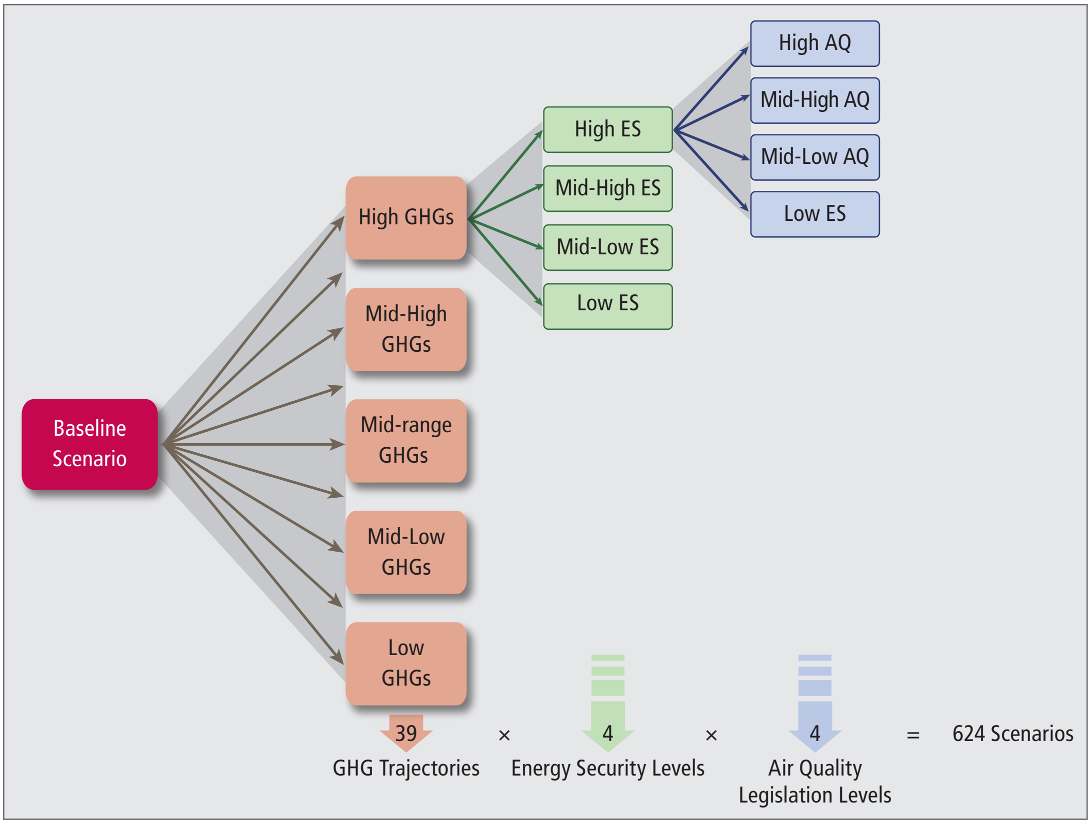

FIGURE 2
Schematic showing the taxonomy of scenarios included in the ensemble

there are four different levels for both energy security and air pollution policy. Hence, in total this leads to 624 unique scenario combinations across the three dimensions, one of which is the standard *GEA-Mix* pathway. Because this ensemble covers such a large portion of the feasible scenario space, energy system costs and other financial metrics (e.g., fuel and carbon prices) naturally span a fairly wide range as well.

TABLE 1
Climate protection indicators and corresponding levels of satisfaction.

Fulfillment	Climate Change [probability of staying within 2°C warming limit]
Weak	<20%
Intermediate	20–50%
Stringent	>50%

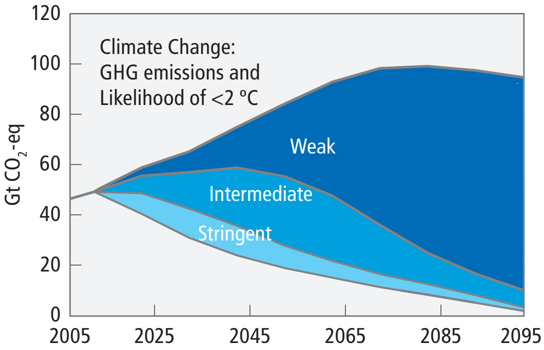

FIGURE 3
Global GHG emissions trajectories for the full scenario ensemble

Figure 3 illustrates the full scenario space across one of the energy sustainability objectives, climate change. The likelihood of holding global warming to less than 2°C is taken as the relevant indicator in this case. The degree to which each scenario (or rather, class of scenarios) fulfills this objective is indicated in the figure by the shaded Weak, Intermediate, and Stringent regions, as described in Table 1. The baseline scenario, which assumes no new climate policies at any point in the future, sees the largest growth in emissions throughout the century and is therefore at the upper bound of the Weak region. Annual emissions in this scenario climb from 49 Gt CO_2-eq in 2010 to 84 $GtCO_2$-eq in 2050.[2] Emissions then peak near 100 Gt in the later part of the century. All other scenarios achieve emissions reductions compared with the baseline, and hence comparatively higher probabilities of meeting the 2°C target. Reaching the 2°C target with greater than 50% probability (Stringent region) requires that global GHG emissions peak in 2020 at levels only marginally higher than today and then be reduced significantly in the decades that follow.

A common storyline for population growth and economic development over the course of the 21st century is shared by all the scenarios in the ensemble. What distinguishes them from each other is how greatly they vary along the climate, pollution/health, security, and cost dimensions. The socio-economic storyline is based on statistically corroborated "middle-of-the-road" assumptions from the scenario literature (Nakicenovic et al., 2006). In all of the scenarios, global population increases from almost 7 billion at present to roughly 9 billion by around 2050, before declining toward the end of the century. Such a trajectory represents a median development path based on demographic projections by the United Nations (United Nations, 2009). The GDP development paths for each of the regions build on the updated IPCC B2 scenario projection by Riahi et al. (2007). Globally-aggregated GDP roughly triples by 2050 and increases more than seven-fold by 2100. Developing and emerging economies are projected to grow faster than currently industrialized countries during this time, with the total economic output of the former surpassing that of the latter by about 2040. On average, global per capita income in the scenarios grows at an annual rate of 2% over the next half-century.

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[2] Note that these GHG estimates include all well-mixed Kyoto greenhouse gases (CO_2, methane, nitrous oxide, sulfur hexafluoride, tetrafluoromethane, and halocarbons).

4. Understanding the Tool: Theory and Practice

General description and operation

The IIASA Energy–Multi Criteria Analysis Policy Tool (ENE-MCA) has been developed at IIASA, partly building upon work carried out in the Global Energy Assessment, and is the result of strong collaboration between the Energy (ENE) and Advanced Systems Analysis (ASA) Research Programs.

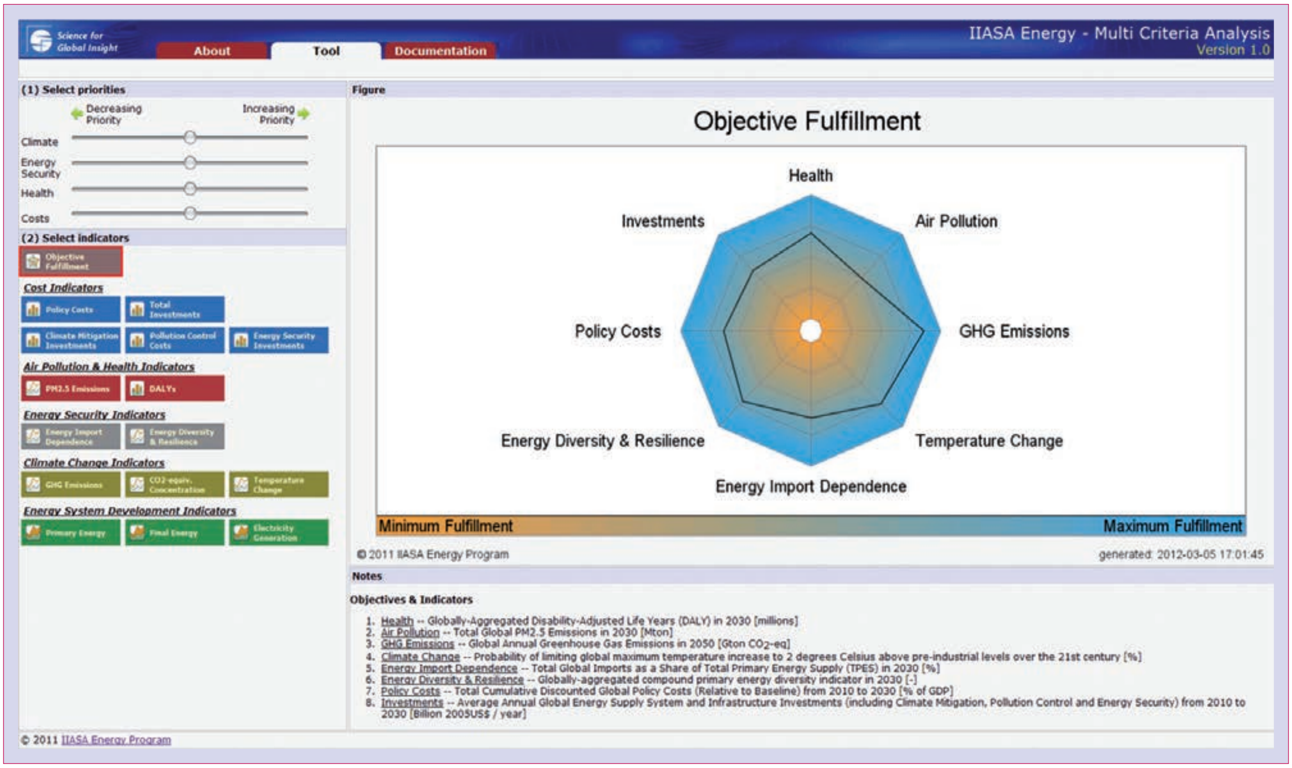
Interested users can find the online tool at the following URL:

www.iiasa.ac.at/web-apps/ene/GeaMCA

The tool allows users to visualize the complex synergies and trade-offs of specific energy and environmental policy choices and to better understand how varying the prioritization of the multiple energy objectives can lead to qualitatively different energy system futures. It does this by supporting users in their analysis of a given set of discrete alternatives, each characterized by more than one criterion. These discrete alternatives are, within the framework of the tool, individual energy and climate model scenarios, in particular those scenarios which have been generated by running a combination of the MESSAGE and MAGICC models, as described previously. The different scenario pathways represent different future states of the world, in which the multiple energy objectives are satisfied to varying degrees. The criteria on the other hand can, in theory, be defined from the values of any of the variables computed by the modeling framework; though in practice, it really only makes sense to focus on a small number of the most important criteria. The current version of the ENE-MCA tool uses the following indicators for representing achievement of the four different objectives:

- **Climate Change** Probability of limiting global maximum temperature increase to 2 °C above the pre-industrial level over the course of the 21st century
- **Energy Security** A globally-aggregated compound primary energy diversity indicator in 2030 (see Section 5)
- **Air Pollution & Health** Globally-aggregated disability-adjusted life years (DALYs) in 2030 (see Section 5)
- **Costs & Affordability** Total cumulative global energy system costs from 2010 to 2030 (including the transformations necessary to achieve the climate change, air pollution control, and energy security requirements of each scenario)

