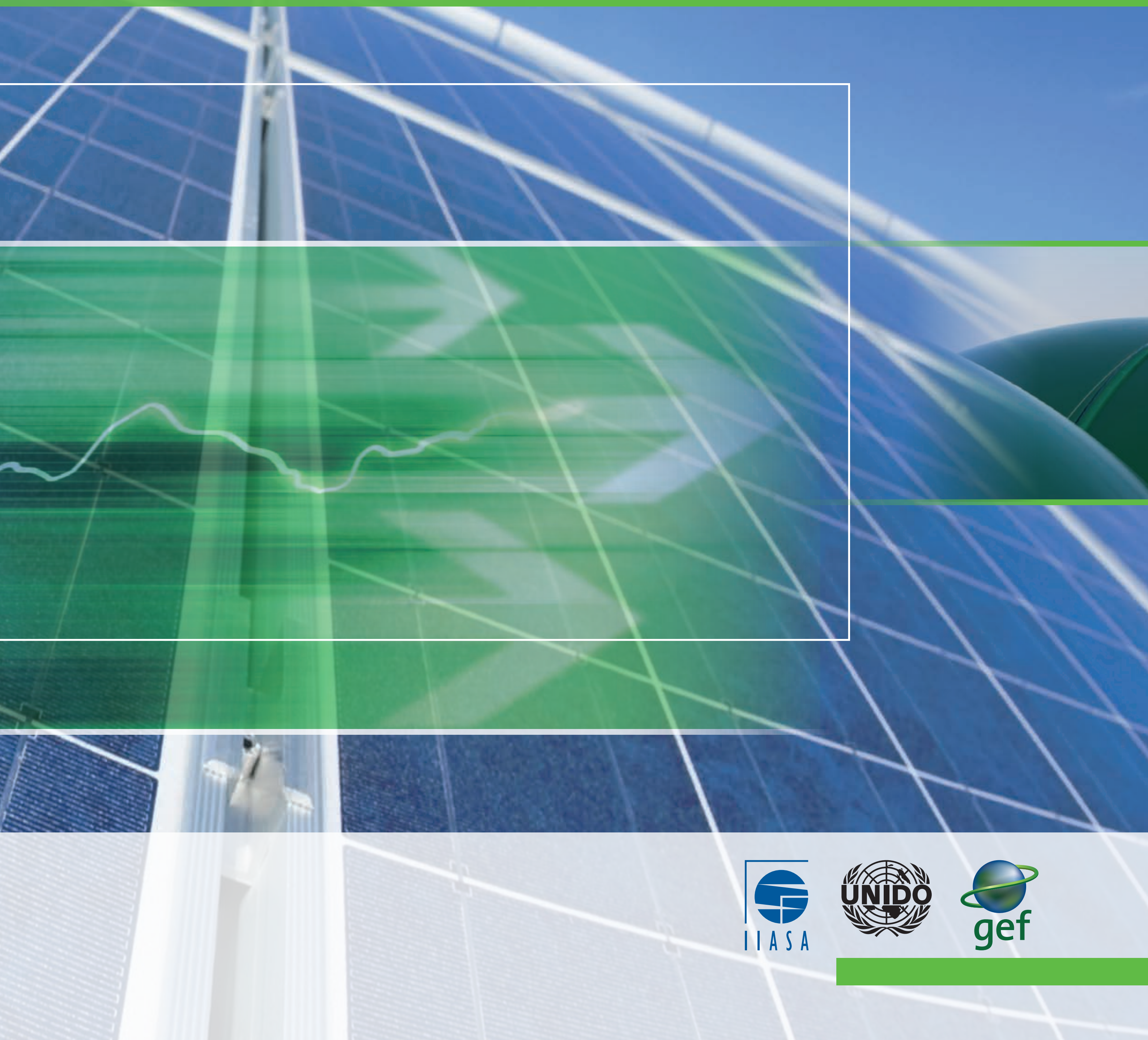
The Next Energy Transition

Transformative Pathways, Choices and Opportunities



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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.

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Forewords

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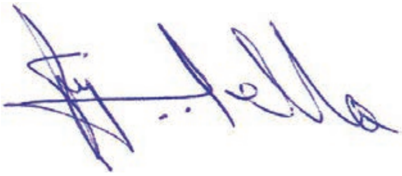
Energy powers human progress, from job generation to economic competitiveness, from strengthening security to empowering women, energy is the great integrator: it cuts across all sectors and lies at the heart of all countries' core interests. I strongly believe that now more than ever, the world needs to ensure that the benefits of modern energy are available to all and that energy is provided as cleanly and efficiently as possible. This is a matter of equity, first and foremost, but it is also an issue of urgent practical importance.

Developed countries face the combined challenge and opportunity of transforming existing energy infrastructure, while developing countries have the opportunity to adopt cleaner, more efficient technology from the start. These objectives reinforce each other in many instances, and achieving them together will power opportunity, maximize socioeconomic development, enhance domestic and international security and help reduce climate change impacts.

The transformational scenario pathways developed by the IIASA Energy Program within the framework of the Global Energy Assessment (GEA) approach the global transition toward sustainable development in an integrated, holistic manner, taking a broad view of the four main energy challenges faced by society in the 21st century: providing universal access to modern energy for all; avoiding dangerous climate change; reducing the impacts of energy on human health and the environment; and enhancing energy security. In other words, achieving sustainable energy—energy that is accessible, cleaner and more efficient—powers opportunity. Recognising the importance of sustainable energy choices, IIASA and UNIDO, with support of the Global Environment Facility (GEF), have partnered to develop specific tools, reports and technical analysis to support decision makers in addressing the challenges of providing energy services for sustainable development throughout the world.

This report uses the GEA as a knowledge platform and aims to inform decision-makers on the scaling-up of low carbon energy technologies, achievement of reductions in greenhouse gas emissions, and the reduction of energy poverty.



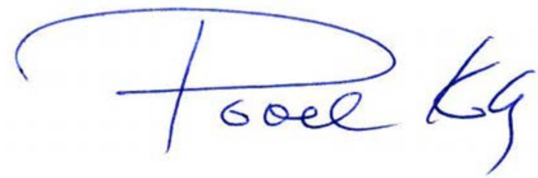
Pavel Kabat
Director/Chief Executive Officer
IIASA

Two decades ago, decision makers from all segments of society gathered in Rio de Janeiro for the United Nations Conference on Environment and Development. The world has undergone a substantial transformation since that time—socially, economically, politically, and in so many other dimensions. Along the way, the International Institute for Applied Systems Analysis (IIASA) has played an active role in informing the policy process at all levels and in all parts of the globe, particularly on issues that are too large or complex for any single nation or scientific discipline to solve on its own.

In particular, by employing rigorous scientific methodologies and a comprehensive framework of systems-level modeling tools, researchers from the Energy Program at IIASA have made a unique and lasting contribution to the field of global change research. Energy Program scientists have for years investigated the various dimensions of socio-economic and technological change and sought solutions for the many social ills of the 21st century that relate to the energy conundrum. Two of the best examples of IIASA's work include the future development pathways and emission scenarios they designed and analyzed in support of the Intergovernmental Panel on Climate Change (IPCC) assessments and the World Energy Council study.

The rich tradition of the Energy Program continues today with the finalization of the Global Energy Assessment (GEA) and the transformational energy pathways that have been developed as a part of this multi-year, multi-stakeholder activity, which aims to help decision makers throughout the world address the challenges of providing energy services for sustainable development. As summarized in this report, the GEA pathways go beyond the existing scenario literature by presenting a comprehensive and integrated analysis of energy challenges, opportunities and strategies, for developing, industrialized and emerging economies. The pathways make clear that, from both a technical and economic perspective, it is entirely feasible to simultaneously (1) mitigate the worst effects of climate change, (2) provide near universal energy access, (3) enhance the security of national and regional energy systems and infrastructures, and (4) improve local air quality in most parts of the globe.

Achieving these multiple objectives for energy sustainability is of course contingent upon sufficient political and social will, as well as the willingness of decision makers to take a more holistic and integrated perspective of the problems we are facing as a society over the coming decades. Thanks primarily to the support of the United Nations Industrial Development Organization (UNIDO) and the Global Environment Facility (GEF), this study and the interactive policy tools that have sprung from it help to inform the evolving dialogue by illuminating some of the complex relationships, synergies and trade-offs between the various dimensions of energy transformation and global change. Having worked at the interface of science and policy for almost three decades, I am personally convinced that this is a critical step in the right direction. For along the path that is sustainability, which will soon take us again through Rio and then beyond, there will be a myriad of choices and opportunities. This report provides sound guidance to decision makers when considering the different directions they could take.



Preface

This report provides a high-level summary of the transformational scenario pathways developed by the IIASA Energy Program within the framework of the Global Energy Assessment (GEA). These pathways approach the global transition toward sustainable development in an integrated, holistic manner, taking a broad view of the four main energy challenges faced by society in the 21st century: providing universal access to modern energy for all; avoiding dangerous climate change; reducing the impacts of energy on human health and the environment; and enhancing energy security. Developing solutions to these challenges is one of the chief aims of policy makers, and for this reason this report attempts to synthesize a multitude of strategic insights that have resulted from the pathways analysis. The overarching objective of the report is to provide guidance on how to facilitate the transformation of the energy system to achieve the multiple energy objectives. Focus is given to the required pace of the transformation at both the global and regional levels, as well as to the types of measures that will be needed to ensure a successful transition.

This report is complemented by three interactive, web-based analytical tools, which have been developed by the IIASA Energy Program in support of this study: (1) the GEA Scenario Database, which documents the full suite of transition pathways in great detail, allowing the user to explore the consequences of different supply and demand-side technology choices for the feasibility and costs of reaching the multiple energy objectives at both the global and regional levels; (2) the IIASA ENE-MCA Policy Analysis Tool, which permits the concurrent assessment of synergies and trade-offs between the multiple energy objectives at the global scale; and (3) the IIASA Energy Access Tool (ENACT), which helps gauge the effectiveness of various energy access policies and measures in the major developing regions of the world.

Main Findings of the Global Energy Assessment Scenario Analysis

Commonalities of the GEA Pathways

The large ensemble of future energy pathways developed by the IIASA Energy Program within the framework of the Global Energy Assessment (the "GEA pathways") shows that it is possible to achieve improved energy access, air quality, and energy security simultaneously, while avoiding dangerous climate change. Doing so will require a technological transformation of the global energy system over the next several decades, as well as the rapid introduction of policies and fundamental political changes toward concerted and coordinated efforts to integrate global concerns into local and national policy priorities. An in-depth modeling and sensitivity analysis illustrates the following commonalities of the GEA pathways:

- Constant and sustained energy efficiency improvements are imperative, in order to reduce the risk that the multiple energy objectives become unreachable. Lowering the energy intensity of the global economy – at improvement rates consistent with the recent past, if not much faster – helps to increase the flexibility of supply and the overall cost-effectiveness of the energy system transformation.
- Low-carbon shares in global primary energy must reach at least 60–80% by 2050. This will necessitate a broad portfolio of supply-side options, including non-combustible renewables, bioenergy, nuclear energy, and carbon capture and storage (CCS). In particular, this translates to:
  - Strong growth in renewable energy beginning immediately and reaching 165–650 exajoules (EJ) of primary energy by 2050.
  - An increasing requirement for storage technologies to support system integration of intermittent wind and solar energy.
  - Growth in bioenergy in the medium term to 80–140 EJ by 2050 (including extensive use of agricultural residues and second-generation bioenergy to mitigate adverse impacts on land use and food production).
  - Nuclear energy playing an important role in the supply-side portfolio in some, but not all, transition pathways. (The assessment of "restricted" portfolio pathways suggests that it is also feasible to phase out nuclear and still meet the sustainability targets.)
  - Fossil CCS as an optional bridging or transitional technology in the medium term, and increasing contribution of biomass with CCS in the long.
  - Aggressive decarbonization is particularly critical in the electricity sector, where low-carbon shares will likely need to reach between 75 and almost 100% by 2050. This means a phase-out of conventional coal power (i.e., without CCS) in the short to medium term, with natural gas power potentially acting as a bridging or transitional technology.
- Transportation sector enhancements, through electrification or the introduction of hydrogen vehicles, can improve end-use efficiency and increase supply flexibility.
- Oil consumption will likely need to peak in the transportation sector by 2030, followed by a phase-out over the medium term. Strong growth of liquid biofuels will be necessary to offset petroleum-based fuels in the short to medium term, after which the mix of liquid and gaseous fuels depends on transportation system choices and technological breakthroughs.
- The availability of energy resources should not limit low-carbon technology deployment on an aggregated global scale but may pose important constraints regionally, particularly in Asia, where energy demand is expected to grow rapidly.
- The transformation of the global energy system would require substantially increased future cash flows:
  - Dedicated efforts to increase global energy-related investments to between US$1.7 trillion and US$2.2 trillion annually, compared with about US$1.3 trillion in annual investment today.

- Out of this total, about US$300 to US$550 billion per year would be for efficiency-related investments on the demand-side.
- Future transitions with a focus on energy efficiency would achieve the targets at more modest cost and, thus, represent the lower bound of the investment range.
- Total energy investments correspond to a small fraction (about 2%) of global gross domestic product (GDP).

The storylines of the required energy system transformations that are quantified and elaborated in the GEA pathways are far richer than these commonalities suggest. Nevertheless, this collation of all the required features of an energy system transformation describes the trunk off which the many choices and possibilities branch. Many of these choices are strongly influenced by one or more of the GEA objectives with respect to energy access, air pollution, climate change, and energy security. Table 1 summarizes some of the main characteristics of the pathways in the context of each objective and the more detailed policy and investment requirements that illustrate how these pathways might be driven.

Policies to Drive the Sustainable Energy Transition

Meeting the sustainability objectives will require further tightening of present and planned legislation and the introduction of new policies:

- Universal access to electricity and clean cooking requires the rapid shift from the use of traditional biomass to cleaner fuels and technologies. This is feasible over the next 20 years provided that sufficient financial resources are made available for investments on the order of US$36 billion to US$41 billion/year (half of it in Africa). Universal access results in significant health benefits of more than 24 million disability-adjusted life years (DALYs) saved in 2030.
- Pollution control measures across all sectors need to be tightened beyond those in present and planned legislation in order to meet World Health Organization (WHO) air quality standards. Estimated global costs to meet the air pollution target are about US$200 billion to US$350 billion annually to 2030 (about 10–20% of energy costs), resulting in about 21 million DALYs saved in 2030.
- Limiting global temperature change to less than 2°C over preindustrial levels can only be achieved through stringent climate policies motivating rapid reductions of global CO_2 emissions from the energy sector, which in the GEA pathways peak around 2020 and decline thereafter to 30–70% below 2000 emissions levels in 2050, eventually reaching zero or even negative CO_2 emissions in the second half of the century.
- Enhanced energy security for regions can be achieved by both limiting dependence on imported fuels and increasing the diversity and resilience of energy systems. A focus on energy efficiency improvement and renewable deployment increases the share of domestic (national or regional) supply in primary energy by a factor of 2 and thus significantly decreases import dependency.

Maximizing Synergies

The GEA pathways illustrate the importance of a holistic and integrated approach to energy policy and planning:

- The simultaneous achievement of energy access, climate change mitigation, energy security, and air pollution control comes at a significantly reduced total energy cost when the multiple economic benefits of each are properly accounted for.
- Above all, stringent climate policy and a rapid decarbonization of the energy system will allow these enormous synergies to be realized.
    - The added costs of air pollution control can be cut by up to US$500 billion annually to 2030 at the global level.
    - The costs of pursuing energy security interests can be reduced to almost zero, translating to an annual cost savings of about US$130 billion in 2030.

Fossil fuel subsidies, particularly to the most affluent parts of the global population, can be lowered by about US$70 billion to US$130 billion per year by 2050. (At present, subsidies of coal and oil products amount to about US$132 billion to US$240 billion per year.)

The Objectives: Progress along Multiple Dimensions

Reaching the economic, environmental and social sustainability objectives of all societies requires that several major energy challenges be successfully overcome and necessitates rapid progress along multiple dimensions. The energy pathways presented in this book describe transformative changes toward these goals. The pathways were developed by the IIASA Energy Program within the framework of the Global Energy Assessment (GEA) to explore technical measures, policies, and related costs and benefits for meeting the following energy objectives:

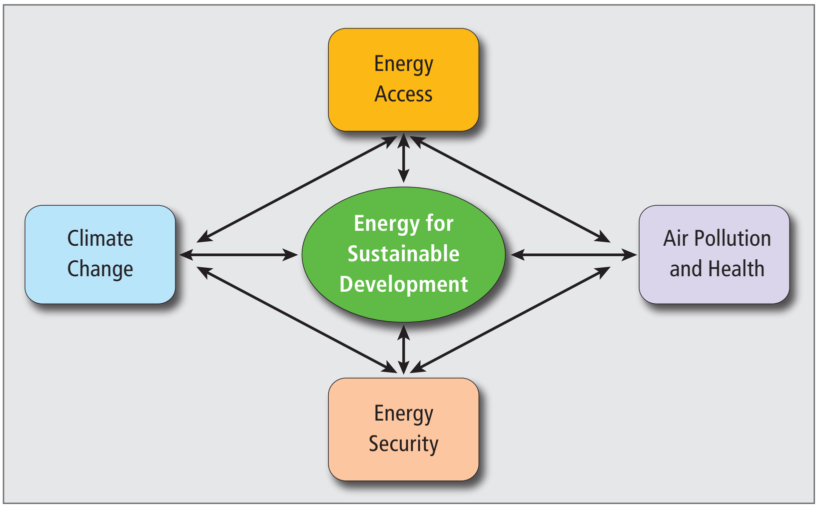


FIGURE 1
Sustainable development means solving the four main energy challenges

- providing almost universal access to affordable clean cooking fuel and electricity for the poor,
- limiting air pollution and health damages from energy use,
- improving energy security throughout the world, and
- avoiding dangerous climate change.

These objectives are defined as quantitative targets in the GEA pathways, i.e., a schedule is specified for meeting each target by a certain point in time (Table 1). The targets are of central importance, since they define the ambitiousness and the magnitude and pace of the required energy system transformation. They act as the major drivers of the pathways, defining the policy stringency and portfolio of measures that are necessary to simultaneously respond to the multiple energy challenges. Because the GEA objectives are strongly normative, the targets are all designed to be ambitious. The GEA pathways nevertheless make clear that all the targets can be reached, if appropriate policies are introduced and energy investments are scaled up considerably.

TABLE 1 Targets for the four main energy challenges, key characteristics of the corresponding transition pathways, and illustrative examples of policies and investments.

Objective	Target and timeline	Pathway characteristics	Examples of policies and investments
Improve energy access	Universal access to electricity and clean cooking by 2030	Diffusion of clean and efficient cooking appliances Extension of both high-voltage electricity grids and decentralized microgrids Increased financial assistance from industrialized countries to support clean energy infrastructure	Microcredits and grants for low-emission biomass and LPG stoves in combination with LPG and kerosene fuel subsidies for low-income populations *Estimated cost to provide clean cooking: US$17 billion to US$22 billion per year to 2030* Grants for high-voltage grid extensions and decentralized microgrids Estimated cost to provide rural grid connections: US$18.4 billion to US$19 billion per year to 2030
Reduce air pollution and improve human health	Achieve global compliance with WHO air quality standards (PM2.5 concentration < 35 μg/m^3) by 2030	Tightening of technology standards across transportation and industrial sectors (e.g., vehicles, shipping, power generation, industrial processes) Combined emissions pricing and quantity caps (with trading) Fuel switching from traditional biomass to modern energy forms for cooking in developing countries	Vehicles: Euro 3–4 standards for vehicles in developing countries by 2030 (e.g., –60% NO_x, PM reductions by 2030) Shipping: Revised MARPOL Annex VI and NO_x Technical Code 2008 (–80% SO_x, NO_x reductions by 2030) Industry/power: rapid desulfurization, de-NO_x, and PM control around the world by 2030 *Estimated cost to meet air pollution targets: US$200 billion to US$350 billion/year in 2030 (about 12% of energy costs); co-benefits of stringent climate mitigation policies reduce overall pollution control costs by about 50–65%*
Avoid dangerous climate change	Limit global average temperature change to 2°C above preindustrial levels with a likelihood >50%	Widespread diffusion of zero- and low-carbon energy supply technologies, with substantial reductions in energy intensity Energy-related CO_2 emissions peak by 2020 and are reduced to 30–70% by 2050 from 2000 levels Globally comprehensive mitigation efforts covering all major emitters Financial transfers from industrialized countries to support decarbonization	Combination of cap-and-trade and carbon taxes (with initial carbon price >US$30/t$CO_2$, increasing over time) *Upscaling of investments into low-carbon technologies and efficiency measures to >$US600 billion/year to 2050* Additional financial transfers to developing countries of about 3–12% of total energy systems costs to 2050, depending on the domestic commitment of industrialized countries
Enhance energy security	Reduce energy import dependence; increase diversity and resilience of energy supply (both by 2050)	Increase in local energy supply options (e.g., renewables to provide 30–75% of primary energy by 2050) Greater diversity of imported fuels and reduction in dependency (e.g., reduce share of oil imports in primary energy by 30–80% by 2050 from 2000 level) Infrastructure expansion and upgrades to support interconnections and backup, including increased capacity reserves, stockpiles, and energy storage technologies	Public procurement strategies and regulations to support local supplies (e.g., renewable obligations) Interconnection and back-up agreements between energy network operators Stockpiling of critical energy resources for coordinated release during acute market shortages Estimated cost of infrastructure upgrades for the electricity grid: >US$310 billion/year by 2050, co-benefits of stringent climate mitigation policies reduce overall security costs (import dependency and diversity) by more than 75%.

The Pathways: Taking a Holistic Approach to Energy

The GEA pathways are designed to describe transformative changes toward a more sustainable future. A specific feature of these pathways is that they simultaneously achieve normative targets related to all four major energy challenges. Emphasis is given to the identification of potential synergies, or in other words, of integrated solutions and "win–win" strategies in addressing multiple energy objectives at the same time. The primary reasons for developing the transformational pathways are, first, to provide a quantitative and qualitative framework for the identification of policies and measures for a transition toward an energy system that supports sustainable development, and second, to facilitate integration of diverse energy issues and consistency across the different chapters of the GEA.

One possible way of understanding the GEA pathways is to regard them as alternative interpretations of one overarching GEA scenario, in which the energy system is transformed under normative, sustainable goals. The pathways highlight different degrees of freedom and routes to these goals. All economic and demographic changes are the same across the pathways, however. They share a common median demographic projection whereby the global population increases from almost 7 billion today to about 9 billion by the 2050s before declining toward the end of the century (UN, 2009). They also possess a common median economic development path, expressed in terms of world gross domestic product (GDP), that allows for significant development in the 50 or so poorest countries in the world (Riahi et al., 2012). Global real per capita income in the GEA pathways grows at an annual average rate of 2% over the next 50 years. This socioeconomic development pathway is chosen to be consistent with global aspirations toward a sustainable future.

There is only one GEA scenario – an overarching storyline of energy system transformation to meet the normative sustainability targets. The GEA pathways – GEA-Efficiency, GEA-Mix, GEA-Supply – represent alternative descriptions of demand- and supply-side energy system transformations under this umbrella.

Although some combination of both supply- and demand-side measures is needed to transform the energy system, emphasis on one side or the other constitutes an important point of divergence between different policy choices that may drive the energy system in alternative directions. Thus, a critical factor is to what extent demand-side efficiency measures together with lifestyle and behavioral changes, can reduce the amount of energy used for mobility, housing, and industrial services, thereby helping to fulfill the GEA's aspirational goals across virtually the whole range of sustainability objectives. If energy demand is low, any of a number of alternative supply-side configurations might be able to fulfill the goals. By contrast, a lower emphasis on reducing energy demand will require a much more rapid expansion of a broader portfolio of supply-side options. Hence, the successful implementation of demand-side policies increases the flexibility of supply-side options, and, vice versa, more rapid transformation of the supply side increases flexibility on the demand side.

Three GEA pathway groups are distinguished within the sustainable GEA scenario to represent different emphases in terms of demand-side and supply-side changes. Each group varies, in particular, with respect to assumptions about the comprehensiveness of demand-side policies to enhance efficiency, leading to pathways of comparatively low energy demand (GEA-Efficiency), intermediate demand (GEA-Mix), and high demand (GEA-Supply). The GEA-Efficiency pathways show the most flexibility on the supply side of the energy system, while GEA-Supply is more flexible on the demand side, requiring much less pervasive introduction of efficiency measures to reduce energy demand for services. The pathways thus explore not only alternative combinations of supply- and demand-side policy portfolios, but also different choices with respect to overall strategy and level of implementation. In this context, the GEA-Mix pathways explore the degrees of freedom offered by more diverse energy systems, from resource extraction to services delivered to end users. The emphasis of GEA-Mix is on the diversity of the energy supply mix, to enhance the system's resilience against innovation failures or technology shocks. This emphasis also implies that the GEA-Mix group of pathways is not necessarily intermediate between the other two groups in terms of other salient scenario characteristics (e.g., the required policy portfolio, costs, fuel choices, or deployment of individual technologies).

Within each larger group of pathways, a range of alternative pathways for the supply-side transformation is explored. Moving to a specific pathway entails critical choices, or "branching points." The first branching point tests the flexibility of different supply-side configurations to fulfill the GEA sustainability objectives, given the levels of energy demand in the pathway group. One aim was specifically to use the GEA Integrated Assessment Models (see Box 1) to explore whether any of the

BOX 1 The GEA Scenario Development Process

The GEA scenario and pathways were developed in parallel by two integrated assessment modeling frameworks and through an iterative and participatory process so as to achieve integration across various chapters of the GEA (Figure 3). Important inputs to the GEA scenarios include quantitative techno-economic information, such as technology costs, energy resources, and potentials, which were provided by other GEA clusters. In addition, a series of workshops and a scenario questionnaire were prepared by the GEA writing team and external experts to solicit input for defining the main characteristics of the GEA scenario taxonomy and the set of objectives for a sustainable energy system with specific targets and timelines. These inputs are used by two modeling frameworks for the development of the GEA pathways: MESSAGE (Messner and Strubegger, 1995; Riahi et al., 2007) and IMAGE (Bouwman et al., 2006).

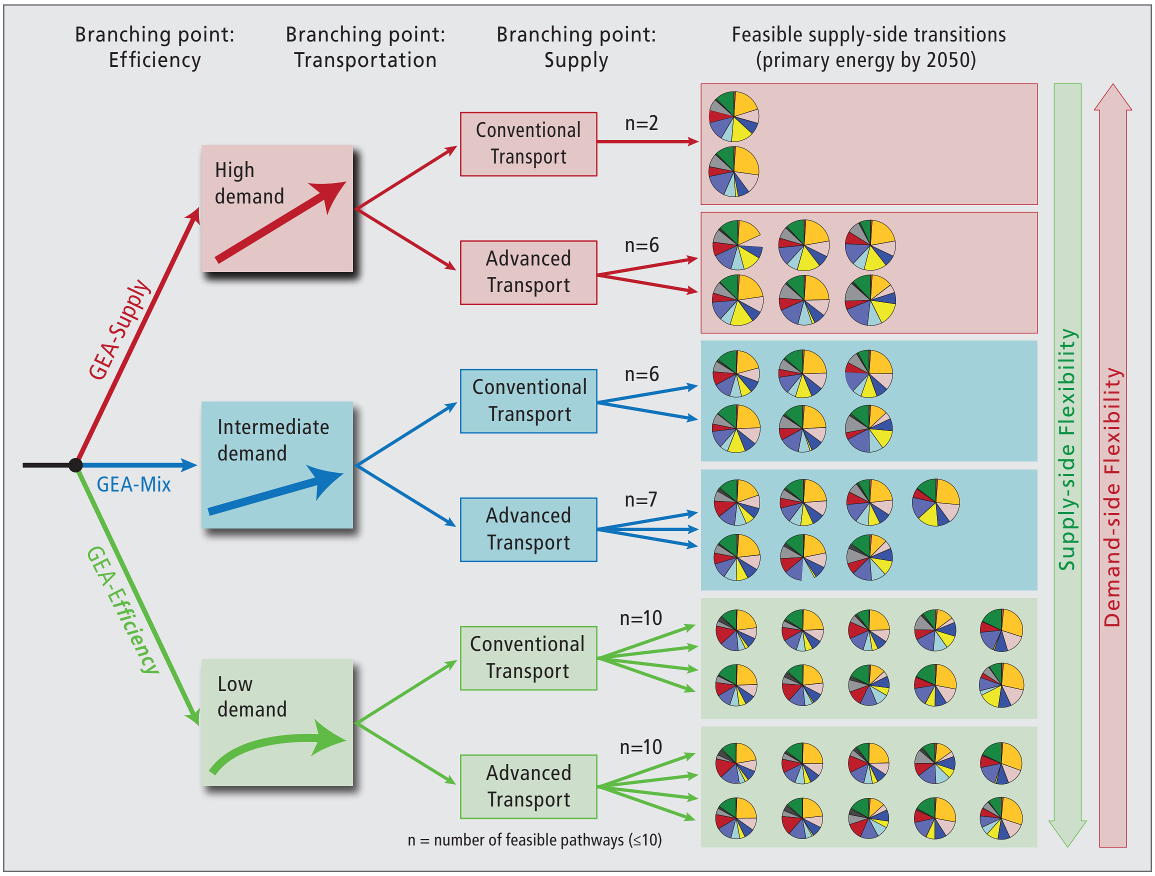


FIGURE 2
Schematic illustration of the GEA pathways and the three branching points. The scenario setup features alternative choices for the combination of demand-side efficiency improvements and supply-side transformations, describing alternative policy emphases that would enable the transformation toward a sustainable energy system. The pie charts represent primary energy portfolios of feasible transformation pathways under different branching point assumptions