Utilization of the MCA tool is comprised of the repetition of a series of steps (usually called iterations; see Figure 5). First, the user specifies his/her



Objectives & Indicators

1. Health -- Globally-Aggregated Disability-Adjusted Life Years (DALY) in 2030 [millions]
2. Air Pollution -- Total Global PM2.5 Emissions in 2030 [Mton]
3. GHG Emissions -- Global Annual Greenhouse Gas Emissions in 2050 [Gton CO_2-eq]
4. Climate Change -- Probability of limiting global maximum temperature increase to 2 degrees Celsius above pre-industrial levels over the 21st century [%]
5. Energy Import Dependence -- Total Global Imports as a Share of Total Primary Energy Supply (TPES) in 2030 [%]
6. Energy Diversity & Resilience -- Globally-aggregated compound primary energy diversity indicator in 2030 [-]
7. Policy Costs -- Total Cumulative Discounted Global Policy Costs (Relative to Baseline) from 2010 to 2030 [% of GDP]
8. Investments -- Average Annual Global Energy Supply System and Infrastructure Investments (including Climate Mitigation, Pollution Control and Energy Security) from 2010 to 2030 [Billion 2005US$ / year]

FIGURE 4
Example screenshot of the ENE-MCA Policy Tool

preferences for the objectives (i.e., criteria) by assigning a relative importance to each. This is done interactively using the slider bars in the upper left portion of the screen (Figure 4). Based on the given preferences, the software finds the alternative (i.e., scenario) that best fits these preferences. The user then decides whether or not the trade-offs between the corresponding criteria values meet her expectations. If not, the user enters a subsequent iteration by modifying the preferences, typically by increasing the importance of the criterion value that she wants to improve, while at the same time decreasing the importance of another criterion that she agrees to compromise. (Note that because the solver always finds an efficient – "Pareto-optimal" – solution, it is not possible to improve the value of any one criterion without compromising the value of another criterion.) This iterative process continues until the user becomes familiar with various combinations of attainable goals (i.e., values for criteria) and finds an efficient alternative that best fits her preferences for trade-offs between the goals. In other words, multi-criteria analysis is a learning process, in which each user explores diverse combinations of attainable values of objectives through successive modifications of her preferences.

Numerous methods have been proposed for MCA (Granat and Makowski, 2000; Wierzbicki et al., 2000; Granat and Makowski, 2009). Each of these is characterized by the way in which: (1) the user preferences are specified, and (2) the Pareto-optimal solution that best fits the given preferences is determined.

Two families of methods that are used in the ENE-MCA tool, and which have been extensively developed at IIASA in recent years, are Pairwise-Outperformance Aggregation and Reference Point (Granat and Makowski, 2000; Wierzbicki et al., 2000; Makowski, 2009; Makowski et al., 2009a; Makowski et al., 2009b). Regardless of the method, however, the fundamental premise allowing a single alternative to be chosen as "best" or "preferred" among a large set of discrete alternatives is based on the concept of Pareto optimality. A Pareto-optimal (also called efficient, or non-dominated) solution is the alternative for which there is no other alternative that has a better value of one criterion and at least equally good values of all other criteria. In other words, for a Pareto-efficient alternative one cannot improve the value of at least one of its criterion without worsening the value of at least one other criterion (Granat and Makowski, 2000; Makowski, 2009). The set of all efficient solutions, therefore, is called the Pareto-set.

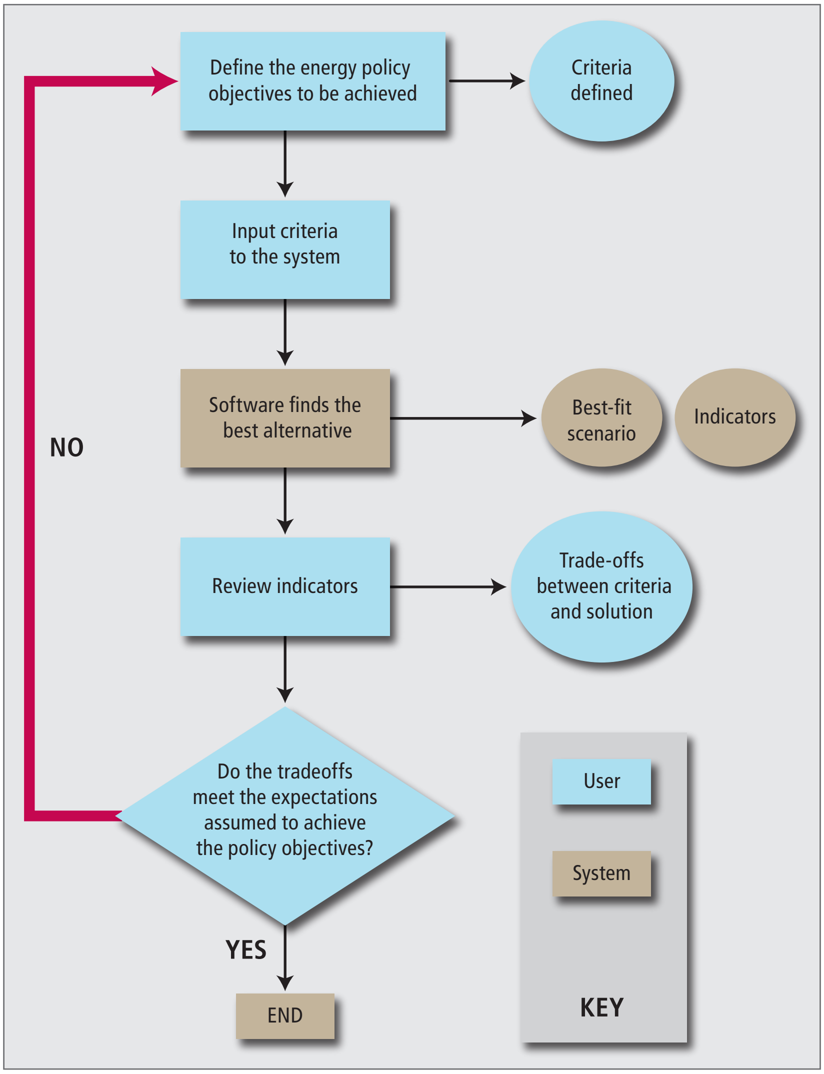


FIGURE 5
Iterative process for evaluating different energy policy objectives

Solutions that do not belong to this set are referred to as dominated (also inefficient, or not Pareto-optimal), as they do not represent rational choices under any circumstances: in other words, one can always find another alternative that is objectively better.

For a non-trivial problem (like that which the ENE-MCA has been designed for), there are many Pareto-optimal alternatives, and because each of them is equally good/efficient from a mathematical point of view, they cannot be objectively ordered from best to worst. Nevertheless, a single user will inevitably prefer some of the efficient alternatives above some others, as some of them will go further in meeting the criteria that she values highest. Hence, there will normally be a large subset of efficient alternatives that are not especially attractive to one user but that may, at the same time, be attractive to someone else. The ENE-MCA software tool, therefore, supports the user in finding the subset of alternatives with the attractive combinations of criteria values, as well as the solution that has the most preferred trade-offs between these values (given the particular preference specification at the time).

Step-by-step user guide

1. Utilizing the interactive slider bars in the upper left portion of the screen (Figure 6), the user specifies his/her preferences for the different objectives (i.e., criteria) by ranking them in order of relative importance

2. Based on the given preference specification, the software finds the single Pareto-optimal alternative (i.e., energy/climate scenario) that best aligns with the chosen preference structure.

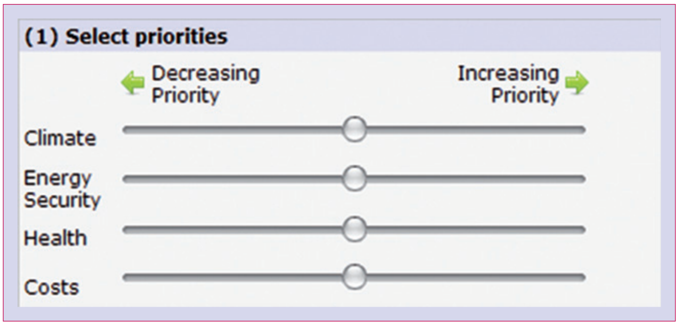


FIGURE 6
ENE-MCA Policy Tool: Interactive slider bars

3. The user can then learn more about the optimal scenario by clicking on the various indicator tabs on the left side of the screen (Figure 7).

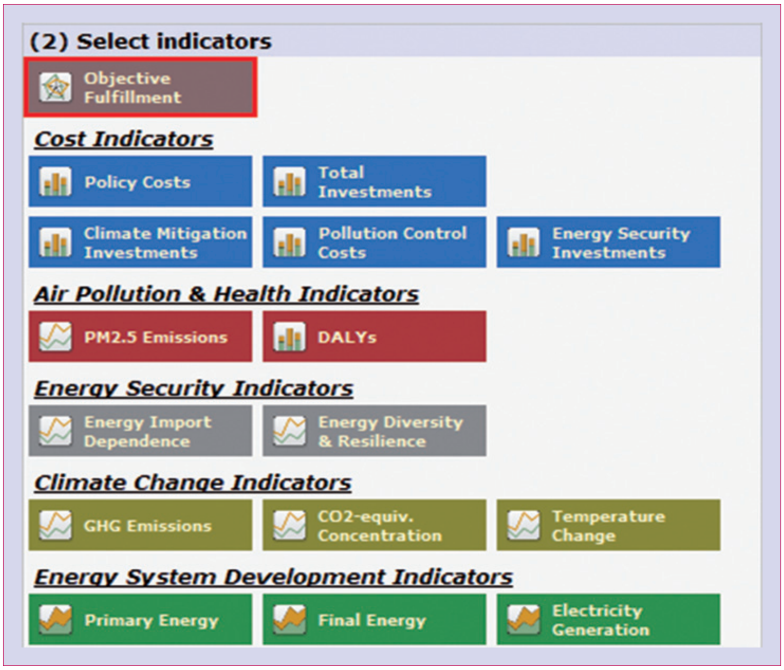
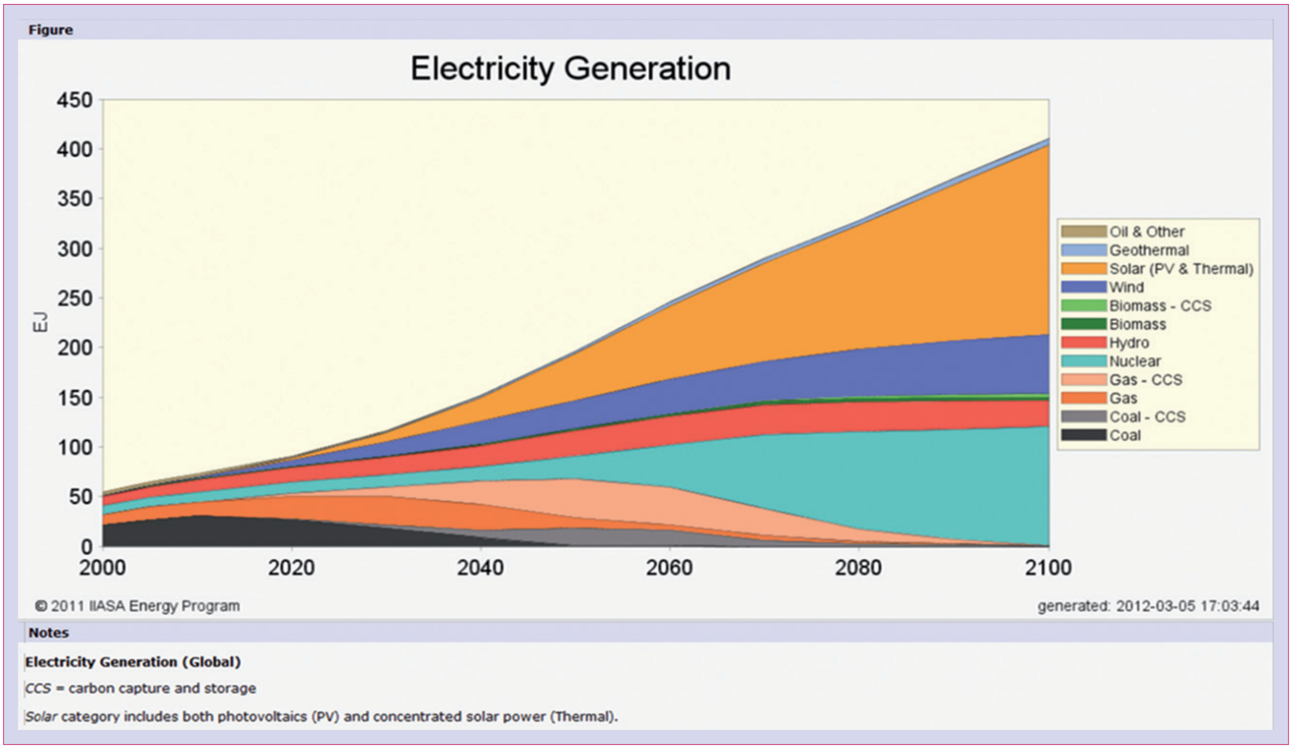