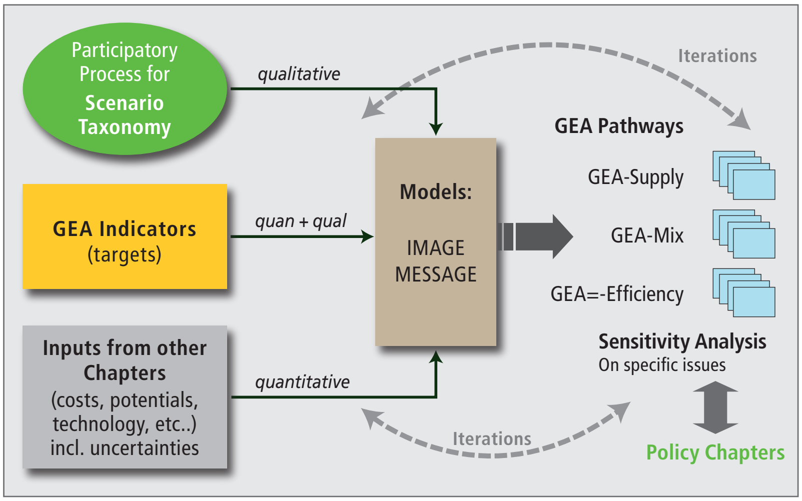


FIGURE 3
The GEA scenario development process

supply options were mandatory. To do this, constraints were set on the portfolio of supply-side options by prohibiting or limiting the availability of specific technologies, including nuclear, CCS, biomass, and other renewables. Another branching point, whose importance was revealed by this supply-side analysis, concerns changes in the transportation system. A "conventional" transportation system relying on liquid fuels (oil, biofuels, liquefied natural gas) has substantively different implications for supply flexibility than an "advanced" system dominated by electric or hydrogen-powered vehicles. The former represents the least discontinuity from current trends, in terms of both end-use technologies and fuel supply and distribution infrastructure, whereas the latter involves a more fundamental transformation, requiring largely new infrastructure systems in the case of hydrogen fuel cell vehicles, or new uses for existing infrastructure in the case of plug-in hybrids or fully electric vehicles. Although any major transformation in an end-use sector that entails fuel switching will impact the energy supply, the magnitude of the impact of such a transformation in the transportation system alone warranted its inclusion as an explicit branching point.

The various branching points lead to a total of 20 alternate pathways within each pathway group, giving a total of 60 alternative GEA pathways (Table 2, Figure 2). Of these, 19 were rejected as they failed to fulfill the GEA objectives: that is, no feasible solution could be found within these pathways that would meet the normative GEA targets summarized in Table 1.

TABLE 2 GEA pathways and branching points.

Branching point 1: *What is the level of energy demand?*	**Branching point 2:** *What are the dominant transportation fuels and technologies?*	**Branching point 3:** *How diverse is the portfolio of supply-side options?*
GEA-Efficiency (low demand) GEA-Supply (high demand) GEA-Mix (intermediate demand)	Conventional (liquid fuels) Advanced (electricity, hydrogen)	Full portfolio (all options) Restricted portfolio (excludes or limits particular options): ■ No CCS ■ No BioCCS ■ No sinks ■ No nuclear ■ No nuclear and no CCS ■ Limited renewables ■ Limited biomass ■ Limited biomass and renewables ■ Limited biomass, no BioCCS, no sinks

Key Features of the Energy Transition

Summary of Findings

Although simultaneous fulfillment of the GEA objectives poses an extremely ambitious task, the GEA scenario analysis shows it is technically possible. The full suite of GEA pathways, grouped according to the aggressiveness with which energy demand can be reduced, highlights the potential role for a range of energy conversion chains from primary energy sources to conversion technologies and on to end-use technologies. Although there are a number of choices available to direct the energy system transformation, there are also a large number of givens – nonnegotiable, nondiscretionary components of an energy transition that must begin in 2010. These commonalities across all pathways are summarized here:

- Improvements to at least the historical rate of energy intensity reduction (more rapid improvements in energy intensity, and thus aggressive efforts to improve end-use efficiency, would increase the flexibility of supply as well as the overall cost-effectiveness of the energy system transformation)
- A rapid shift from traditional biomass to widely accessible, clean, flexible energy forms
- Important regional constraints on availability of energy resources, although such constraints do not limit deployment on an aggregated global scale
- A broad portfolio of supply-side options, focusing on low-carbon energy from renewables, bioenergy, nuclear, and CCS
  - Strong growth in renewable energy beginning immediately; a rising requirement for storage technologies to support the integration of intermittent wind and solar power into electrical grids
  - Strong bioenergy growth in the medium term, with extensive use of agricultural residues and, in the medium term, nonagricultural feedstocks (second-generation bioenergy), to mitigate adverse impacts on land use and food production
  - Nuclear energy as an important part of the supply-side portfolio in many transition pathways, although it is also feasible to phase out nuclear completely
  - CCS as an optional bridging or transitional technology in the medium term – unless energy demand is high, in which case CCS becomes necessary
- Aggressive decarbonization in the electricity sector (especially in the high-demand case); a rapid phase-out of conventional coal power (i.e., without CCS); natural gas power as a bridging or transitional technology in the short to medium term
- At least some electrification of the transportation sector, even in a conventional liquid fuels–based system
- Continued dominance of oil among liquid and gaseous fuels into and beyond the medium term; strong growth in liquid biofuels in the medium term; thereafter the mix of liquid and gaseous fuels depends on transportation system choices and technological breakthroughs
- Substantial increases in investment on both the demand and the supply side (including energy infrastructure)
- Concerted and aggressive policies to support energy system transformation, including strong regulation and standards and externality pricing

The GEA transition pathways show that simultaneously achieving the multiple objectives for energy sustainability – along the dimensions of climate change, energy access, energy security, and air pollution and health – will require a scaling up of global energy investments:

- Investment levels must increase by almost a factor of 2 compared with today, corresponding to annual investments of between US$1.7 trillion and US$2.2 trillion, or about 1.8–2.3% of global GDP.
- On the energy supply-side, the transformation of the system is achieved through pronounced shifts of investment away from the upstream fossil fuel sector to downstream electricity generation and

transmission. Consequently, the share of upstream fossil fuel–related supply-side investment in total investment decreases from 30% at present to about 12–23% by 2050. At the same time, electricity investment increases its share on average from about 42% to up to 68% by 2050.

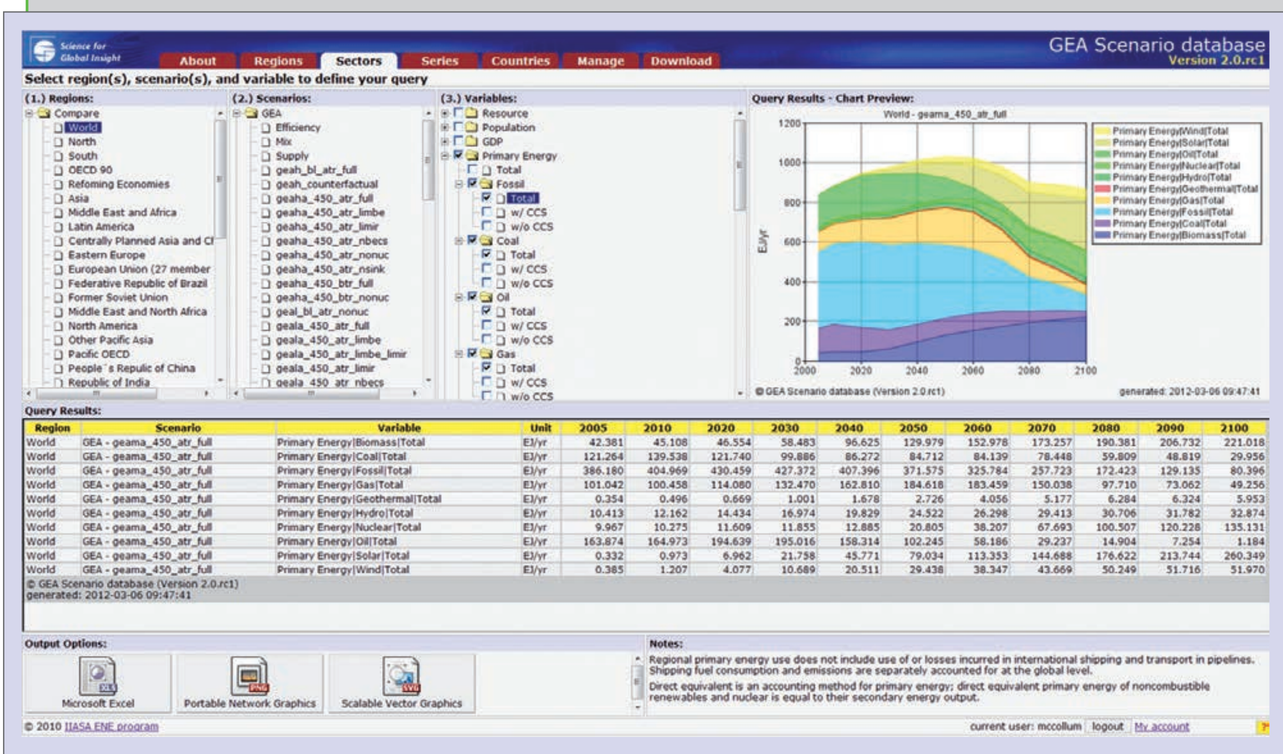
- Among all supply-side options, the largest increase in investment needs is for renewable power generation, ranging from US$160 billion/year to US$800 billion/year in 2050 (compared with US$160 billion/year in 2010).
- Global average electricity grid investment (including storage to allow the integration of intermittent renewables) by 2050 increases to between US$310 billion and US$500 billion/year, compared with US$260 billion in 2010.
- Investment in CCS ranges from zero to about US$65 billion/year in 2050, and investment in nuclear is between US$5 billion and US$210 billion/year.
- Energy investments vary quite dramatically by region across the GEA pathways. Notably, with their rapidly growing economies and populations, the investment needs in the developing world will be much larger than in currently industrialized countries over the course of this century.

BOX 2 The GEA Scenario Database

An interactive Web-based database tool allowing users to view, analyze, and export all output from the full suite of GEA transition pathways

URL: **www.iiasa.ac.at/web-apps/ene/geadb**

Detailed scenario data for the individual GEA pathways are publicly available in the GEA database. This data includes socio-economic indicators; resource, fuel, and technology utilization profiles, emissions trajectories and concentration pathways, prices of resources and fuels, and various other types of information. The GEA database provides interactive features for data visualization and a user interface for the download of scenario information in different formats.



Energy Demand and Energy Efficiency

The adequate provision of energy services is a prerequisite for human well-being and productivity, and ultimately it is the demand for these services that drives the energy system and its continuing expansion. Increasing affluence has historically been one of the major drivers of energy demand, and both the quantity and the quality of energy services determine in turn the magnitude of environmental and social impacts associated with the energy system. A subset of these impacts are addressed by the normative objectives enshrined in the overarching GEA scenario.

Energy services are typically provided by end-use technologies, which convert energy from a particular form (biomass, petroleum, natural gas, electricity, and so forth) into services useful to a final consumer (heating and cooking, mobility, industrial processing, entertainment, and others). Consequently, end-use technologies and the efficiency with which they convert energy into useful services are inseparably connected with the levels and types of energy services demand. As a result, one can identify three broad and interrelated approaches to tackling demand-side challenges in the energy system:

- Improve technological efficiency – e.g., increase vehicle fuel efficiency
- Change the structure of energy services demand – e.g., substitute physical mobility with "virtual" mobility enabled by electronic communications
- Reduce the level of energy services demand – e.g., reduce travel needs by living closer to work or amenities.

Reducing wasteful energy use in buildings, transport and industry is the single most important strategy for achieving energy sustainability, especially in the near to medium term.

Although all three of these approaches are explored in the GEA pathways as means of reducing final demand for energy, the emphasis here is on efficiency improvements. Through its potential to decouple energy demand from economic growth, energy efficiency represents a central lever for policy to target. Moreover, efficiency contributes to all the sustainability objectives. The degree to which efficiency improvements can limit energy demand growth is – by design – one of the main distinguishing characteristics of the GEA pathways.

Energy intensity metrics are widely used to represent the overall energy productivity of an economy or sector. Energy intensity is defined as energy used per unit of output and is typically expressed in megajoules per US dollar (MJ/US$) of GDP or value added. The final energy intensity of the global economy has fallen historically at a rate of about 1.2%/year since the early 1970s. However, some regions have over certain periods experienced substantially more rapid reductions. For example, China's energy intensity declined at a rate of about 4%/year between 1990 and 2000 (followed by a slower decline in the subsequent period). Despite the energy efficiency and intensity improvements that have already been implemented to date, energy intensity improvements can continue for a long time to come, as the efficiency of the energy system remains far from the theoretical potential. Although the full realization of this potential may never be possible, many estimates indicate that energy intensity reductions of a factor of 10 or more may be possible in the very long run (Nakicenovic et al., 1993; Gilli et al., 1995; Nakicenovic et al., 1996).

The degree of energy intensity improvement is a crucial uncertainty for the future. All three groups of GEA pathways depict energy intensity futures that are driven by policies to improve energy efficiency, leading to global energy intensity improvement rates at or above historical experience. This is partly a result of increasing importance of some low income regions with relatively high rates of intensity improvement – but also of the assumed move away from inefficient traditional fuels in the developing world. Energy intensity improvements, thus, vary significantly at the regional level, with some regions developing also slower than the historical rate, particularly in the GEA-Supply and Mix pathways. The resulting global average reduction in energy intensity varies across the GEA pathways between about 1.5% and 2.2% annually to 2050. The lower end of the range is slightly faster than the historical experience, whereas the higher end is roughly double that and corresponds to a reduction in energy intensity of 60% by 2050. Cumulatively, these intensity improvements lead to substantial differences in per capita energy demand across the three pathway groups (see Figure 4).