FIGURE 7
ENE-MCA Policy Tool:
Results selection tabs



Electricity Generation (Global)

CCS = carbon capture and storage

Solar category includes both photovoltaics (PV) and concentrated solar power (Thermal).

FIGURE 8
ENE-MCA Policy Tool:
Results window

Once a tab is selected, a graphic will load on the right side of the screen (such as in Figure 8). A variety of graphics can be viewed for the selected optimal scenario. The figures summarize, for example,

- Costs (of climate mitigation, energy security improvement, pollution control, etc.);
- Energy system development (primary and final energy, electricity generation);
- Greenhouse gas trajectories, temperature changes, CO_2-eq concentration paths;
- Air pollutant emissions and their related health impacts; and
- Energy security (diversity/resilience and import dependence indicators).

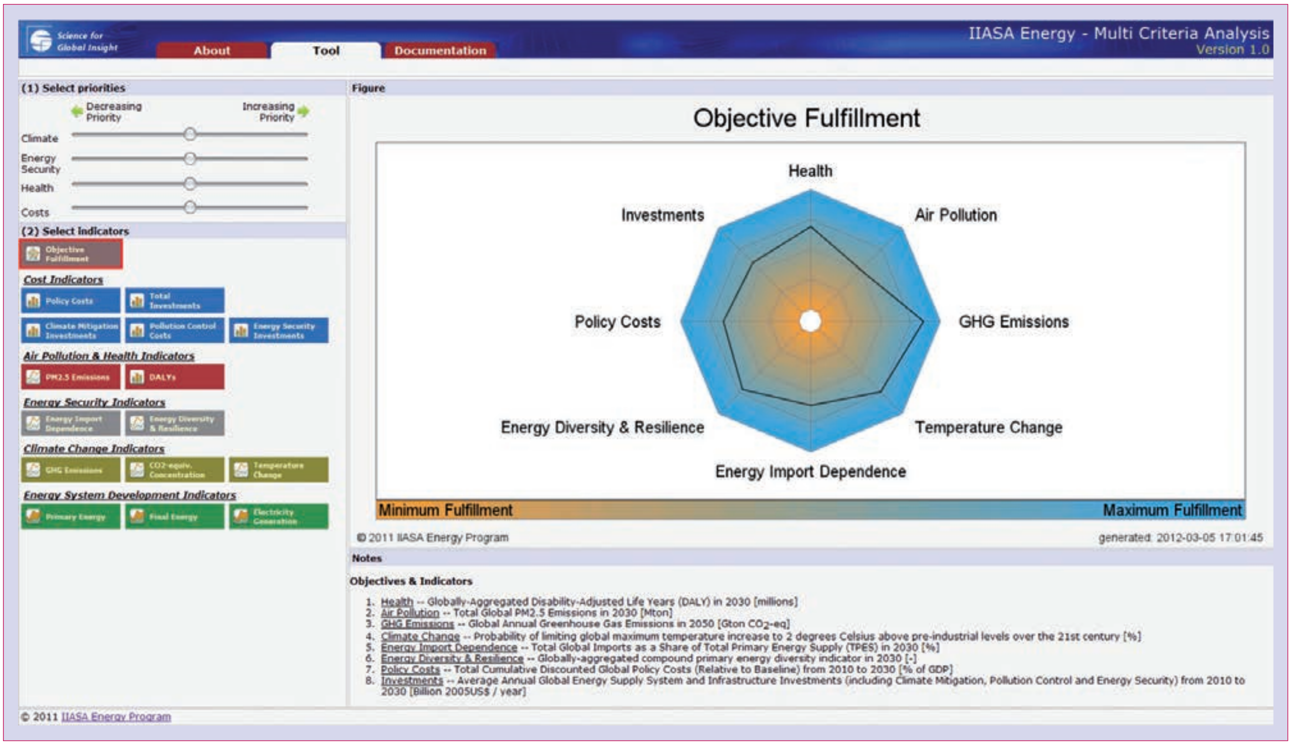
Below each graphic, the user finds a notes section that provides some additional explanation about the information being presented in the corresponding figure.

4. After fully exploring the scenario results, the user returns to the first step and begins a new iteration by moving the interactive slider bars to new positions (Figure 6), thereby modifying the ranking structure of the various objectives. Typically, this means increasing the importance of the criterion value that the user wants to improve, while at the same time decreasing the importance of other criteria that she agrees to compromise. At this point, based on the updated preference specification, the software will calculate and present a different Pareto-optimal scenario from before (unless the previously selected optimal scenario is also the optimal one under this new ranking structure).

Practical example and explanation of indicators

The following discussion provides a practical example of how to use and understand the output of the ENE-MCA Policy Tool. For simplification, a single set of user preferences for the various energy sustainability objectives is used throughout, in this case assuming a user assigns equal weighting simultaneously to all criteria.

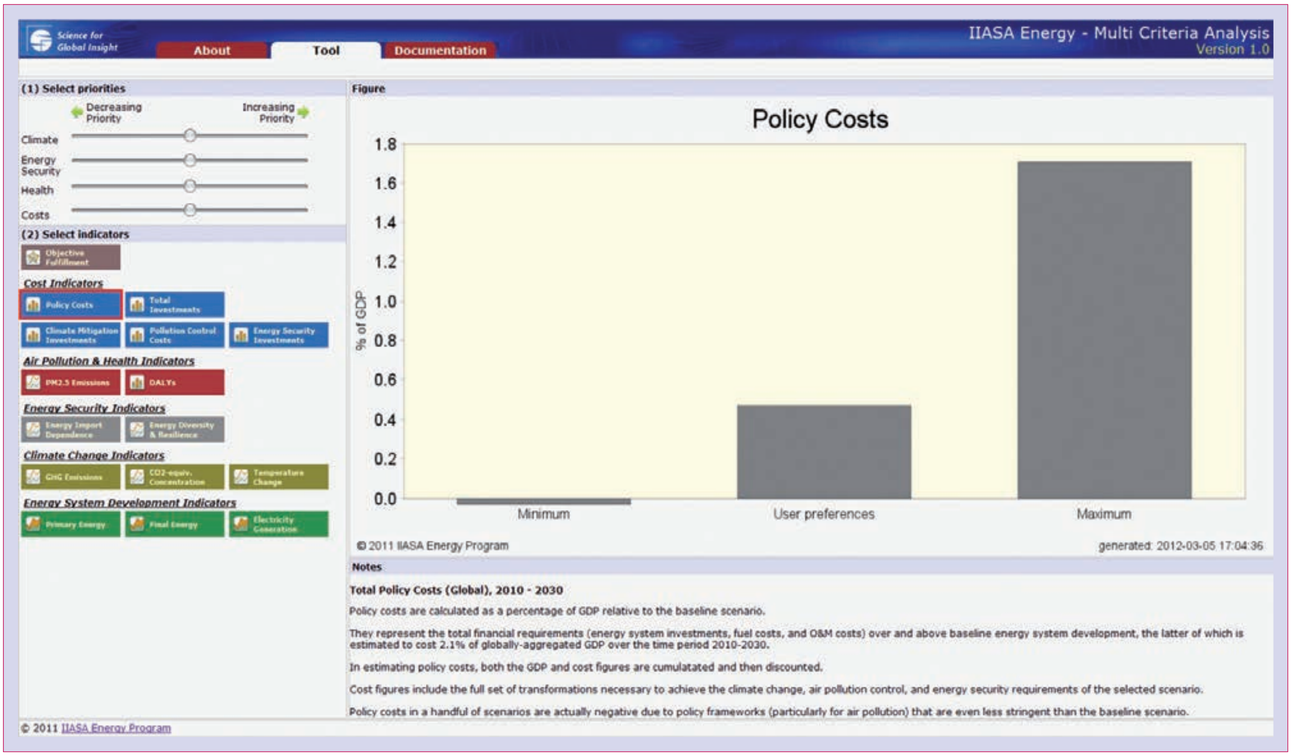
The first indicator tab uses a spider plot to summarize, for the optimally chosen scenario that best meets the user-defined set of preferences, fulfillment of the multiple objectives (Figure 9). Each objective is represented by two different metrics, and descriptions of the individual metrics are given in the notes section below the plot. Because these metrics are all in different units, the scale along each dimension is normalized. This means objective fulfillment values toward the outer edges of the spider plot are preferred. Thus, the user would ideally like to push fulfillment values outward for the objectives that they prioritize the most, whereas objectives holding less priority to the user may possess values that are closer to the center.



Objectives & Indicators

1. Health -- Globally-Aggregated Disability-Adjusted Life Years (DALY) in 2030 [millions]
2. Air Pollution -- Total Global PM2.5 Emissions in 2030 [Mton]
3. GHG Emissions -- Global Annual Greenhouse Gas Emissions in 2050 [Gton CO_2-eq]
4. Climate Change -- Probability of limiting global maximum temperature increase to 2 degrees Celsius above pre-industrial levels over the 21st century [%]
5. Energy Import Dependence -- Total Global Imports as a Share of Total Primary Energy Supply (TPES) in 2030 [%]
6. Energy Diversity & Resilience -- Globally-aggregated compound primary energy diversity indicator in 2030 [-]
7. Policy Costs -- Total Cumulative Discounted Global Policy Costs (Relative to Baseline) from 2010 to 2030 [% of GDP]
8. Investments -- Average Annual Global Energy Supply System and Infrastructure Investments (including Climate Mitigation, Pollution Control and Energy Security) from 2010 to 2030 [Billion 2005US$ / year]

FIGURE 9 ENE-MCA Policy Tool Indicator: Objective Fulfillment



Total Policy Costs (Global), 2010 - 2030

Policy costs are calculated as a percentage of GDP relative to the baseline scenario.