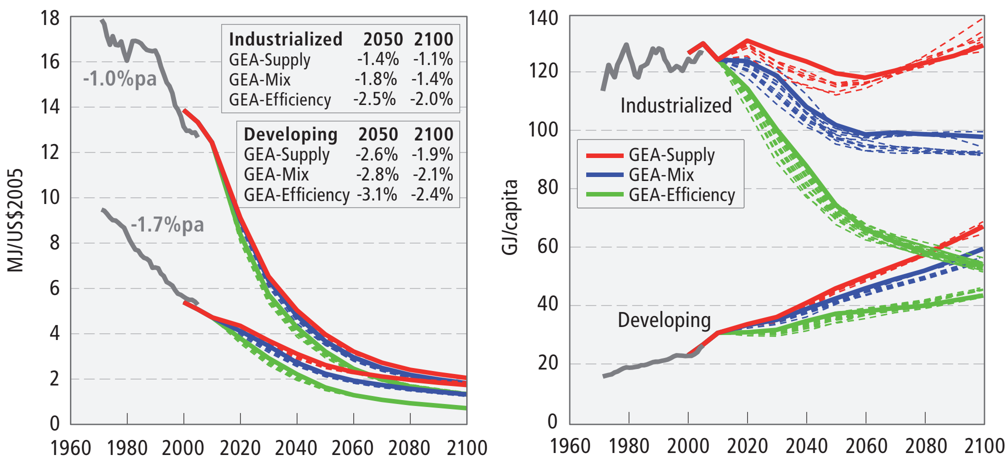


FIGURE 4
Historical and projected energy intensity (left panel) and per capita final energy use (right panel) in the developing and industrialized worlds. Solid lines denote the illustrative GEA pathways within each of the three pathway groups; dashed lines show changes in energy intensity due to supply-side variations. The inset in the left panel shows rates of improvement in energy intensity (calculated using GDP at market exchange rates) between 2005 and 2050 and between 2005 and 2100. *Source of historical data*: IEA (2010).

Studies have shown that it is possible to improve energy intensity radically through a combination of behavioral changes and the rapid introduction of stringent efficiency regulations, technology standards, and environmental externality pricing (in order to mitigate "rebound effects"[1]). The group of GEA-Efficiency pathways depicts such a development with a radical departure from historical trends. The overarching finding of the Global Energy Assessment is that the rapid energy intensity improvements depicted by the GEA-Efficiency group of pathways are feasible with currently available technologies. The necessary magnitude and pace of change, however, will require a fundamental shift in the way energy is used across all major sectors of the economy and will undoubtedly necessitate concerted and dedicated demand-side policies and measures (see Table 3). Because the GEA-Efficiency group of pathways deliberately explores the consequences of demand-side interventions, it leads to substantial declines in per capita energy use in the industrialized world (Figure 4). Yet, given expected economic growth in the developing world, per capita energy demand continues to increase in these regions over the course of the century, although at a considerably slower pace than in the other GEA pathways groups.

If the GEA-Efficiency pathways group depicts the upper bound of potential efficiency improvements and the lower bound of energy demand in the GEA pathways, then the GEA-Supply pathways group depicts the opposite, that is, the lower bound of potential efficiency improvements, thereby giving rise to an upper bound of energy demand across all GEA pathways. The GEA-Supply pathways place much less emphasis on efficiency and other demand-side measures, focusing instead on supply-side transformations. In the GEA-Supply pathways, the long-term improvement rate in global energy intensity over the course of the century is slightly above the historical record. As a result, per capita energy use in the industrialized world stays at roughly 2005 levels, while per capita demand in the developing world catches up to the former, increasing by almost a factor of two in the long term (Figure 4).

The GEA-Mix pathways group is characterized by intermediate efficiency improvements, giving rise to energy intensities, both economy-wide and per capita that lie between the aggressive GEA-Efficiency pathways and the less prescriptive demand-side trends of the GEA-Supply pathways (Figure 4).

Table 3 summarizes the various sectoral measures to improve end-use efficiency that drive the GEA pathways, particularly the GEA-Efficiency group. The GEA-Efficiency

[1] Rebound effects describe an increase in demand for energy services as improvements in efficiency lower their effective cost. These effects can be direct (the savings from greater efficiency are spent on the same energy service), indirect (the savings are spent on a different energy service), or economy-wide (the savings contribute to economic and income growth, which increases demand). Rebound effects can be mitigated by price and other policies.

pathways assume successful, rapid and widespread implementation of efficiency and demand management policies and measures over the next several decades, substantially reducing final energy demands below levels that would be expected in an "efficiency-as-usual" baseline scenario (Figure 5). The GEA-Mix and GEA-Supply groups are a bit less optimistic in this regard.

TABLE 3 Sectoral measures to improve end-use efficiency in the GEA pathways.

Buildings (Residential & Commercial)	Transportation	Industry
■ Potential efficiency gains for thermal demands in buildings are among the highest across all end-use sectors; however, electricity consumption for appliances is expected to increase. ■ Achieving these gains requires the rapid introduction of strict building codes and retrofit standards for almost the complete global building stock over the period to 2050. The rate of retrofit would need to increase to about 3% annually, about three times the historical rate. ■ In the GEA-Efficiency group of pathways, policies to improve thermal insulation as well as retrofits to advanced building types (passive house standards or lower) lead to improvements in energy use per unit of floor area by a factor of 4 in the industrialized world, from about 400–900 MJ/m^2 down to 100–230 MJ/m^2 by 2050. Improvement rates in the developing world are a factor of 2 to 3. ■ Demand for energy from centralized sources and grids is further reduced by the adoption of technologies that enable space heating and cooling with net zero use of centralized energy. These include solar water heating, solar heating, air-source or ground-source heat pumps powered by solar photovoltaics, and biomass-based heating.	■ In the GEA-Efficiency pathways group, about half of the overall improvement in transport energy intensity by 2050 comes about through technical efficiency improvements across all modes of passenger transportation. The compound global effect of these efficiency gains reduces fuel consumption from about 1.7 MJ/km in 2005 to 1.3 MJ/km by 2050. Gains are largest for road vehicles, with some significant differences across world regions (the range is from 1.9 to 0.9 MJ/km). ■ The other half of the overall intensity improvement is achieved by reducing demand for mobility as an energy service (e.g., by substituting travel with teleconferencing) and shifting demand for mobility to public transportation (e.g., trains and buses). Despite these actions, transport demand continues to grow in absolute terms. ■ Increasing affluence leads to a 5-fold growth in car ownership in the developing world, even in the GEA-Efficiency pathways (from 2 to 11 cars per 100 people by 2050). The expected growth in the absence of any policies to support public transportation and limit car ownership would be some 30% higher still. ■ In freight transport, there is a pronounced switch toward higher shares of railway transportation combined with improvement in the overall efficiency by about a factor of 2 by 2050, from 1.3 MJ/t-km (tonne-kilometers) on average in 2005 down to 0.7 MJ/t-km in 2050.	■ Widespread adoption of best available technology for new investments (15% improvement). ■ Retrofit of existing plants to improve energy efficiency, e.g., use of combined heat and power, pumps, fans, compressed air and steam systems, and so on (15% improvement). ■ Optimization of energy and material flows through systems design, quality improvements, lifecycle product design, and enhanced recycling. ■ Further electrification and a switch to 25% renewable energy throughout the manufacturing industry (10% improvement, though balanced by a similar efficiency loss from widespread adoption of CCS). ■ In the GEA-Efficiency pathways, energy efficiency in the industrial sector improves by about 1.5%/year, resulting in overall demand of about 200 EJ in 2050, around 20% below what it would be in the absence of a concerted approach to demand-side transformation. This equates to a 50% reduction in the overall energy intensity of industrial production. ■ Iron and Steel Making: new smelting reduction processes; wider application of gas-based direct reduced iron; electricity and hydrogen as process fuels in the long term. ■ Chemical and Petrochemical Products: new technologies such as membrane processes, new catalytic conversion routes, new olefin production processes (e.g., based on ethanol feedstock) and process intensification. ■ Cement Making: increase the share of alternative cementing materials including Bainite cement, volcanic ash, geopolymers, and limestone additives. ■ Pulp and Paper Making: Process re-design for lignin removal in chemical pulping plants; more efficient use of black liquor residues, perhaps through gasification, and new drying technologies for paper making; structural shifts from paper to electronic media. ■ Aluminum Making: adoption of wetted drained cathodes and inert anodes to eliminate carbon anode technology; potential for a further increase in aluminum recycling rates is rather limited.

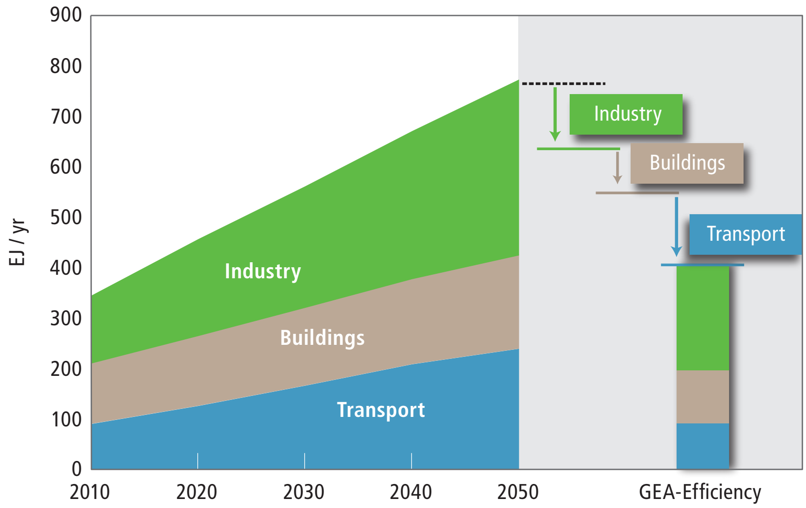


FIGURE 5
Final energy demand growth in an "efficiency-as-usual" scenario and potential reductions in 2050 realized through full implementation of the various sectoral measures to improve end-use efficiency. Note: The baseline scenario already assumes replacement of inefficient, traditional biomass with modern cooking fuels.

Energy Supply Portfolios

While there is undoubtedly a large portfolio of supply-side options (different forms of energy and their attendant conversion technologies) available to meet the growing energy demands of the 21st century, a wide range of factors will ultimately shape and constrain their individual potentials. The clearest determining factors relate to cost, efficiency, resource availability, and other performance attributes. In the GEA pathways, still other factors come into play, given the ambitiousness of the sustainability objectives and the energy transition required to reach the associated targets (see Table 1). For instance, energy access objectives constrain the use of traditional fuels in developing countries; energy security objectives limit the amount of energy trade and foster increasing diversity of energy supply; climate change objectives constrain the use of carbon-intensive energy forms; and health objectives ensure low emissions of harmful air pollution. In addition to these technological and sustainability criteria are other factors that influence are sure to influence the projected success of the various supply-side options. For example, some options require advanced technological knowledge, which is not universally available. Other options face barriers to a rapid scaling up (Wilson, 2009), such as integrating high proportions (e.g., 20% or more) of intermittent energy sources (particularly wind and solar) in electricity grids. Still other options face issues of public acceptance. Nuclear energy in some countries is an obvious example, but a few forms of renewable energy, such as large-scale hydropower, bioenergy, on-shore wind and CCS, offer others. Nuclear also entails other societal risks related to accidents or the proliferation of weapons-grade fissile material. Finally, the requirements of some supply-side options in terms of new physical infrastructure and distribution systems are highly capital intensive but face initially low overall demand, and thus are often unattractive to both private investors and resource-limited public investors.

In light of all these potential issues, the approach taken in the Global Energy Assessment is to elaborate the broadest possible decision space, or range of possibilities, in terms of supply-side portfolios in each of the three GEA pathway groups (GEA-Efficiency, GEA-Mix, and GEA-Supply). First, the full range of supply-side options is considered, subject to cost, performance, and system integration constraints but always respecting the overarching need to comply with the GEA targets. As noted earlier, the level of demand has a significant impact on supply-side flexibility, with the greater efficiency improvements and reductions in energy services demand of the GEA-Efficiency group of pathways leaving more options open on the supply side. Next, this maximal decision space is reduced in stepwise fashion. The impacts of major changes in the transportation system on this unrestricted supply portfolio are explored, and finally the impacts of specific restrictions or omissions of particular supply-side options are considered, in order to reflect the sensitivities or concerns surrounding their widespread deployment. These restricted supply portfolios as well as the transportation analysis provide a broad sensitivity analysis around the unrestricted supply portfolio, illustrating which options are "musts" and which others are choices, indicating how important certain supply-side options are for a sustainable energy transition, and exploring the "option values" of different technology clusters that might, for example, guide future investment decisions.

In total, nine different restricted supply portfolios are explored for each of the six possible combinations of GEA-Efficiency, GEA-Mix, and GEA-Supply pathway groups and two transportation system transformations (Conventional and Advanced). Together with the unrestricted portfolios, this results in 60 unique pathways (3 levels of demand × 2 transportation systems × 10 supply portfolios), of which only 41 are able to feasibly meet the GEA's stringent targets for sustainability. The various restricted portfolio pathways, as well as the rationales for including them in the portfolio analyses, are summarized in Table 4. The results of the analyses are shown in Figure 6. The 19 blank columns, each marked with an X, indicate those pathways that were not feasible given the portfolio restrictions.

A headline conclusion of the portfolio analysis is that the low level of energy demand in the GEA-Efficiency group of pathways makes it possible to reach the sustainability objectives in the absence of both nuclear energy and CCS. For the intermediate and high levels of energy demand under the GEA-Mix and GEA-Supply pathways, respectively, excluding either nuclear or CCS is typically possible, but in the high-demand case this requires transforming the transportation system away from liquid fuels. Another important insight from the portfolio analysis is that the low energy demand in the GEA-Efficiency pathways also enables an energy transition with limited contributions from bioenergy, without BioCCS and without relying on carbon sink management. All of these land use-related supply options could have potentially adverse impacts on the global environment and, thus, remain controversial. Moreover, the speed and urgency of the supply-side transition is quite different across the pathway groups. Namely, with the ambitious effort on the demand side in the GEA-Efficiency pathways, the change from current supply-side structures can be less rapid. In 2030, with the exception of wind and solar (which grow considerably in absolute terms), the primary energy supply mix in the GEA-Efficiency pathway is only modestly different from that of today. In contrast, the GEA-Mix and, in particular, the GEA-Supply pathways require more radical changes in energy supply over the next two decades. This includes a more rapid scaling up of all renewable supply options, and CCS, which by 2030 needs to remove up to 10% of CO_2 emissions from fossil fuel combustion in the GEA-Supply pathways, increasing to about 50% by 2050. The same is true for nuclear energy, which in the GEA-Efficiency pathway (with an unrestricted supply portfolio) continues to contribute about the same amount of energy as today or less through 2050, whereas in the GEA-Mix and GEA-Supply pathways a two- to five-fold increase up to 2050 is observed.