They represent the total financial requirements (energy system investments, fuel costs, and O&M costs) over and above baseline energy system development, the latter of which is estimated to cost 2.1% of globally-aggregated GDP over the time period 2010-2030.

In estimating policy costs, both the GDP and cost figures are cumulatated and then discounted.

Cost figures include the full set of transformations necessary to achieve the climate change, air pollution control, and energy security requirements of the selected scenario.

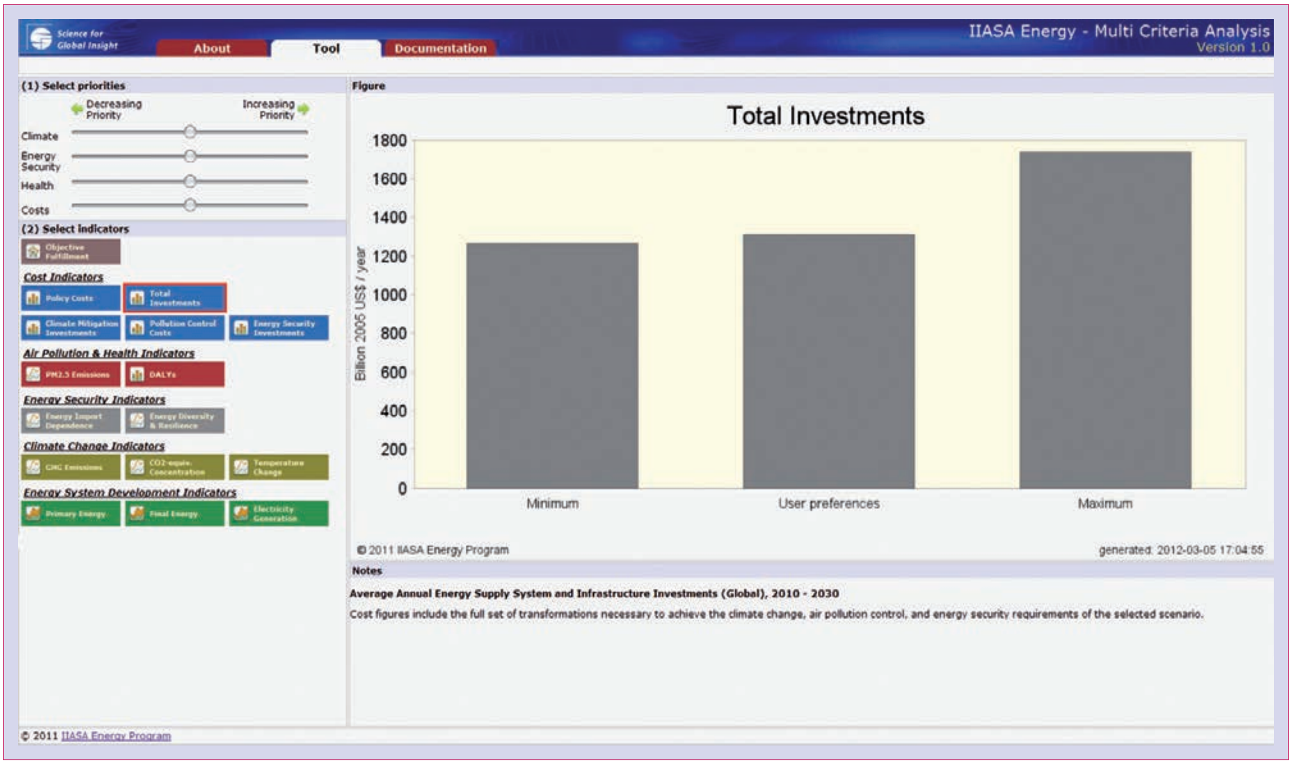
Policy costs in a handful of scenarios are actually negative due to policy frameworks (particularly for air pollution) that are even less stringent than the baseline scenario.

FIGURE 10 ENE-MCA Policy Tool Indicator: Policy Costs

Several different cost indicators allow the user to interpret how their chosen scenario compares to other scenarios in the full ensemble. One such indicator is total global policy costs between 2010 and 2030 (Figure 10). Policy costs represent the total financial requirements (i.e., energy system investments, fuel costs, and O&M costs) over and above baseline energy system development, the latter of which is estimated at 2.1% of globally-aggregated GDP during the time period 2010–2030. The cost figures include the full set of transformations necessary to achieve the climate change, air pollution control, and energy security requirements of the selected scenario. Note that policy costs can actually be negative due to policy frameworks (particularly for air pollution) that are even less stringent than in the baseline scenario.

Another available cost indicator is average annual energy supply and infrastructure investments between 2010 and 2030 at the global level (Figure 11). These cost figures also include the full set of transformations necessary to achieve the climate change, air pollution control, and energy security requirements of the selected scenario.

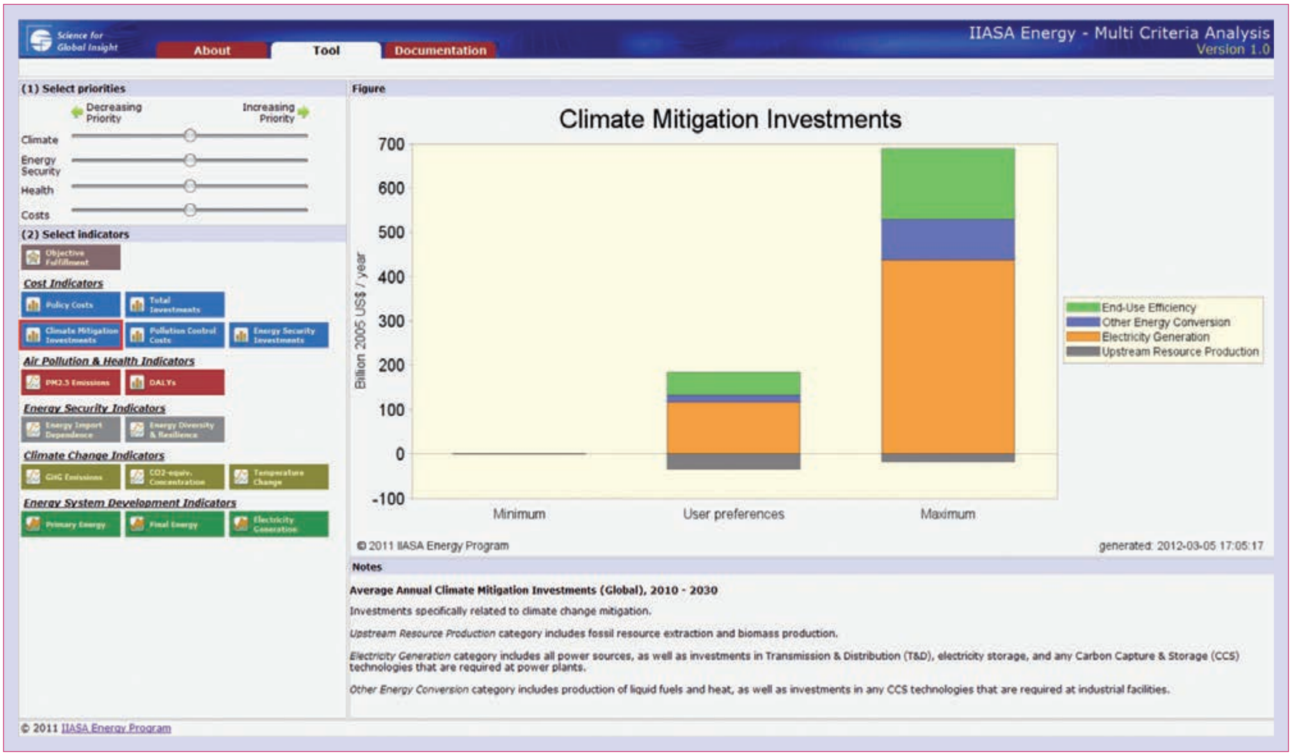
Three indicator tabs look more deeply into the cost of achieving each specific energy sustainability objective. For example, average annual global climate mitigation investments between 2010 and 2030 summarize in which energy-producing and -consuming sectors the investments are made (Figure 12).



Average Annual Energy Supply System and Infrastructure Investments (Global), 2010 - 2030

Cost figures include the full set of transformations necessary to achieve the climate change, air pollution control, and energy security requirements of the selected scenario.

FIGURE 11 ENE-MCA Policy Tool Indicator: Total Investments



Average Annual Climate Mitigation Investments (Global), 2010 - 2030

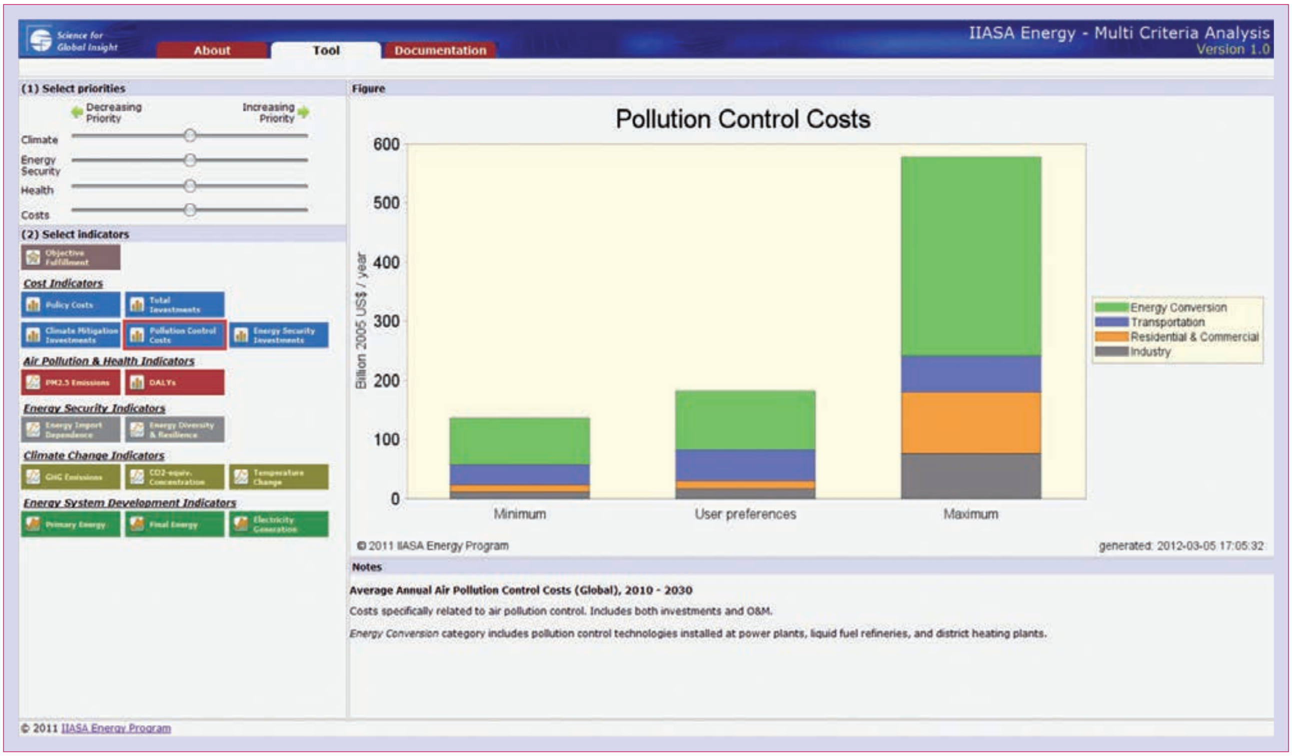
Investments specifically related to climate change mitigation.