Furthermore, how the transportation sector is configured has profound implications for supply-side flexibility. Under the Advanced Transportation setup, the GEA-Supply group of pathways is still feasible if either BioCCS, carbon sink enhancement,

TABLE 4 Overview of restricted supply portfolios in the GEA pathways.

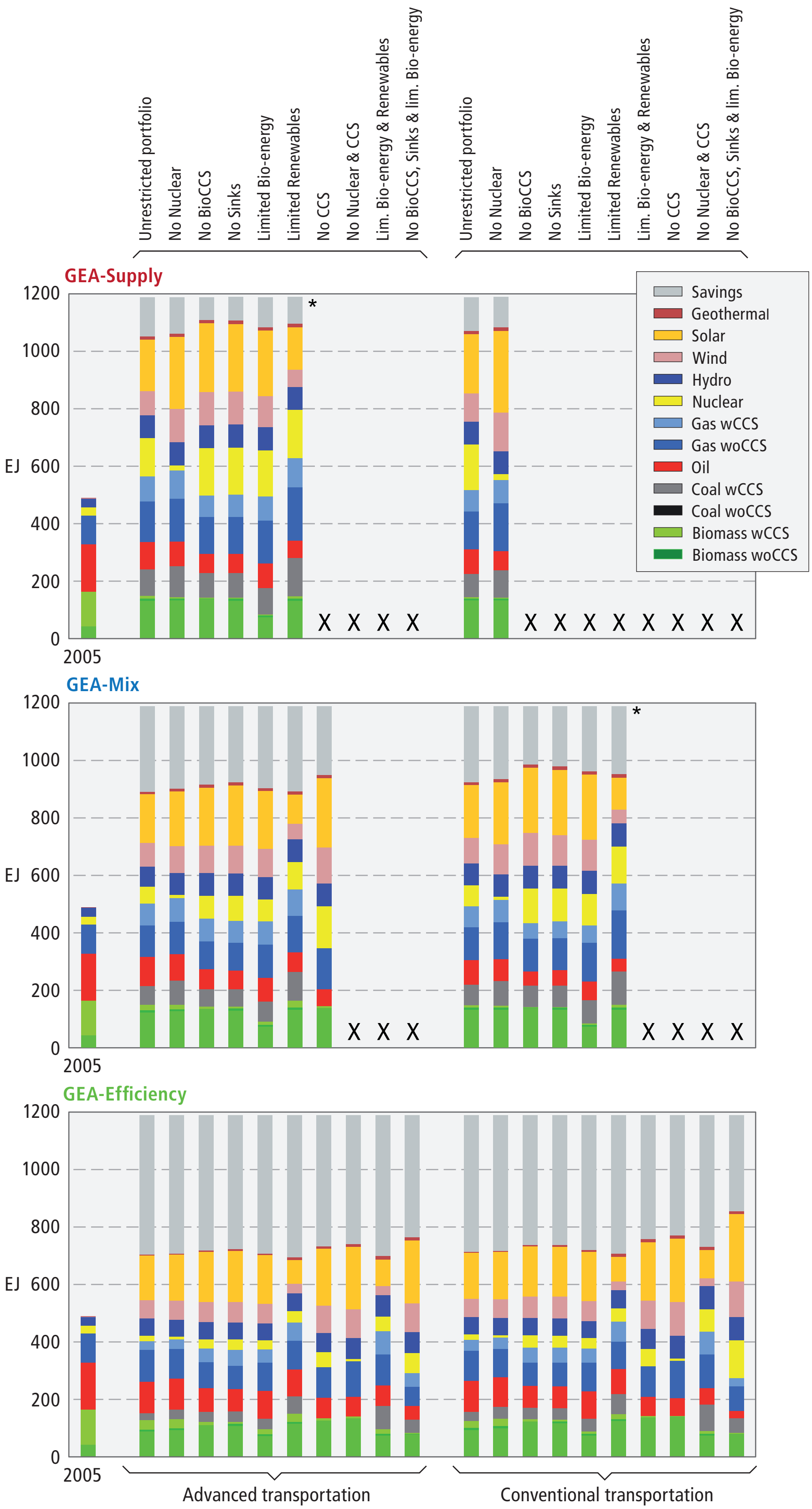
Supply-side option	Main rationales for restriction	Restricted portfolio pathways	Description
Carbon capture and storage (CCS)	■ Storage availability ■ Social acceptability ■ Infrastructure requirements ■ Environmental risks	No CCS[1]	CCS excluded
Bioenergy with CCS (BioCCS)	See entries for CCS and bioenergy	No BioCCS[1]	Bioenergy used only for co-firing in fossil CCS facilities (no dedicated BioCCS facilities)
Carbon sinks (afforestation)	■ Resource availability ■ Land use impacts ■ Political acceptability	No sinks	No additional afforestation beyond baseline assumption of no net global deforestation from 2070 onward
Bioenergy	■ Resource availability ■ Land use impacts ■ Food security risks ■ Environmental risks	Limited bioenergy	Bioenergy potential reduced to 50% of central estimate to reflect potential implementation issues for sustainable bioenergy (<130 EJ/yr throughout the 21st century)
Nuclear energy	■ Environmental risks ■ Social acceptability ■ Proliferation risk	No nuclear[1]	No new nuclear power plants built after 2020, leading to full phase-out after 2060 (assuming 40-year plant lifetime)
Renewable energy	Systems integration	Limited renewables	Intermittent renewables (wind, solar) restricted to supplying no more than 20% of electricity consumption
Combinations[2]		■ Limited bioenergy + Limited renewables ■ No nuclear + No CCS ■ No BioCCS + No sinks + Limited bioenergy	

[1]Option was fully excluded from the portfolio; for other options the restriction was implemented in terms of limited potentials.
[2]See individual options for rationales and descriptions.

FIGURE 6

Composition of global primary energy supply in 2005 and 2050 for the three GEA pathway groups under alternative transportation sector assumptions and supply portfolios. Xs indicate infeasible pathways. Pathways marked with an asterisk (*) are bordering on infeasibility, with carbon prices slightly higher than defined in the note below. Energy savings are calculated by comparison with a hypothetical case with energy intensity improvements compatible with historical trends and no additional climate and energy policies.

*Feasibility is technically defined here as the inability of the supply side to deliver the (fixed) useful energy demand. As uncertainties grow over time, a modest undersupply of service demands of up to 5% beyond 2050 is still interpreted as feasible. As in other studies (e.g., Clarke et al. (2009)), this concept is operationalized by declaring pathways with carbon prices higher than US\$1000/tCO_2 (discounted back to 2012 at a 5% real interest rate) as infeasible, because these pathways see significant penetration of so-called demand backstop penetration. This relaxation may lead to limited comparability of economic indicators (e.g., energy-related investments) across the restricted portfolio pathways after 2050.



nuclear energy, full bioenergy supply, or the large-scale deployment of other renewable energy is excluded from the supply portfolio. In contrast, under the Conventional Transportation setup, only nuclear energy can be excluded to keep the GEA sustainability targets within reach. The situation is somewhat improved in the GEA-Mix group of pathways, where the Conventional Transportation setup still allows for the same choices as the Advanced Transportation setup under high energy demand (i.e., GEA-Supply). CCS turns out to be a crucial technology under these conditions, because in the absence of a major transition to electricity or hydrogen, or both, biofuels are the only alternative available to decarbonize the sector. As in the GEA-Supply groups of pathways, the limited sustainable bioenergy potential is a constraining factor, and CCS is important to remove the carbon from bioenergy feedstocks that does not end up in the liquid biofuel itself.

Commonalities and Choices across the GEA Pathways

Despite major differences in the levels of energy demand and in the nature of transportation system transformation, the GEA pathways share certain supply-side characteristics. All show a decarbonization of the supply mix away from conventional fossil fuels, especially coal. All show an ever-increasing share of energy services demand being met by renewable energy, particularly by the end of the century. And all show a substitution of traditional biomass with modern, cleaner forms of bioenergy. These commonalities are pervasive features of all the transition pathways for the global energy system toward the sustainability objectives. They can be interpreted as “musts,” that is, required elements of the supply-side transformation if the access, environmental, and security objectives are to be fulfilled.

Despite the flexibility and choices available to direct the energy system transformation, a large number of commonalities across the pathways points to robust and nondiscretionary elements of the transition whose implementation would need to begin immediately.

In other areas, the three illustrative pathways have major points of difference. The most obvious, and the most influential, is the level of energy demand, which distinguishes the pathways by design. Emphasis on demand-side transformation varies massively between the GEA-Efficiency pathways and the GEA-Supply pathways at the extremes. Another point of difference, again by design, is the nature of transformation in the transportation sector, either Conventional, with an ongoing reliance on liquid fuels, or Advanced, a more radical departure from historical trends and existing infrastructures and technologies. These points of difference are analogous to broad, systemic choices about how and where to direct attention, investment, and policies in order to transform the energy system. None of the outcomes of these choices precludes a transition pathway that fulfills the GEA sustainability objectives: all are therefore feasible within these normative bounds. However, the interdependencies within the energy system mean that choices made in one part of the system have potentially major enabling or constraining effects elsewhere.

The following sections highlight, more specifically, the commonalities and choices revealed by the GEA pathways analysis. The focus here is on six critical areas on the supply side: electricity generation, liquid and gaseous fuels, fossil resource extraction, low-carbon energy, carbon capture and storage, and bioenergy and land use.

Electricity Generation

- Conventional coal power generation has to decrease very soon, and by 2030 should not supply more electricity than today (Figure 7). This implies that new construction of coal power plants without CCS must stop, and that some existing plants will have to be retired prematurely or, if possible, retrofitted with CCS.
- Natural gas power generation, mostly in combined-cycle configurations but also as gas turbines for load balancing, sees considerable growth until around 2030 and only thereafter faces a decline. Gas power can be considered a short- to medium-term bridge or transitional technology until longer-term options become more available at scale.

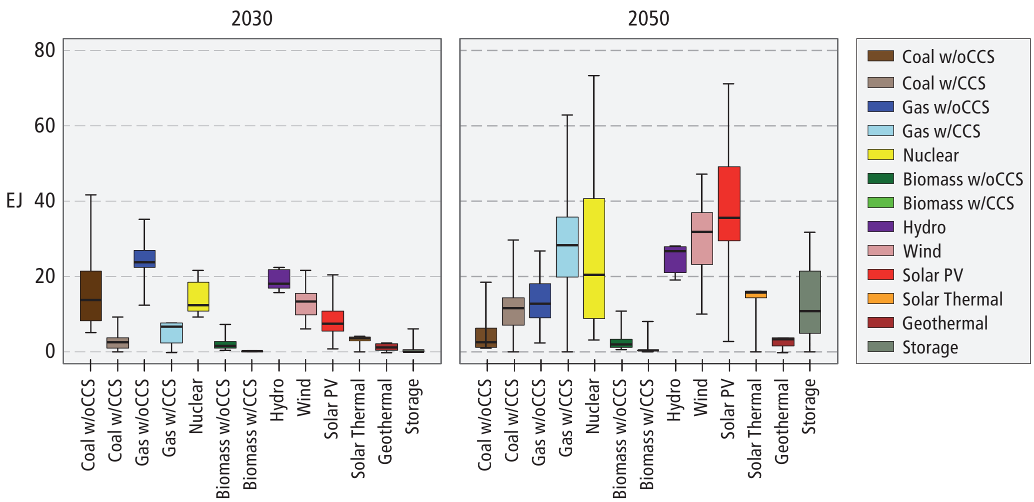


FIGURE 7
Electricity supplied by different generation technologies in 2030 and 2050 in the GEA pathways. The boxes represent interquartile (25th–75th percentile) ranges, and the horizontal lines within boxes represent medians across all feasible GEA pathways. Error bars indicate the full range across all feasible pathways.

- Renewable power technologies show significant increases compared with the role they play in electricity generation today. This is clearly visible in Figure 7. Relatively mature technologies such as hydropower and onshore wind experience strong growth to 2030 and to 2050, with limited variability between pathway groups. Solar photovoltaic and solar thermal (i.e., concentrated solar power, CSP) are more variable and show stronger deployment after 2030, although by 2020 the average deployment shows a multifold increase compared with today's levels. Biomass and geothermal electricity generation show much lower deployment levels on average compared with these other renewable technologies.
- Storage technologies, which could play an important role in the case of very high deployments of intermittent sources (wind, solar photovoltaic, and to a

lesser extent CSP), particularly after 2020, will have to become available on a large scale. This can be supplemented with demand-side-management and/or so-called smart-grids. Like the renewables themselves, storage technologies are diverse, unevenly distributed (e.g., pumped storage hydropower), and in some cases less mature, more costly, and more dependent on new infrastructures (e.g., hydrogen electrolyzers and fuel cells) and business models.

- Fossil CCS provides a bridge or transitional option for the power sector. However, in contrast to conventional gas power generation, this is not common to all pathways, as the most efficient pathways do not necessarily include CCS. The most attractive option to combine with CCS in power generation is natural gas, with its cleaner fuel supply chains, lower upstream GHG emissions, higher conversion efficiencies, and significantly lower capital intensity. However, this is not entirely consistent with current R&D activities, which are focused on coal power generation with CCS. The focus on coal is, in turn, driven by the relative cost and abundance of the resource, as well as concerns over dependence on imported gas. Interest in gas with CCS is particularly weak in coal-rich regions such as China.
- Bioenergy with CCS plays an increasingly important role under more stringent climate stabilization targets; however, the deployment focus can be in either the electricity or the synthetic fuels sector, depending on the overall system configuration.
- Nuclear power represents the major choice, in terms of supply-side flexibility, that emerges from the GEA pathways analysis. Nuclear energy could certainly become one of the central sources of electricity generation by 2050, if effective technological, institutional, governance and legal frameworks are introduced to avoid present risks of nuclear energy, including in particular the risk of proliferation. It is thus important to emphasize that in all pathways nuclear power can also be fully phased out after 2060, with no new plants built after 2020. That said, the global "choice" of excluding nuclear power from the supply mix has implications for energy costs, as do any of the other restricted portfolio options.