Upstream Resource Production category includes fossil resource extraction and biomass production.

Electricity Generation category includes all power sources, as well as investments in Transmission & Distribution (T&D), electricity storage, and any Carbon Capture & Storage (CCS) technologies that are required at power plants.

Other Energy Conversion category includes production of liquid fuels and heat, as well as investments in any CCS technologies that are required at industrial facilities.

FIGURE 12 ENE-MCA Policy Tool Indicator: Climate Mitigation Investments



Average Annual Air Pollution Control Costs (Global), 2010 - 2030

Costs specifically related to air pollution control. Includes both investments and O&M.

Energy Conversion category includes pollution control technologies installed at power plants, liquid fuel refineries, and district heating plants.

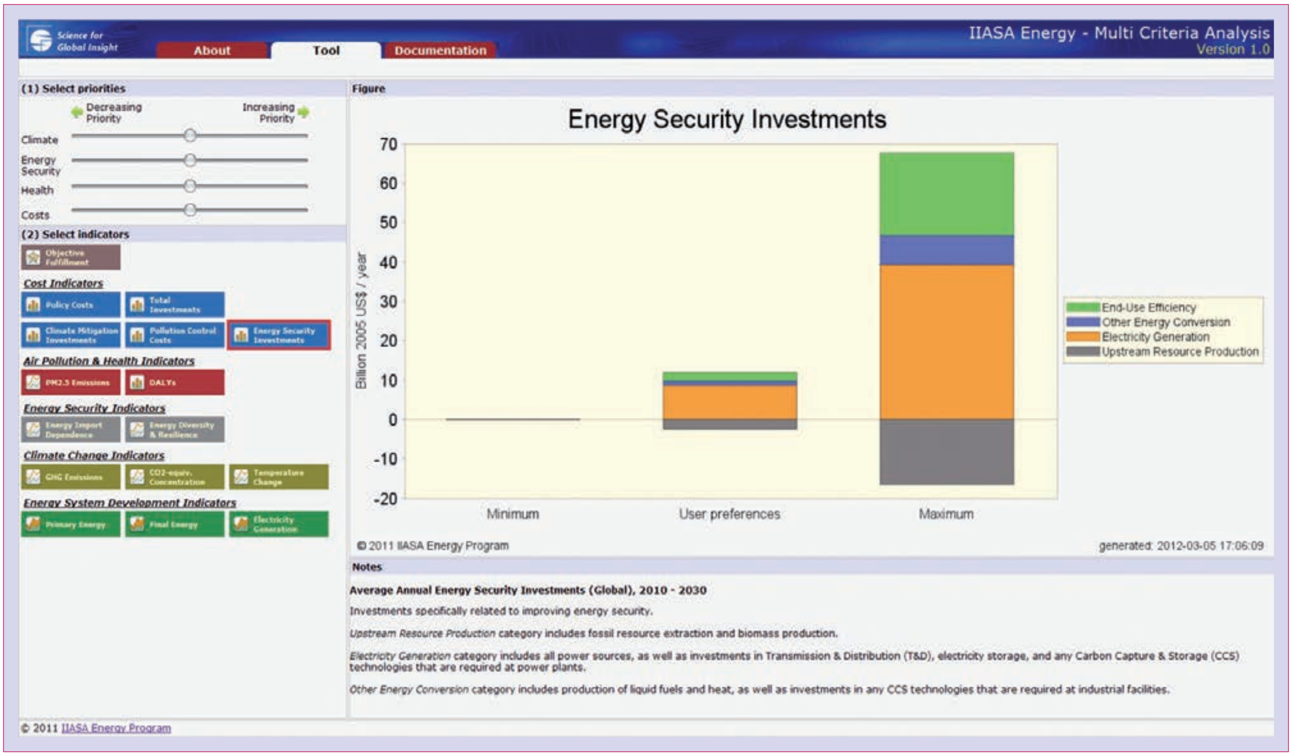
FIGURE 13 ENE-MCA Policy Tool Indicator: Pollution Control Costs

Investments in upstream resource production are negative in many scenarios because of the reduced investments in fossil resource extraction that climate mitigation entails.

Average annual global air pollution control costs (2010–2030) summarize the investment and O&M costs related to reducing pollution across various energy-producing and -consuming sectors (Figure 13). Costs are always non-zero and positive, even in the scenario with minimal pollution control costs, because all scenarios of the ensemble assume some level of pollution legislation over the next several decades.

Average annual energy security investments (2010–2030) represent the globally-aggregated investment requirements of improving energy security across all countries and regions in the medium term (Figure 14). In scenarios where energy security is of at least some priority, investments in upstream resource production can potentially be negative, due to the reduced need for fossil resource extraction.

Two additional air pollution and health indicators are available to the user that do not relate to costs. One indicator shows the global PM2.5 emissions trajectory (2000–2100) for the selected scenario as well as the range of trajectories for all other scenarios in the ensemble (Figure 15). Lower pollutant emissions lead to improved air quality, which in turn reduces human health impacts. Note that



Average Annual Energy Security Investments (Global), 2010 - 2030

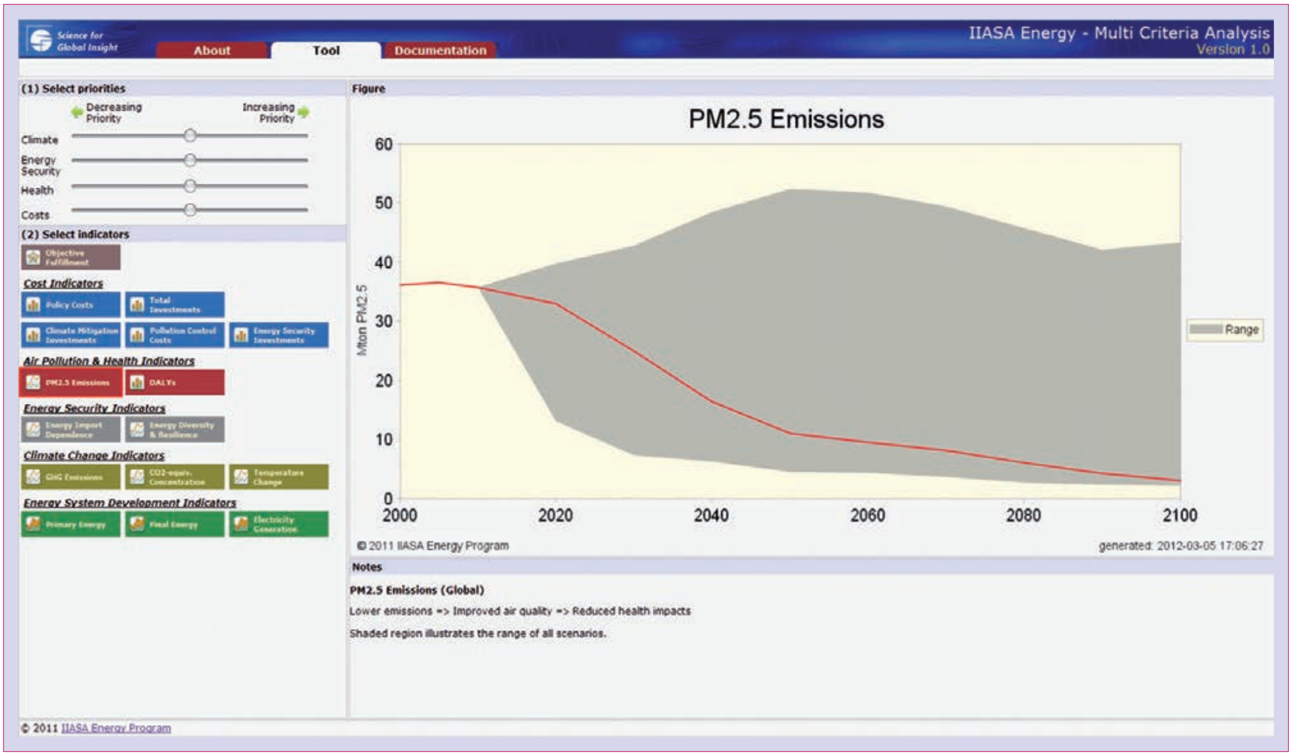
Investments specifically related to improving energy security.

Upstream Resource Production category includes fossil resource extraction and biomass production.

Electricity Generation category includes all power sources, as well as investments in Transmission & Distribution (T&D), electricity storage, and any Carbon Capture & Storage (CCS) technologies that are required at power plants.

Other Energy Conversion category includes production of liquid fuels and heat, as well as investments in any CCS technologies that are required at industrial facilities.

FIGURE 14 ENE-MCA Policy Tool Indicator: Energy Security Investments



PM2.5 Emissions (Global)

Lower emissions => Improved air quality => Reduced health impacts

Shaded region illustrates the range of all scenarios.

FIGURE 15 ENE-MCA Policy Tool Indicator: PM2.5 Emissions

Disability-Adjusted Life Years (Global), 2030

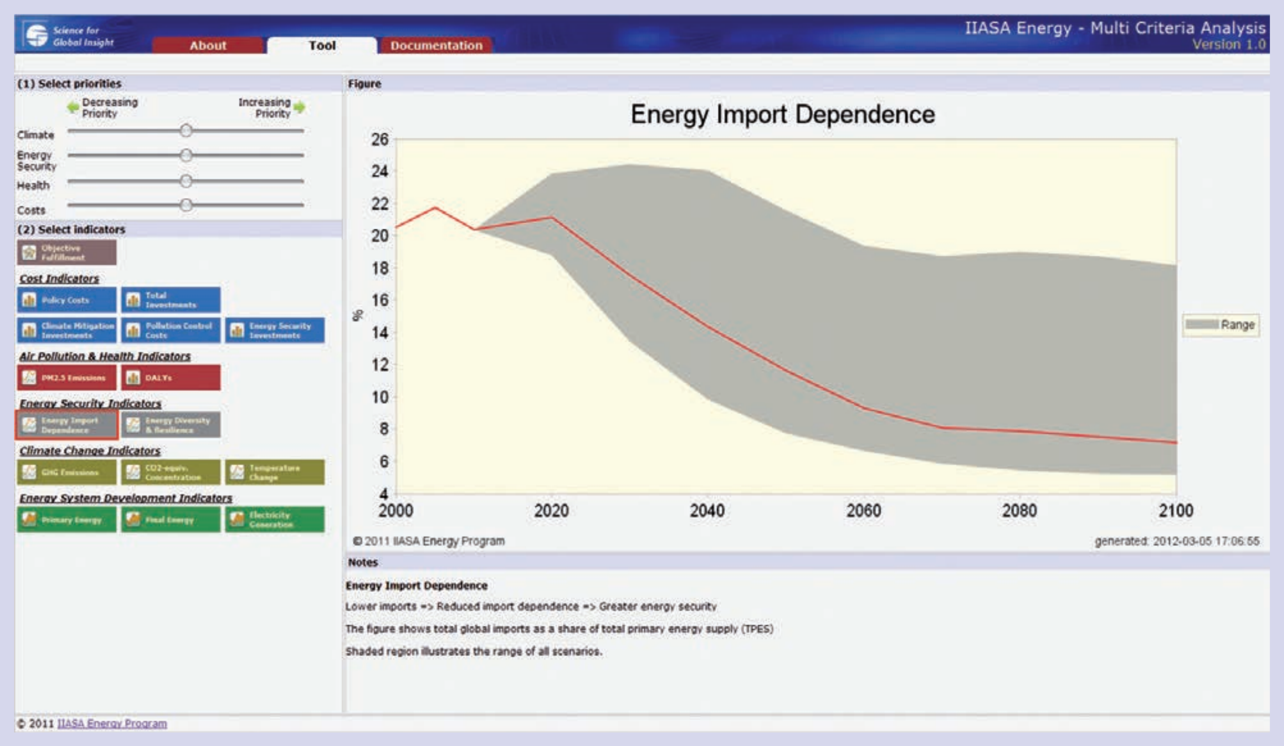
Lower DALYs => Improved global health

FIGURE 16 ENE-MCA Policy Tool Indicator: Disability-adjusted Life Years although global emissions are shown in the figure, the numbers are built up from spatially-explicit modeling studies at the local and national level.

A second indicator tab summarizes the disability-adjusted life years (DALY) in 2030 for the user-selected scenario and how that scenario compares to the best and worst performing scenarios in the full ensemble along this particular dimension (Figure 16). A lower DALYs count implies an improvement in global health. Estimation of DALYs is directly related to the PM2.5 emissions trajectories shown in the related indicator tab.

Energy security is represented, first, by the progression of global energy import dependence over time (Figure 17). This is calculated as the total globally-aggregated quantity of imports (into all countries and regions) as a share of total global primary energy supply. The idea is that lower imports (or rather reduced global trade of energy commodities) leads to reduced import dependence, which in turn contributes to improved energy security.

The second indicator used to represent energy security is a global diversity and resilience indicator (Figure 18). This compound indicator is based on the Shannon index and takes into account both the diversity of primary energy resources



Notes

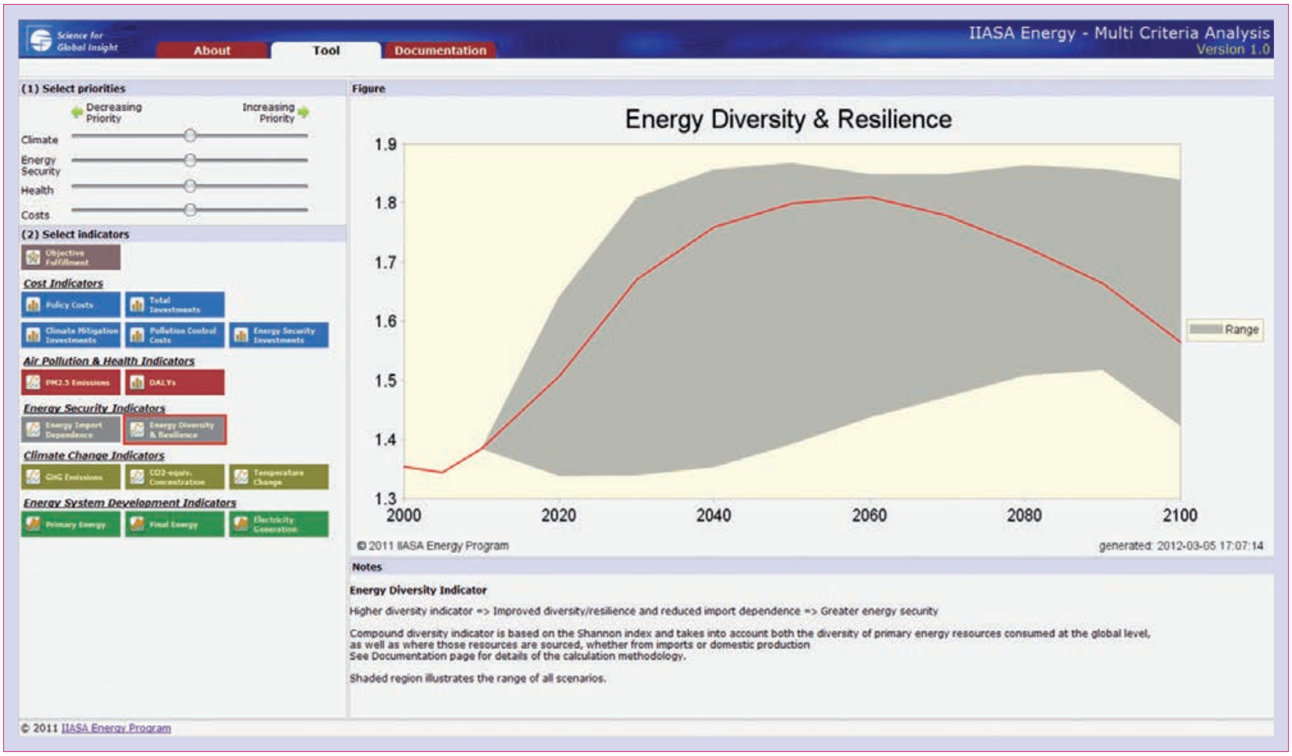
Energy Import Dependence

Lower imports => Reduced import dependence => Greater energy security

The figure shows total global imports as a share of total primary energy supply (TPES)

Shaded region illustrates the range of all scenarios.

FIGURE 17 ENE-MCA Policy Tool Indicator: Energy Import Dependence



Notes

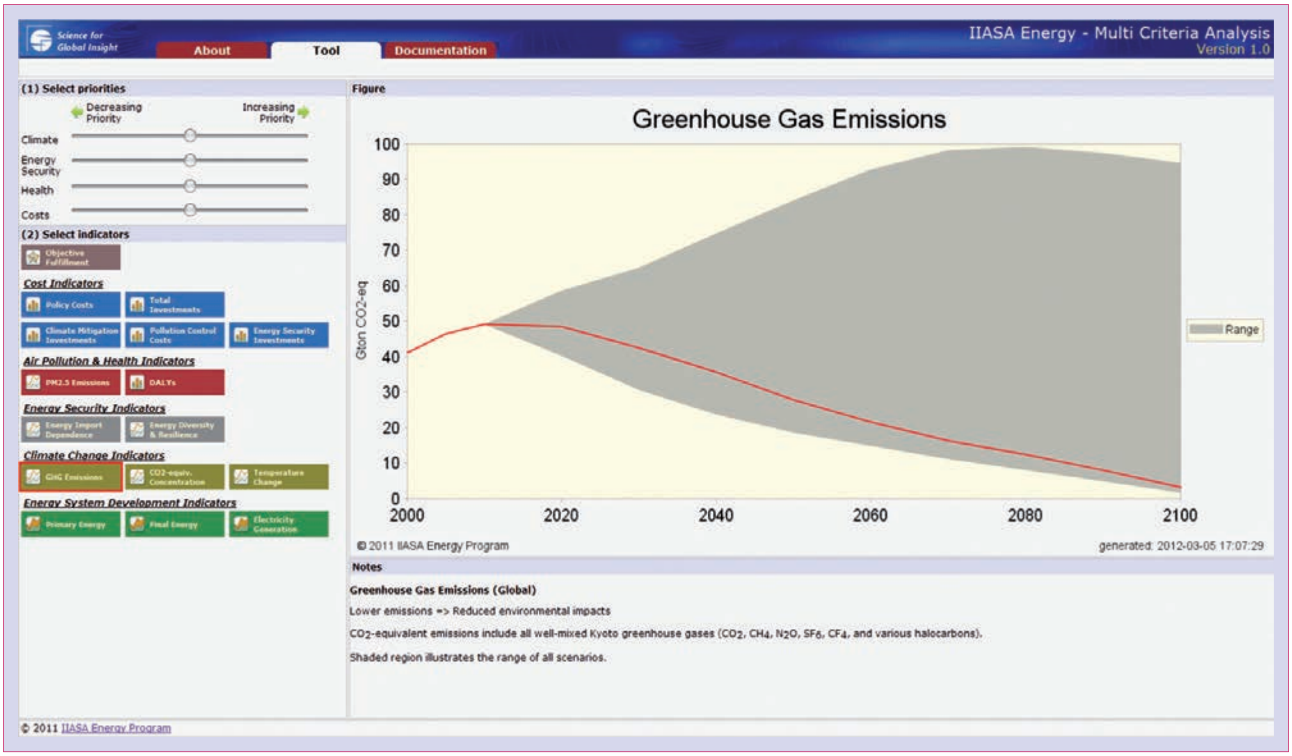
Energy Diversity Indicator

Higher diversity indicator => Improved diversity/resilience and reduced import dependence => Greater energy security

Compound diversity indicator is based on the Shannon index and takes into account both the diversity of primary energy resources consumed at the global level, as well as where those resources are sourced, whether from imports or domestic production
See Documentation page for details of the calculation methodology.

Shaded region illustrates the range of all scenarios.

FIGURE 18 ENE-MCA Policy Tool Indicator: Energy Diversity & Resilience



Notes

Greenhouse Gas Emissions (Global)

Lower emissions => Reduced environmental impacts

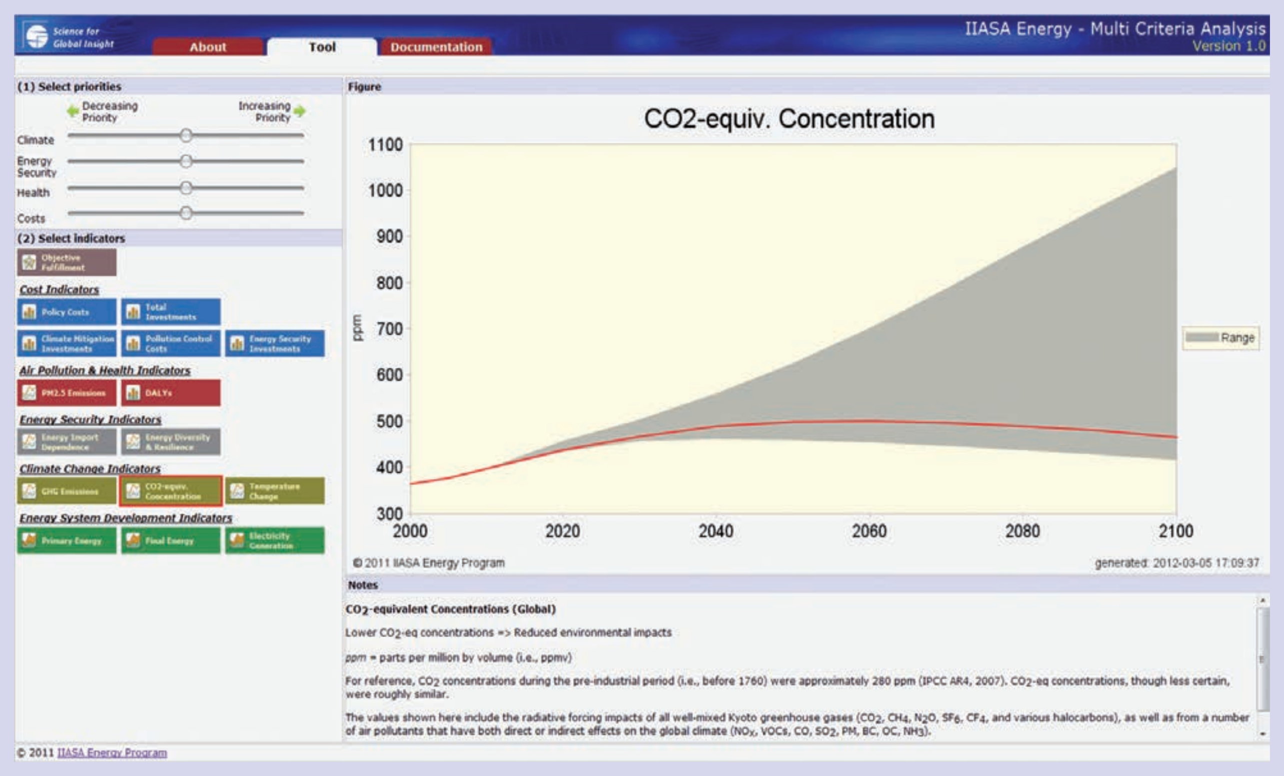
CO_2-equivalent emissions include all well-mixed Kyoto greenhouse gases (CO_2, CH_4, N_2O, SF_6, CF_4, and various halocarbons).