Liquid and Gaseous Fuels

- Oil will continue to dominate the production of liquid and gaseous fuels (as energy carriers destined primarily for the transportation sector) in the short to medium term, contributing between 100 and 200 EJ in 2030. (See Figure 8, noting that oil refining is off the scale.)
- The biofuel contribution grows substantially in the medium term (Figure 8). This occurs both in regions that already have supportive policies in place (e.g., Brazil, the United States, and the European Union), but increasingly also in other regions with advantageous conditions for biofeedstock production (e.g., sub-Saharan Africa and Australia/New Zealand). By 2030 the range

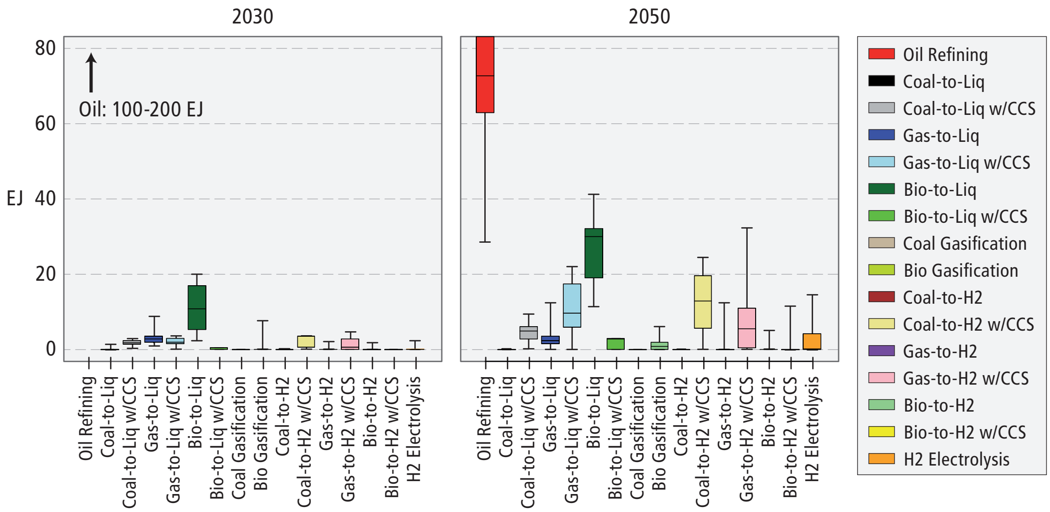


FIGURE 8
Deployment of liquid and gaseous fuel production technologies in 2030 and 2050 in the GEA pathways. Boxes represent interquartile (25th–75th percentile) ranges, and horizontal lines within boxes represent medians of all feasible GEA pathways. Error bars indicate the full range across all feasible pathways.

is somewhere between today's level and around 20 EJ, the latter of which corresponds to almost a 10-fold increase over 20 years. Even assuming greater penetration levels of electricity and hydrogen as transportation energy carriers in the medium and long term, as in the Advanced Transportation setup, biofuels continue to play an important transitional role over the next several decades. And in the very long term (beyond 2050), liquid biofuels may still have an important role in, for example, aviation and heavy freight transport. Once second-generation biofuel technologies become available at a larger scale, sometime between 2020 and 2030, a pronounced diversification of biofuel production is foreseen.

- The potential substitution of oil products with synthetic fuels from natural gas (gas-to-liquid conversion) is effectively a choice rather than a common feature across all pathways. Coal-to-liquid conversion, on the other hand, plays a less important role at the global scale even with CCS, except in regions with abundant coal resources.
- In terms of gaseous fuel production, biomass gasification is limited even in 2050 (depending on the choices made with respect to bioenergy production), although it can be readily integrated into existing natural gas infrastructures. The major choices with respect to gaseous fuels concern hydrogen; but again, these depend on the choices made with respect to Conventional versus Advanced Transportation systems and, within the latter, whether electricity or hydrogen is the preferred route (although hydrogen can also supply some industrial applications). If the build-up of a hydrogen-only infrastructure turns out to be too ambitious, the injection of hydrogen into the gas grid is a favorable (relatively low-cost) option that can help reduce direct CO_2 emissions in the end-use sectors. If it is derived from fossil fuels, however, hydrogen is an attractive option only in combination with CCS. In the longer term its predominant source would be nuclear or renewable energy.

Fossil Resource Extraction

- The GEA pathways, in general, show peak oil and gas behavior over the course of the century; however, this is not because of the assumed physical scarcity of hydrocarbons, but rather due to the sustainability targets built into the GEA scenario, in particular the climate objectives, which inherently puts limitations on the use of fossil fuels.
- Coal extraction declines significantly over the next couple of decades across almost all transition pathways. However, after 2030, when CCS could become available at a larger scale, two distinct developments are possible, leading to a very wide range of possible levels of coal extraction by 2050. If CCS is excluded as a supply-side option, then coal extraction has to almost completely disappear by the middle of the century (only in the GEA-Mix and GEA-Efficiency pathway groups, where exclusion of CCS still allows the GEA sustainability targets to be feasibly met). On the other hand, if CCS can be successfully deployed at scale, a revival of coal extraction, reaching current levels and even going beyond, is an option. The absolute level depends on overall energy demand: in general, coal extraction is highest in the GEA-Supply group of pathways, followed by the GEA-Mix and the GEA-Efficiency groups.
- The extraction of conventional hydrocarbons lies within a smaller range than that of the unconventional categories (see Rogner (1997) for a definition of these categories), largely because the former still play an important role during the transition toward a sustainable energy system over the coming decades. Unconventional oil and gas resources tend to play a significant role only under specific conditions because of their relatively more energy- and emissions-intensive extraction processes.

Low-Carbon Energy

- Across all pathways, 60–90% of total global primary energy supply must come from low-carbon sources[2] by 2050.
- By far the most complete decarbonization has to be achieved in electricity generation, and this has to be done relatively quickly. The global low-carbon threshold is in the range of 40–60% by 2020, starting from today's share of around 35% (mostly from nuclear and hydropower). By 2050, almost full decarbonization of electricity generation (80–100%) is required. This implies the need for a continued expansion of renewable electricity generation and of nuclear power, or a rapid commercial deployment of CCS, or both. Financing for these mostly very capital intensive technologies and technology transfer mechanisms to enable deployment in developing countries remain major challenges.

[2] In the GEA pathways analysis, low-carbon energy includes nuclear energy, renewables, and fossil with CCS at the primary energy level and in electricity generation, and at the final energy level fuels without direct CO_2 emissions (i.e., decarbonized electricity, district heat, and hydrogen) as well as solid biomass and biofuels.

- In the transportation sector, the threshold level of low-carbon energy is 10% by 2020, which represents a significant increase a starting point that is close to zero at present. By 2050, low-carbon energy shares in transport have to reach a range of 35–75%, depending on the demand level.
- Renewable energy sources play an important role in essentially all GEA transition pathways. Even under the Limited Bioenergy and Limited Renewables pathways, renewable energy sources reach some 40% of total global primary energy supply by 2050.
- The contribution of renewables varies considerably by region (Table 5).
One reason for this is the resource supply curves (i.e., technical potential as well as resource quality) for the various renewable energy sources, which differ significantly across regions. Second, the availability of low-carbon supply-side alternatives (nuclear energy and fossil CCS), which ultimately determine the economic potential for renewable energy sources, is also strongly region dependent. Third, the tradability of renewable energies or of secondary energy carriers derived from them is very heterogeneous. Whereas liquid biofuels are easy to trade and can even rely on existing infrastructures, the scope for trading electricity (e.g., from wind, solar photovoltaic and CSP, and hydropower) at the global scale is much more limited, and for heat (e.g., solar thermal, geothermal), trade is not an option at all. This generally leads to higher exploitation rates of bioenergy potentials than of other renewables.

TABLE 5 Ranges of renewable energy deployments across the GEA Pathways, by region, 2050 (in Exajoules unless otherwise stated).

Region	Bioenergy	Hydropower	Wind	Solar[1]	Geothermal	All renewables	All renewables as % of total
Sub-Saharan Africa	8.8–40.5	2.0–5.5	0.0–19.6	0.5–25.5	0.0–0.3	11.4–91.4	31–94
Centrally Planned Asia and China	6.9–24.7	9.7–10.3	3.7–8.8	0.9–40.1	0.0–0.3	21.2–84.2	24–50
Eastern Europe	1.3–2.8	0.8–1.0	0.7–5.0	0.2–6.1	0.0–0.3	2.9–15.3	23–85
Former Soviet Union	2.9–10.1	2.7–15.8	1.4–7.4	0.3–9.7	0.0–1.0	7.4–43.9	25–93
Latin America and the Caribbean	10.5–22.5	10.7–17.6	3.6–12.4	0.5–21.8	0.0–1.8	25.3–76.1	40–100
Middle East and North Africa	1.2–5.1	0.8–1.2	1.3–8.7	0.5–15.8	0.0–0.3	3.8–31.1	17–40
North America	10.0–21.5	7.2–7.9	2.6–36.7	1.2–41.6	0.0–3.4	21–111	38–89
Pacific OECD	3.4–11.3	1.4–1.7	0.6–4.9	0.2–5.4	0.1–0.8	5.7–24	26–89
Pacific Asia	5.0–11.9	1.9–7.2	1.0–2.0	0.4–14.5	0.2–1.3	8.6–36.9	15–63
South Asia	5.2–20.8	3.5–4.3	1.1–6.7	1.0–79.0	0.0–0.2	10.7–111	21–65
Western Europe	3.9–11.0	5.7–7.6	3.0–30.2	0.7–28.9	0.1–2.1	13.4–79.8	34–83
World	*78.3–139*	*49.9–80.1*	*28.5–134*	*7–285*	*0.6–11.9*	*164–651*	*28–74*

NOTES Ranges cover the full spread of the restricted supply portfolios. Values are calculated as primary energy supply using the substitution method.

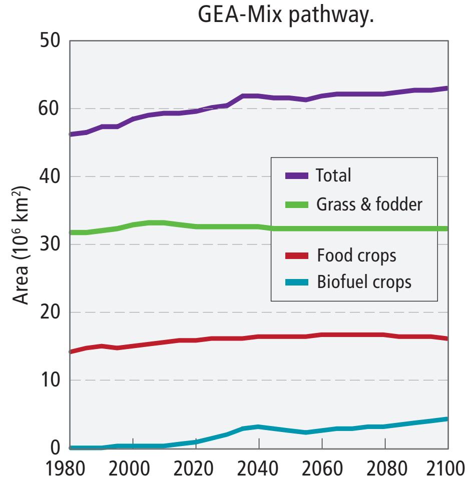
Carbon Capture and Storage

- In those pathways that do not exclude CCS as an option, considerable amounts of CO_2 would need to be stored between 2020 and 2030, quickly rising to much larger levels by 2050, at which point cumulative storage needs to be no less than 55 $GtCO_2$ and probably closer to 250 $GtCO_2$. The bulk of this would come from fossil CCS.
- Bioenergy in combination with CCS takes off only around 2040 but increases its contribution considerably in the latter half of the century.
- Under low demand pathways, as in the GEA-Efficiency group, CCS is a choice, not a "must."

Bioenergy and Land

- The main commonality of the GEA pathways, with respect to bioenergy, is its increasing role in the global energy system, rising to almost 150 EJ by 2050 and 225 EJ by 2100 (thus, well within the range of scenarios in the literature (Clarke et al., 2009)).
- In the longer term, biomass can also play an essential role in achieving low GHG concentration targets by making negative emissions a possibility when bioenergy is combined with CCS.
- The impacts of this increased bioenergy production depend on several factors. First and foremost, first-generation bioenergy production routes may lead to extensive land use (either directly or indirectly) and are therefore likely to have negative impacts on biodiversity and food security. These impacts are expected to be considerably less for second-generation biofuels and electricity generation feedstocks (Dornburg and Faaij, 2005). The potential impacts of bioenergy on other policy and sustainability objectives imply that additional policies and strict monitoring of bioenergy and its land use implications will be necessary.
- A considerable part of the biomass consumed in the GEA pathways is supplied from residues, thus conforming to sustainability criteria.
- The GEA pathways imply an increase in land use for bioenergy production, though land availability does not appear to be a constraining factor in the GEA pathways. The exact amount of land used depends strongly on assumed yield increases and the types of bioenergy that are utilized. Still, bioenergy remains a relatively small category compared with other forms of land use (Figure 9). At the same time, the increase in land for bioenergy production in the GEA pathways is about equal to the total rise in agricultural land use, meaning that there is likely to be some further biodiversity loss and land scarcity. In the context of the GEA sustainability objectives, it will thus be particularly important that policies be put in place that can avoid a strongly adverse impact on crop prices (or the risk of such impacts in a situation of sharply rising energy prices).

FIGURE 9
Land use in the illustrative GEA-Mix pathway.



Financing the Energy System Transition

A core concern of the GEA transition pathways is to explore strategies to overcome the current, extremely inequitable distribution of incomes and the associated lack of access to clean and efficient energy services worldwide, while at the same time improving the environmental performance of energy end use and supply. When viewed through this lens, the world in 2050 will indeed look decidedly different from today. Current distinctions between low- and higher-income countries will be largely obsolete, as even the regions with the lowest per capita incomes today (sub-Saharan Africa and South Asia) will have advanced to lower-middle-income levels (annual per capita incomes in 2005 dollars of US$5000–10,000), while other developing regions (Centrally Planned Asia and China, Latin America and the Caribbean) will have attained middle-class incomes and lifestyles (US$15,000–20,000) characteristic of many OECD countries in the 1990s. The GEA transition pathways thus describe a pattern of conditional convergence in incomes.

Given this increasing affluence worldwide, the biggest challenge revealed by the GEA pathways faces not energy consumers, who can confidently expect expanded and improved levels of energy services in the future, but rather entrepreneurs and policymakers. They need to embrace decidedly different views from those widely held today, focusing on energy services provision rather than mistakenly viewing technology- and policy-dependent levels of primary energy use as immutable, given consumer demand. Policymakers also need to embark on different policies, ones that combine both carrots and sticks, to include stricter building, appliance, and vehicle efficiency standards and changes in relative prices through taxes, subsidies, feed-in tariffs, and other measures. This would open up new business opportunities (e.g., for energy services companies), thereby creating new markets (e.g., for efficiency technologies) and leveraging the power of market forces to meet social concerns and public policy choices.

At the present time, total global energy supply-side investments are estimated at about US$960 billion.[3] This corresponds to approximately 2% of global GDP, a relatively small share, but one that varies greatly among countries at different stages of economic development. At 3.5% of GDP on average, energy investments are a much larger part of the economy in the developing world than in the industrialized world, where they average just 1.3% of GDP.

[3] This detailed, bottom-up cost calculation for the entire energy sector, which was conducted within the Global Energy Assessment, includes resource extraction (e.g., coal mining, oil wells) through development and production to delivery and transmission; it also accounts for historical capacity extensions (and replacement schedules).

The magnitude of investments is considerably more uncertain on the demand-side, because of a lack of reliable statistics and difficulties in clearly defining what constitutes a purely energy-related investment. Present estimates are that around US$300 billion (with a range of about US$100 billion to US$700 billion) is invested annually in energy components at the end-use service level, such as engines in cars, boilers in building heating systems, and compressors, fans, and heating elements in large household appliances. Accounting in addition for the full cost of demand-side energy technologies (not only the energy components, i.e., the entire cost of a car) would increase investment – but also uncertainty – by about an order of magnitude, to about US$1700 billion (with a range of US$1000 billion to US$3500 billion).

- Transforming the energy system requires a massive scale-up of energy investments.
- A focus on energy efficiency allows achieving the multiple GEA objectives at lower costs.

Figure 10 summarizes present investment for individual supply-side sectors, as well as for energy components on the demand-side. Investments are most capital intensive in the power sector, which includes generation, transmission, and distribution. This sector thus accounts for about 42% of total investment, with generation (US$270 billion) accounting for about the same share as transmission or distribution (US$261 billion). The remaining supply-side investment is dominated by the fossil fuels upstream sector: US$130 billion for natural gas, US$210 billion for oil, and US$33 billion for coal. As mentioned above, the uncertainties are particularly large for demand-side investments, which account for at least 24% of total investment. The composition of energy sector investments

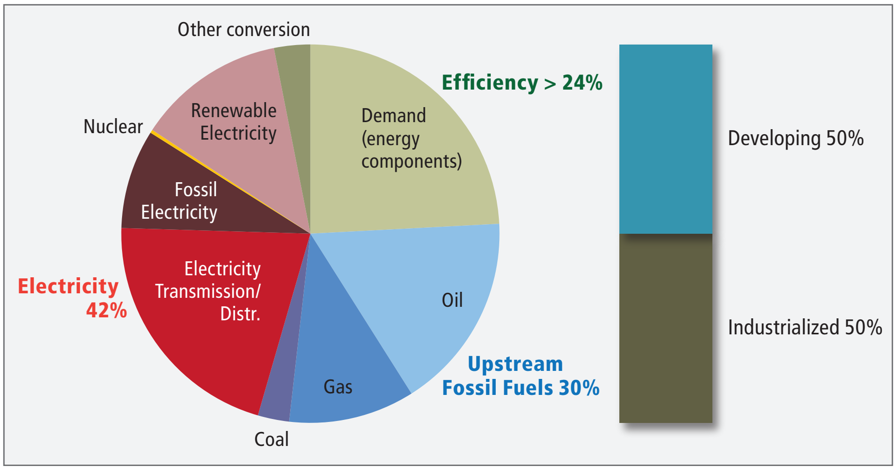


FIGURE 10
Composition of energy investment in 2010. Total supply-side investment, excluding investment in fossil fuel exploration, is about US$960 billion. In addition, about >US$300 billion investments are made into energy components at the demand level.

has been especially dynamic in the past few years. Renewable energy investment, in particular, grew at an unprecedented rate of more than 50% annually between 2004 and 2008, and is presently about US$190 billion (of which US$160 billion was in power generation). By comparison, investment in fossil power generation in 2010 was about US$110 billion.

The GEA transition pathways make clear that simultaneously achieving the multiple objectives for energy sustainability – along the dimensions of climate change, energy access, energy security, and air pollution and health – will require a scaling up of global energy investments by almost a factor of 2 compared with today, corresponding to annual investments of between US$1.7 trillion and US$2.2 trillion, or about 1.8–2.3% of global GDP. At these levels the effect of such investment patterns on the macroeconomy would be relatively small. Compared to a counterfactual (baseline) scenario without policy interventions to achieve the GEA sustainability targets, the projected loss to consumption by 2050 ranges from 0.6% for the GEA-Efficiency pathways, to 1.4% for the GEA-Mix pathways, up to about 2.0% for the GEA-Supply pathways. This should be compared with 200% growth in overall consumption over the same period.

In addition to the need to scale up investment, all the GEA pathways depict significant changes in the structure of the investment portfolio. On the supply-side, for instance, the transformation of the system is achieved through pronounced shifts of investment away from the upstream fossil fuel sector to downstream electricity generation and transmission. Consequently, the share of upstream fossil fuel–related supply-side investment in total investment decreases from 30% at present to about 12–23% by 2050 (Figure 10). At the same time, electricity investment increases its share on average from about 42% to up to 68% by 2050.

Among all supply-side options, the largest increase in investment needs is for renewable power generation, ranging from US$160 billion/year in 2050 in pathways with restricted renewables penetration to US$800 billion/year in pathways without CCS and nuclear power (compared with US$160 billion/year in 2010). Another priority for future investment is in building electricity transmission and distribution systems with sufficient operation and capacity reserves to increase reliability, as well as in power storage to allow the integration of intermittent renewables. Global average electricity grid investment (including storage) by 2050 thus increases to between US$310 billion and US$500 billion/year across the GEA pathways, compared with US$260 billion in 2010.

Investment in CCS ranges from zero to about US$65 billion/year in 2050, and investment in nuclear is between US$5 billion and US$210 billion/year.

The higher-bound estimates correspond to pathways in each GEA pathway group that assume limited potential for other technologies, while the lower-bound estimates stem from pathways where nuclear power and CCS are excluded from the technology portfolio.

Energy investments vary quite dramatically by region across the GEA pathways. Notably, with their rapidly growing economies and populations, the investment needs in the developing world will be much larger than in currently industrialized countries over the course of this century. Where exactly these capital flows originate is not yet certain, however. The GEA pathways – owing to the modeling approaches that were used to develop them – address the question of when and how to spatially allocate scarce investments to meet the sustainability objectives most cost-effectively, but they do not explicitly quantify who pays for those reductions. That will depend, to a large extent, on international agreements.

Policies to Mobilize Financial Resources

Although the GEA pathways reveal considerable uncertainty about future needs for investment in specific technology options, they clearly illustrate that present investment in energy is neither sufficient nor compatible in structure with a sustainable investment portfolio. Mobilizing the required financial resources for the transformation will thus be a major challenge, especially in the near term. An important characteristic of the energy sector is its long-lived capital stock, with lifetimes for infrastructure and energy conversion facilities of 30 to 60 years and sometimes longer. This longevity translates into high inertia in energy supply systems, impeding rapid transformation. Hence, the energy investment decisions of the next several years are of central importance, since they will have long-lasting implications and will critically shape the direction of the energy transition path for many years to come.

Increasing investment in the energy system as depicted by the GEA pathways requires the careful consideration of a wide portfolio of policies in order to create the necessary financial incentives. This portfolio needs to include regulations and technology standards in sectors with relatively low price elasticity, in combination with externality pricing, to avoid rebound effects, as well as targeted subsidies to promote specific "no-regrets" options while addressing affordability. In addition, attention needs to be given to building an enabling technical, institutional, legal, and financial environment to complement traditional deployment policies (particularly in the developing world).

Table 6 identifies effective combinations of policies for specific technology options and puts these in the context of the required future investment needs.

TABLE 6 Energy investments needed to achieve GEA sustainability objectives and illustrative policy mechanisms for mobilizing financial resources.

	Investment (billions of US$/year)		Policy mechanisms			
	2010	2010–2050	Regulation, standards	Externality pricing	Carefully designed subsidies	Capacity building
Efficiency	n.a.[a]	290–800[b]	*Essential* (elimination of less efficient technologies every few years)	*Essential* (cannot achieve dramatic efficiency gains without prices that reflect full costs)	*Complement* (ineffective without price regulation, multiple instruments possible)[c]	*Essential* (expertise needed for new technologies)
Nuclear	5–40[d]	15–210	*Essential* (waste disposal regulation and, of fuel cycle, to prevent proliferation)	*Uncertain* (GHG pricing helps nuclear but prices reflecting nuclear risks would hurt)	*Uncertain* (has been important in the past, but with GHG pricing perhaps not needed)	*Desired* (need to correct the loss of expertise of recent decades)[e]
Renewables	190	260–1010	*Complement* (renewable portfolio standards can complement GHG pricing)	*Essential* (GHG pricing is key to rapid development of renewables)	*Complement* (feed-in tariff and tax credits for R&D or production can complement GHG pricing)	*Essential* (expertise needed for new technologies)
CCS	<1	0–64	*Essential* (CCS requirement for all new coal plants and phase-in with existing)	*Essential* (GHG pricing is essential, but even this is unlikely to suffice in near term)	*Complement* (would help with first plants while GHG price is still low)	*Desired* (expertise needed for new technologies)[e]
Infrastructure[f]	260	310–500	*Essential* (security regulation critical for some aspects of reliability)	*Uncertain* (neutral effect)	*Essential* (customers must pay for reliability levels they value)	*Essential* (expertise needed for new technologies)
Access[g]	n.a.	36–41	*Essential* (ensure standardization but must not hinder development)	*Uncertain* (could reduce access by increasing costs of fossil fuel products)	*Essential* (grants for grid, microfinancing for appliances, subsidies for cooking fuels)	*Essential* (create enabling environment: technical, legal, institutional, financial)

[a] Global investments into efficiency improvements for the year 2010 are not available. Note, however, that the best-guess estimate from Chapter 24 of the Global Energy Assessment for investments into energy components of demand-side devices is by comparison about US$300 billion per year. This includes, for example, investments into the engines in cars, boilers in building heating systems, and compressors, fans, and heating elements in large household appliances. Uncertainty range is between US$100 billion and US$700 billion annually for investments in components. Accounting for the full investment costs of end-use devices would increase demand-side investments by about an order of magnitude.

[b] Estimate includes efficiency investments at the margin only and is thus an underestimate compared with demand-side investments into energy components given for 2010 (see note 1).

[c] Efficiency improvements typically require a basket of financing tools in addition to subsidies, including, for example, low- or no-interest loans or, in general, access to capital and financing, guarantee funds, third-party financing, pay-as-you-save schemes, or feebates as well as information and educational instruments such as labeling, disclosure and certification mandates and programs, training and education, and information campaigns.

[d] Lower-bound estimate includes only traditional deployment investments in about 2 GW capacity additions in 2010. Upper-bound estimate includes, in addition, investments for plants under construction, fuel reprocessing, and estimated costs for capacity lifetime extensions.

[e] Note the large range of required investments for CCS and nuclear in 2010–2050. Depending on the social and political acceptability of these options, capacity building may become essential for achieving the high estimate of future investments.

[f] Overall electricity grid investments, including investments for operations and capacity reserves, back-up capacity, and power storage.

[g] Annual costs for achieving almost universal access by 2030 (including electricity grid connections and fuel subsidies for clean cooking fuels).

In addition, the costs and policies for different options are compared with those for promoting energy access (see the next section for further details). Different types of technologies and objectives will require different combinations of policy mechanisms to attract the necessary investment. Table 6 thus distinguishes among various mechanisms: "essential" policy mechanisms are those that must be included for a specific option to achieve the rapid energy system transformation; "desired" policy mechanisms are those that would help but are not a necessary condition; "uncertain" policy mechanisms are those where the outcome will depend on the policy emphasis and thus might favor or disfavor a specific option; and "complement" policies are those that are inadequate on their own but could complement other essential policies.

As the table illustrates, future investment needs are comparatively modest for some objectives, such as access; though to achieve all objectives simultaneously, a variety of different policy mechanisms, including subsidies, regulation, and capacity building need to be in place. Regulation and standards are also essential for almost all the other options; externality pricing (e.g., a carbon tax to promote the diffusion of renewables, CCS, or efficiency) might also be necessary for capital-intensive technologies to achieve rapid deployment. Capital requirements for energy infrastructure are among the highest of the options listed in Table 6. Thus, high priority needs to be given to future policies (including regulations) to address security and reliability aspects of the energy infrastructure. In addition, subsidies will need to ensure that customers can afford the reliability levels they value.

How the Pathways Expand Energy Access for the Poor

The energy inequalities of the modern world run deep: the poorer three-quarters of the world's population uses only 10 per cent of its energy; about 1.5 billion people still lack proper access to electricity, and around 3 billion are without access to modern fuels for cooking. Most rural and low-income urban households in developing nations still depend predominantly on biomass (including charcoal) to meet their cooking energy needs. Electricity, even when available, is rarely used for cooking. Therefore, access to modern fuels is as important as access to electricity, if not more important, for meeting the energy needs of most developing country households.

All GEA transition pathways are consistent with meeting a target of almost universal energy access (to both clean cooking fuels and electricity for household energy needs) by 2030. Doing so requires that between US$36 billion and US$41 billion be spent annually over the next two decades. About half of the amount would be needed to improve access to electricity and the rest to improve access to clean cooking fuels. The largest share of this spending (more than a third of the total cost to achieve clean cooking fuel access and two-thirds of the electrification bill) will need to occur in sub-Saharan Africa. Costs of this magnitude are exceedingly small (less than 5% of global energy sector investment today); however, the benefits would be enormous. Energy access policies and measures will result in averting between 0.6 million and 1.8 million premature deaths, on average, every year until 2030, or a savings of over 24 million DALYs annually. Additional benefits include substantial time savings for women and children and the potential for improved livelihood opportunities.

- Achieving universal access to clean cooking fuels and electricity requires that between US$36 billion and US$41 billion be spent annually over the next two decades, the largest share in sub-Saharan Africa.
- Energy access policies and measures will help to avoid between 0.6 million and 1.8 million premature deaths, on average, every year until 2030.
- Microcredits and grants for modern cookstoves, fuel subsidies, high-voltage electricity grid extensions, and the proliferation of decentralized microgrids represent potentially successful mechanisms for achieving the energy access goals.
- The GHG emissions impacts of providing universal energy access are negligible.

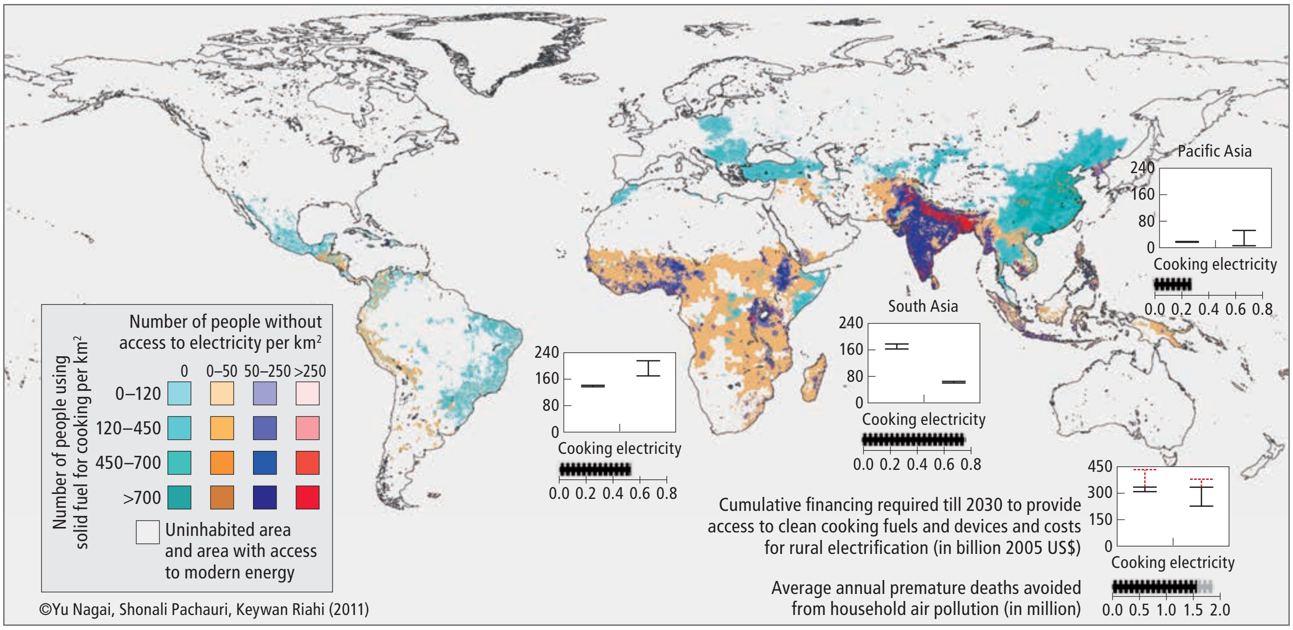


FIGURE 11
Density of population lacking access to modern energy carriers in 2005 and costs and health benefits of achieving a universal cleaner cooking and electrification goal by 2030. Colored areas show people per km^2 without access to electricity and those that use solid fuels for cooking, e.g., dark blue and red areas are where people do not have access to electricity and cook predominately by solid fuels. Cumulative investment requirements (in billion 2005 US$) between 2010 and 2030 are shown for three developing regions and for the globe as a whole. Also shown is the estimated population that would die prematurely if household air pollution remains unchanged in 2030.