Shaded region illustrates the range of all scenarios.

FIGURE 19 ENE-MCA Policy Tool Indicator: Greenhouse Gas Emissions consumed at the global level, as well as where those resources are sourced, whether from imports or domestic production. (The calculation methodology is briefly explained in Section 5.) Higher values of the diversity and resilience indicator indicate improved energy security worldwide. Note that in many scenarios, particularly in scenarios where climate mitigation is prioritized above all else, the diversity and resilience indicator increases quickly from today until about mid-century as a result of substantially greater utilization of renewable energy sources. Then, as fossil energy sources are phased toward the end of the century and as renewable energy comes to dominate, the indicator declines.

Global greenhouse gas emissions trajectories (2000–2100) are shown in one of the climate change indicator tabs, both for the selected scenario as well as the range of trajectories for all other scenarios in the ensemble (Figure 19). GHGs include all well-mixed Kyoto greenhouse gases (CO_2, CH_4, N_2O, SF_6, CF_4, and various halocarbons).

The impacts of the specific GHG and air pollutant emissions trajectories for the user-selected scenario are illustrated with two figures. First, global atmospheric CO_2-equivalent concentrations – in terms of parts per million by volume (i.e., ppmv) – are shown over time (Figure 20). The concentrations include the radiative forcing



CO_2-equivalent Concentrations (Global)

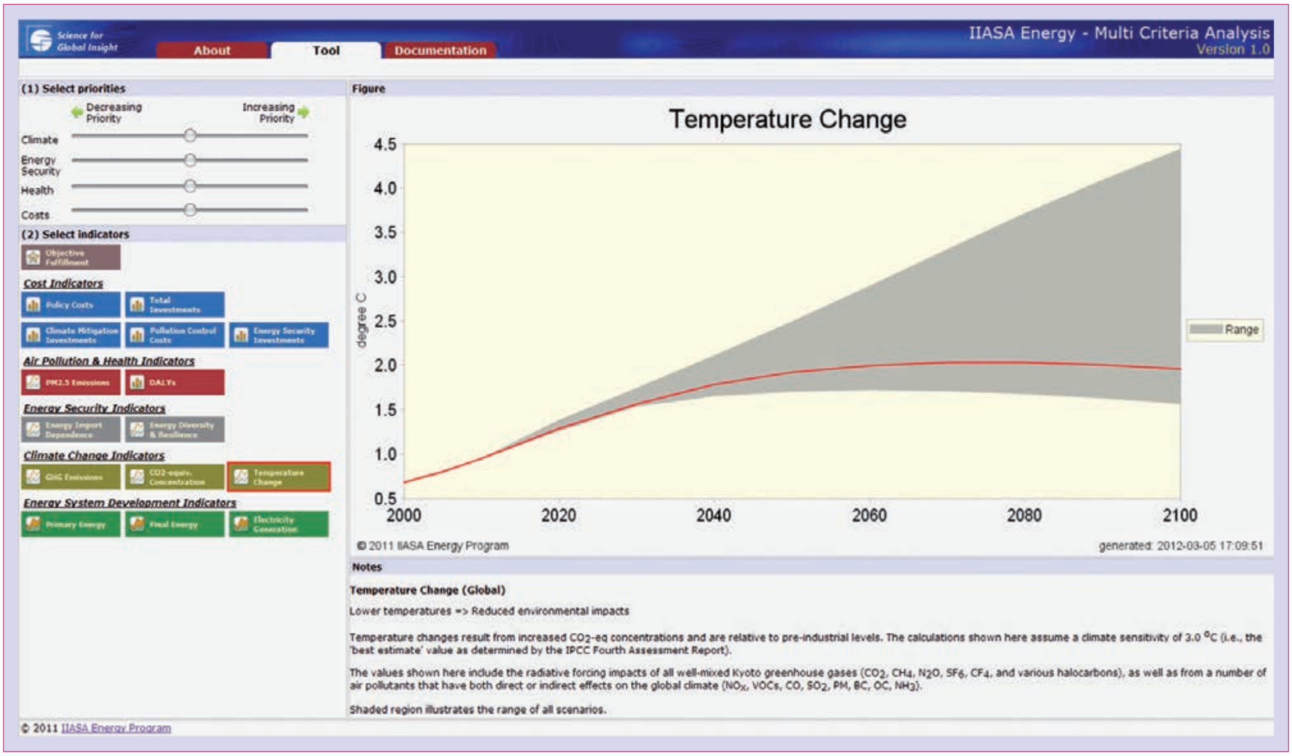
Lower CO_2-eq concentrations => Reduced environmental impacts

ppm = parts per million by volume (i.e., ppmv)

For reference, CO_2 concentrations during the pre-industrial period (i.e., before 1760) were approximately 280 ppm (IPCC AR4, 2007). CO_2-eq concentrations, though less certain, were roughly similar.

The values shown here include the radiative forcing impacts of all well-mixed Kyoto greenhouse gases (CO_2, CH_4, N_2O, SF_6, CF_4, and various halocarbons), as well as from a number of air pollutants that have both direct or indirect effects on the global climate (NO_x, VOCs, CO, SO_2, PM, BC, OC, NH_3).

FIGURE 20 ENE-MCA Policy Tool Indicator: Atmospheric CO_2-eq Concentrations



Temperature Change (Global)

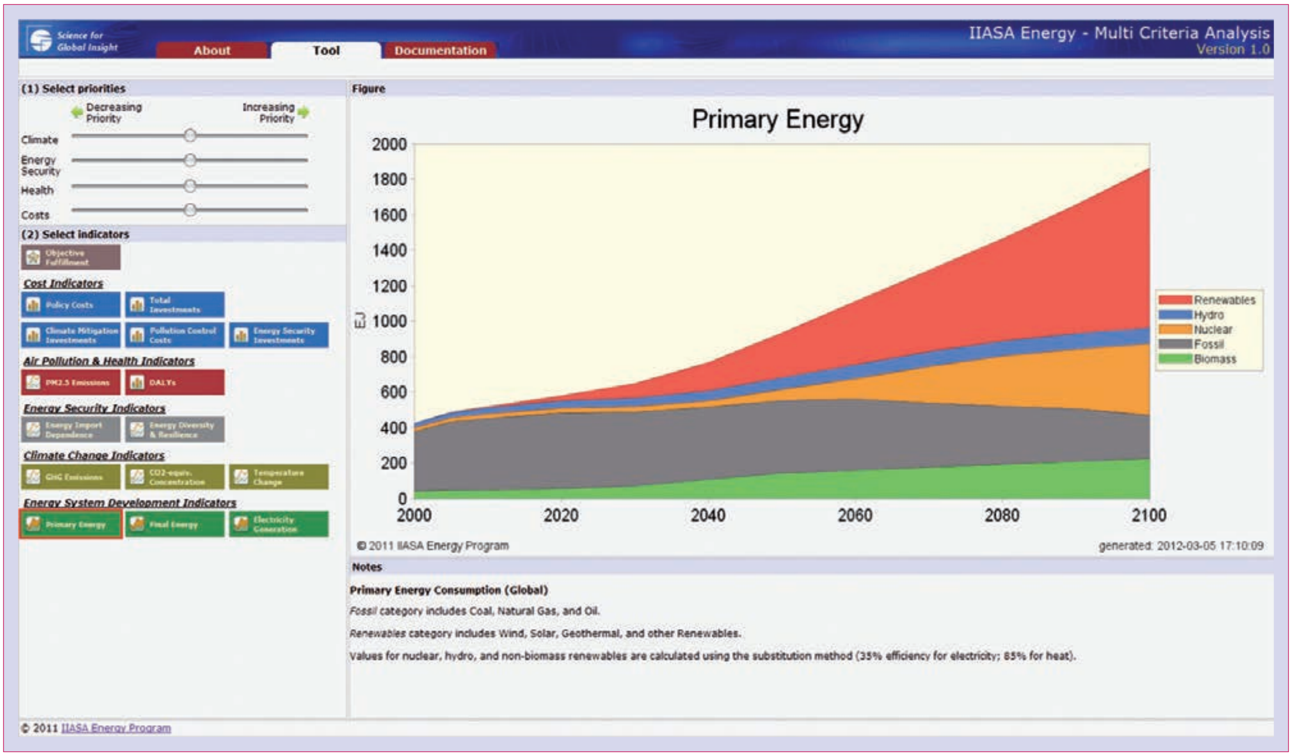
Lower temperatures => Reduced environmental impacts

Temperature changes result from increased CO_2-eq concentrations and are relative to pre-industrial levels. The calculations shown here assume a climate sensitivity of 3.0 °C (i.e., the 'best estimate' value as determined by the IPCC Fourth Assessment Report).

The values shown here include the radiative forcing impacts of all well-mixed Kyoto greenhouse gases (CO_2, CH_4, N_2O, SF_6, CF_4, and various halocarbons), as well as from a number of air pollutants that have both direct or indirect effects on the global climate (NO_X, VOCs, CO, SO_2, PM, BC, OC, NH_3).

Shaded region illustrates the range of all scenarios.

FIGURE 21 ENE-MCA Policy Tool Indicator: Temperature Change



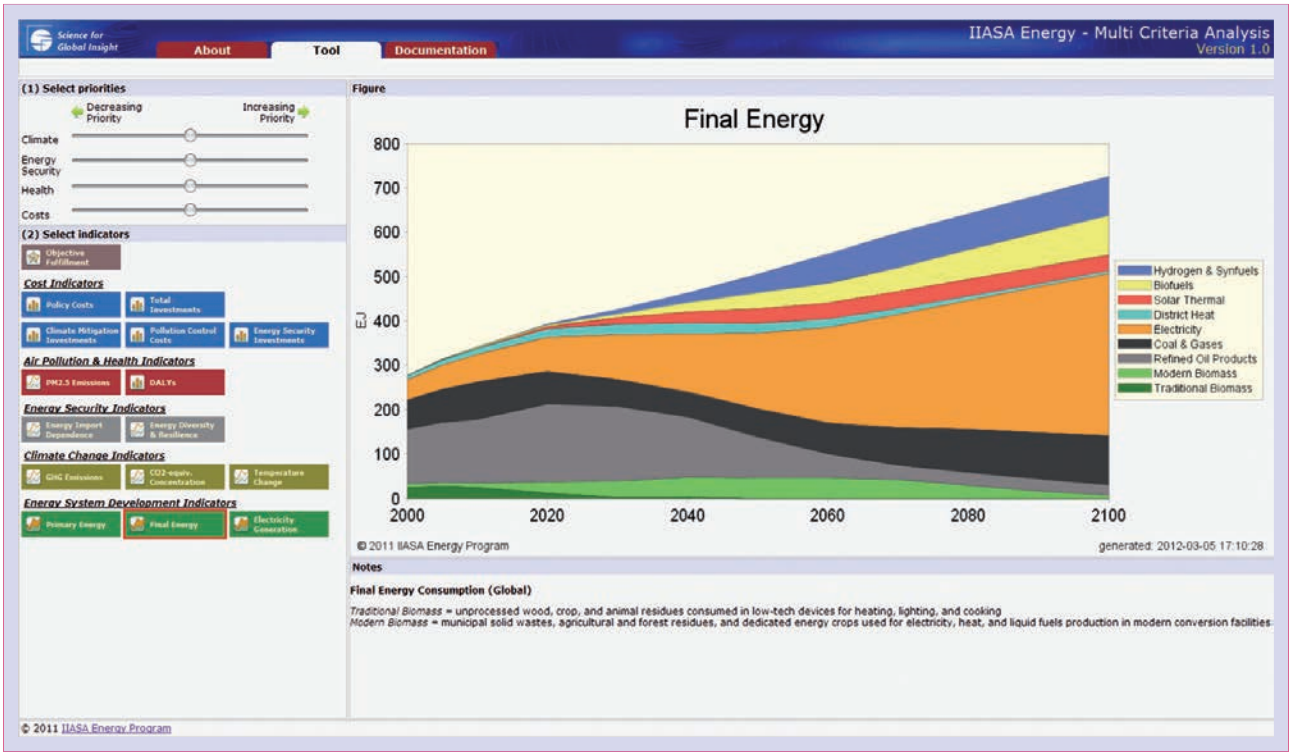
Primary Energy Consumption (Global)

Fossil category includes Coal, Natural Gas, and Oil.

Renewables category includes Wind, Solar, Geothermal, and other Renewables.

Values for nuclear, hydro, and non-biomass renewables are calculated using the substitution method (35% efficiency for electricity; 85% for heat).

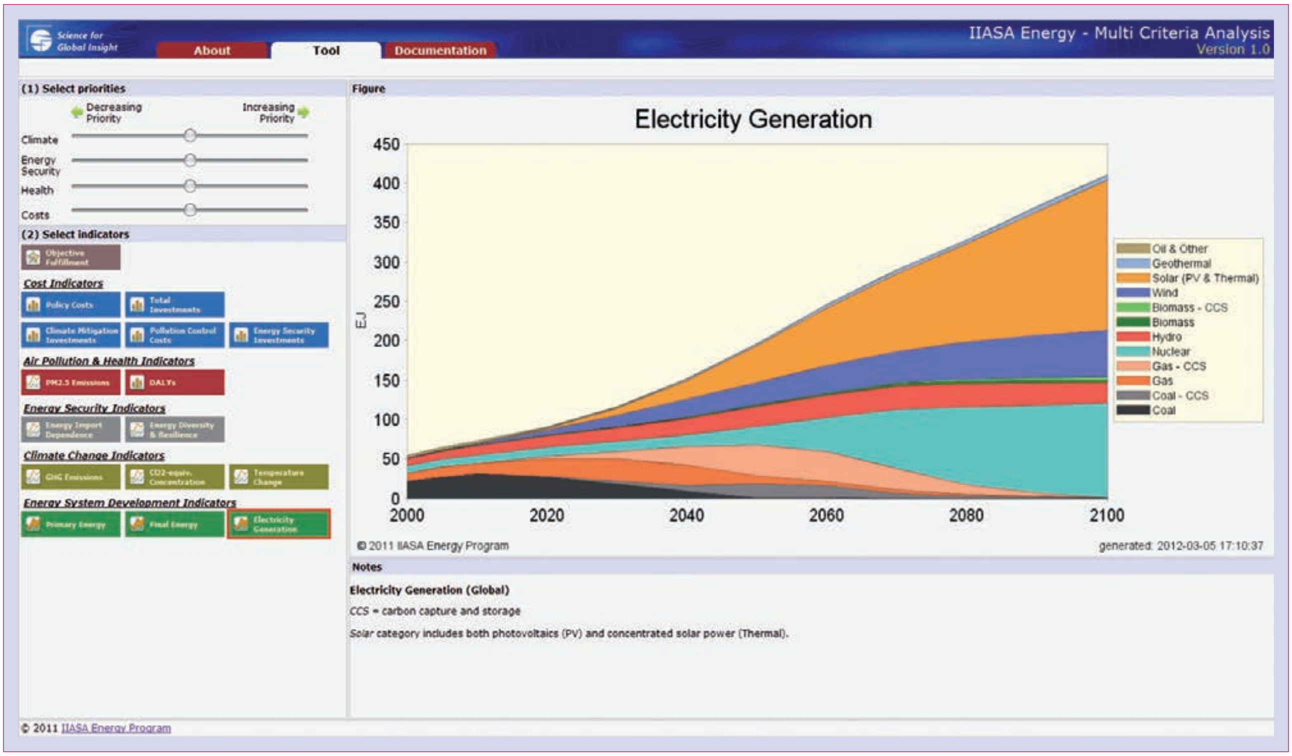
FIGURE 22 ENE-MCA Policy Tool Indicator: Primary Energy Consumption



Final Energy Consumption (Global)

Traditional Biomass = unprocessed wood, crop, and animal residues consumed in low-tech devices for heating, lighting, and cooking
Modern Biomass = municipal solid wastes, agricultural and forest residues, and dedicated energy crops used for electricity, heat, and liquid fuels production in modern conversion facilities

FIGURE 23 ENE-MCA Policy Tool Indicator: Final Energy Consumption



Electricity Generation (Global)

CCS = carbon capture and storage

Solar category includes both photovoltaics (PV) and concentrated solar power (Thermal).

FIGURE 24 ENE-MCA Policy Tool Indicator: Electricity Generation impacts of all well-mixed Kyoto greenhouse gases (CO_2, CH_4, N_2O, SF_6, CF_4, and various halocarbons), as well as from a number of air pollutants that have both direct or indirect effects on the global climate (NO_x, VOCs, CO, SO_2, PM, BC, OC, NH_3). A second figure translates these changes in CO_2-eq concentrations into global warming, or rather projected temperature changes above pre-industrial levels (Figure 21).

Three indicator tabs allow the user to explore the actual energy and resource mixes of their selected scenario and how those mixes change over the course of the 21st century at the global level. One figure shows primary energy consumption (Figure 22), another depicts final energy consumption (Figure 23), and the third illustrates electricity generation (Figure 24).

5. Additional Information

Energy security modeling

The precise definition of security can vary quite widely depending on the context (Kruyt et al., 2009; Sovacool and Brown, 2010). In the United States, for example, the discussion often centers around imported oil; in Europe the corollary is natural gas. In developing countries, security often means obtaining access to reliable and adequate energy supplies in order to meet rapidly growing demands. Yet, while the specific definition may vary in each case, diversity tends to be an important theme throughout. Hence, in the ENE-MCA tool the energy security objective is represented with an indicator that measures global primary energy diversity and resilience. This compound indicator, which derives from the Shannon index (Stirling, 1994; Jansen et al., 2004; Kim et al., 2009; Kruyt et al., 2009), takes into account the diversity of primary energy resources as well as where those resources are sourced, whether they come from imports or domestic production. The indicator increases with growing diversity of the resource mix, but at the same time decreases at higher levels of import dependency. In the aggregate, however, the higher the diversity indicator for a given country or region (relative to other countries/regions or to other points in time), or for the world as a whole, the more secure is its energy system.

$$I = -\sum_j \{(1 - m_j) \cdot (p_j \cdot \ln p_j)\}$$

where

I – compound energy diversity indicator (resources + imports)
p_j – share of primary energy resource j in total primary energy supply
m_j – share of primary energy resource j that is supplied by (net) imports

Air pollution and health impacts modeling

Air pollutant emissions depend on the structure and composition of the energy system and on the nature of the pollution control strategies employed. Hence, the pollutant emissions trajectories of each of the scenarios in the ensemble are determined by the stringency of policy in three key areas: pollution control, climate mitigation, and energy security. As with greenhouse gas emissions, each scenario of the large ensemble possesses unique emissions trajectories for sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOC), carbon monoxide (CO), black carbon (BC), organic carbon (OC), ammonia (NH_3), and fine particulate matter (PM2.5). Typical pollution control strategies to limit the generation of these chemical species include utilization of low-sulfur fossil fuels (especially for coal and petroleum-based fuels) and application of "end-of-pipe" technologies, such as flue gas desulfurization, selective catalytic reduction, electrostatic precipitators, and particulate filters, for both stationary and mobile sources. In addition, pollution can be reduced through measures that are typically thought of as climate mitigation strategies: energy efficiency improvements, combined heat and power (CHP), fuel switching (e.g., from coal and oil to natural gas), and utilization of nuclear and renewable energy technologies.

To estimate air pollutant emissions and pollution control costs for each MESSAGE energy scenario, data and output from IIASA's Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model was utilized (Amann et al., 2009).[3] At each level of air pollution legislation stringency and for each pollutant and region, emissions factors were obtained from GAINS for the corresponding energy technologies in MESSAGE. In addition, for a given level of pollution control stringency, GAINS was used to estimate the cost of installing all necessary pollution control equipment by energy technology. In this respect, care was taken not to double-count MESSAGE and GAINS technology costs.

For the purposes of this analysis, in order to span the scenario space along the pollution/health dimension, four different levels of stringency are considered for air pollution legislation (Table 2). For further details on the types of controls assumed for the different policy packages, see Chapter 17 of the Global Energy Assessment manuscript (Riahi et al., 2012), as well as Rafaj et al. (2010) and Rao et al. (forthcoming).

Health impacts from air pollution are calculated for each of the eleven MESSAGE model regions by estimating disability-adjusted life years (DALYs) attributable to exposure to anthropogenic emissions of PM2.5.[4] This time-based measure

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[3] We gratefully acknowledge Shilpa Rao and Wolfgang Schöpp for their invaluable roles in translating the pollutant emissions factors and cost estimates from GAINS to MESSAGE.

[4] Note that these aggregated estimates are built up from considerably more spatially-explicit modeling studies that utilize spatial emission data at 0.5 degree resolution worldwide.

TABLE 2 Description of air pollution policy packages

Air Pollution Policy Package	Description
FLE	***Frozen Legislation*** No improvement in air quality legislation beyond 2005 in any region
CLE	***Current and planned Legislation*** Air quality legislation is enacted in every region where it currently exists or is planned (baseline case)
SLE	***Stringent Legislation*** Feasible, aggressive air quality legislation is enacted in all regions; exceeds CLE levels (implementation level by region is 70% of what could theoretically be achieved via MFR)
MFR	***Maximum Feasible Reduction*** Best practice technologies of today are required in every region by 2030; represents the theoretical limit to pollution control

combines years of life lost due to premature mortality and due to time lived in states of less than full health. Further details on the methodology can be found in Rao et al. (forthcoming). Descriptions of how to calculate DALYs, in general, are given by Krewitt et al. (2002) and Wilkinson et al. (2009), though it should be noted that the methodology used specifically for this study, as described in Rao et al. (forthcoming), adopts unique assumptions.

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