The detailed access modeling of the Global Energy Assessment is conducted using two separate frameworks: MESSAGE–ACCESS (Ekholm et al., 2010) and IMAGE (Bouwman et al., 2006). Three regions receive particular attention – sub-Saharan Africa (including Sudan), South Asia, and Pacific Asia – as these are the areas where lack of access is currently the most acute (Figure 11). These regions account for over 85% of the total global population without access to electricity and over 70% of the global population still dependent on solid fuels.

Various scenarios simulating different combinations of policy packages are modeled to determine their impact on access to cooking fuels in these regions, as well as the costs of such policies.[4] The main policies considered to encourage a more rapid transition away from solid fuels for cooking include fuel subsidies – to reduce the cost of cleaner fuels – and grants or microlending – to make access to credit easier and lower households' cost of borrowing. Both of these measures would make it cheaper and easier for households to purchase both the fuel and the end-use equipment (cook stoves). Purchase of the stoves needed to use cleaner fuels often involves a capital outlay beyond the reach of poor and rural households, which often have irregular cash inflows.

[4] Although the specific choice of fuels and cooking technologies will certainly need to be context-specific, the GEA access scenarios use liquefied petroleum gases (LPG) as a proxy. This should not in any way be interpreted as an endorsement of LPG as the best of the available choices. Clearly, other alternative cooking fuels, such as biogas, natural gas, and other emerging sources such as ethanol gel and dimethyl ether, in combination with different stove technologies, might be better suited to certain regions or nations. In some cases, there might even be a transition to electricity for cooking.

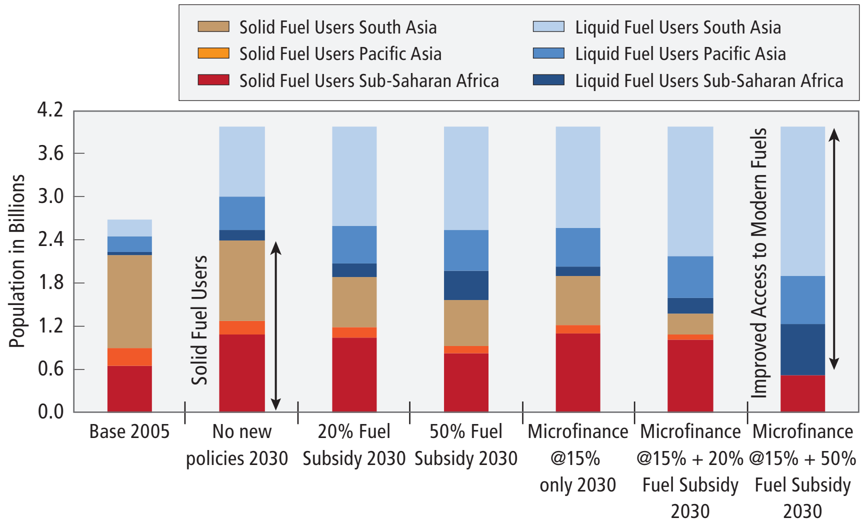


FIGURE 12
Impact of alternative policy scenarios on access to clean cooking fuels in three developing regions. Subsidies are relative to consumer price levels and are additional to existing subsidies.

The impact of the alternative policy packages considered on the numbers of people dependent on solid fuels varies across the different regions from slight to dramatic (Figures 11 and 12). A subsidy policy that reduces the price of clean fuels by 20% below existing prices in each region would reduce the number dependent on solid fuels in all three regions from 2.4 billion (in the case with no new policies) to 1.9 billion. A policy that separately provides cheaper microfinance options for upfront costs and the purchase of end-use equipment would also reduce the number to 1.9 billion (assuming the interest charged on loans is 15%/year). Combining a fuel subsidy with microfinance, on the other hand, is found to be more effective in all regions in accelerating a shift away from solid fuels than either a subsidy-only policy or providing microfinance alone, as Figure 12 also shows. However, even the policy scenario that combines a subsidy of 50% on the existing price with microfinance still leaves about 500 million people reliant on solid fuels in 2030, virtually all of them in sub-Saharan Africa.

The costs of policies aimed at encouraging a more rapid transition to the use of clean cooking fuels depend on the combination of the policy instruments deployed and the extent of the subsidy, as shown in Table 7. Clearly, the choice of policies, the stringency of the targets, and the exact combination of clean fuels and end-use stove technologies promoted are likely to be specific to each country or region. However, the GEA access analysis presented here is indicative of the range of costs that would be expected. What is clear from this analysis is that although fuel subsidies are necessary to increase access for the poorest households and regions, subsidies alone are likely to be less effective in accelerating a transition to the use of clean fuels for cooking than a policy that combines subsidies with improved access to credit through microfinance institutions. Such a policy would make it easier for households to cover the capital costs associated with a switch to cleaner fuels.

Fuel subsidies are often considered controversial in many nations, and a number of developing countries already have generous subsidies on kerosene and LPG. Although such subsidies may be justified on social grounds, they have often resulted in market distortions, been appropriated largely by richer consumers, and led to poor economic returns for energy suppliers and distributors. However, "smart" and targeted subsidy schemes and lifeline tariffs for poor customers can be designed and have proved successful, as in the case of the Bolsa Familia program in Brazil, which couples assistance to low-income families for the purchase of LPG fuel with mandatory child school attendance. Removing subsidies in a phased manner once incomes reach a level where households have the ability to pay can be challenging for governments but can be achieved if coupled with increased social spending in other areas. For the design and implementation of more targeted subsidy schemes and removal of nonmarket barriers, additional enabling conditions will need to be created in these nations. This will require additional capacity building to strengthen the administration of governance systems and local institutions.

Improving access to electricity offers some different challenges than for cooking fuels. What is essentially required is an acceleration of the current pace of electrification in the least developed countries and regions of the world. The problem is, decisions about where to expand electrification are typically

TABLE 7 Cumulative financing required to provide access to clean cooking fuels and devices in developing Africa and Asia, 2010–2030 (in billions of US$).

Policy intervention	Region	Fuel subsidy	New LPG stoves	Improved biomass cook stoves	Total, all three regions
20% fuel subsidy	Sub–Saharan Africa	7.54	0.43	8.98	59.6–67.2
	Pacific Asia	3.47	0.75	2.93	
	South Asia	27.56	6.41	9.11	
50% fuel subsidy	Sub-Saharan Africa	91.71	3.60	6.93	202.2–214.3
	Pacific Asia	10.42	0.95	3.01	
	South Asia	81.49	7.55	8.60	
Microfinance only[1]	Sub-Saharan Africa	0.00	2.19	9.66	21.6–31.2
	Pacific Asia	0.00	0.87	3.05	
	South Asia	0.00	6.54	8.92	
Microfinance + 20% fuel subsidy	Sub-Saharan Africa	9.04	0.89	8.72	85.0–100.0
	Pacific Asia	5.35	1.28	2.43	
	South Asia	50.87	12.88	8.56	
Microfinance + 50% fuel subsidy	Sub-Saharan Africa	130.67	6.52	5.20	315.2–339.4
	Pacific Asia	16.72	1.71	2.60	
	South Asia	152.65	15.97	7.36	

[1] It is assumed that no public costs are associated with microlending and that microfinance institutions are able to recover their full costs from the interest charged. However, these can be considered costs if purchase of the stoves is financed from public grants

grounded in standards or criteria for electrification, and in general such criteria support electrification in places where it is cheapest. Thus, utilities often select projects that require the least infrastructure investment relative to demand. Villages or communities that are closest to existing grids, that have the highest population density, or where economic activity is greatest are generally connected to the grid first. Expanding the grid to the poorest households or to most remote rural regions is typically not the logical choice from an economic perspective for electric utilities or developing country governments.

Figure 13 shows, for each region, the additional connection capacity and total cumulative investment needed until 2030 to achieve rural electrification in each developing region and compares results across the two modeling frameworks used. The largest investment needs, not surprisingly, are in sub-Saharan Africa, where cumulative investment to achieve universal access amounts to an additional US$230 billion cumulatively between 2010 and 2030. In Pacific Asia and South Asia, the majority of investment is already expected to take place in the no new policies case (due to higher population densities and rising incomes), so that the additional investment needed is lower. In total, additional investment for universal access in the three regions is estimated at about US$300 billion cumulatively.

The energy demand and climate impacts of alternative policies for improving access to electricity and clean fuels for cooking are relatively modest. This is explained by either rapid adoption of improved biomass stoves (which double the efficiency of combustion)

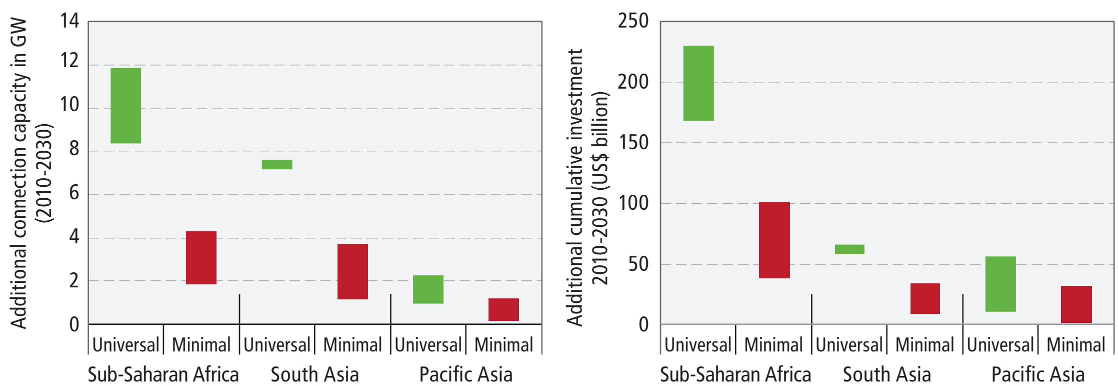


FIGURE 13
Additional connection capacity and cumulative investment required to achieve almost universal rural electrification in three developing regions. In general, the range in estimates depicted in the figure reflects the difference between the results from the two alternative models used. Two different levels of demand are assumed for household consumption within the models, corresponding to different electricity service levels: High demand (Universal access, 420 kW-h/household/year) and Low demand (Minimal access, 65 kW-h/household/year).

or a shift away from biomass to more efficient LPG for cooking and from kerosene to electricity for lighting. In the most optimistic access scenario, for example, electricity demand in the three developing regions is projected to rise from 1.7 EJ in 2005 to 5.7 EJ by 2030 (displacing about 6.6 EJ of kerosene); total LPG demand increases from 1.1 EJ to 9.4 EJ; and biomass demand declines from 13.4 EJ to 1.7 EJ. Note that such an increase in LPG would represent less than half of energy consumption in 2005 in the Western European transportation sector alone. For these reasons, the implications of universal access policies on GHG emissions are negligible, even declining marginally.

BOX 3 The IIASA Energy Access Tool (Energy–ENACT)

An interactive Web-based scenario analysis tool gauging the effectiveness and impacts of various energy access policies and measures in the major developing regions of the world

URL: **www.iiasa.ac.at/web-apps/ene/ENACT**

The ENACT policy tool is based on the Global Energy Assessment energy access scenarios and methodology and allows policy makers and other users to select alternative rural electrification targets and other access policies (such as fuel subsidies and microfinance) to encourage a more rapid transition to clean, modern forms of energy in the households of the developing world. The interactive PC-based software presents in real-time quantitative estimates of the impacts of the chosen policies and targets in each region and how various combinations of measures compare to each other in terms of health impacts, energy demand, GHG emissions, and funding requirements.

The policy tool focuses its analysis on three major world regions – sub-Saharan Africa, South and Pacific Asia, which face the most acute lack of access today. It allows for assessing policies and measures to enhance access to electricity and modern fuels and stoves for cooking in the residential sector.

How the Pathways Preserve the Environment and Improve Human Health

Climate Change

The Global Energy Assessment adopts, as one of its main sustainability objectives, a target of limiting global average warming to 2°C above preindustrial levels. Such a limit reflects the current political focus, as enshrined in global agreements like the Copenhagen Accord, and is consistent with Article 2 of the United Nations Framework Convention on Climate Change to "avoid dangerous anthropogenic interference with the climate system." The 2°C target is one of the fundamental drivers of the demand- and supply-side transformations portrayed in the GEA pathways. This section focuses on the consequences of the transformation for the required reductions of GHG emissions, the pace at which the energy system will need to decarbonize, and associated costs.

- To ensure a high likelihood of limiting global warming to 2°C, thus avoiding dangerous climate change, global CO_2 emissions need to peak by about 2020 and then be reduced 30–70% by 2050 relative to 2000.
- Emissions must decline to almost zero or even negative levels in the long term.
- This requires a rapid introduction of climate change mitigation policies and measures over the next decade to stop emissions growth and a strengthening of those measures in the medium term.
- Measures include widespread diffusion of zero- and low-carbon energy supply technologies, with substantial reductions in energy intensity.
- Financial transfers from industrialized countries will be needed to support decarbonization efforts in the developing world.
- Present 2020 emissions reduction pledges under the Copenhagen Accord are inconsistent with the vast majority of the GEA pathways (i.e., the 2°C target).

The GEA pathways aim at achieving the ambitious 2°C target with maximum likelihood, while at the same time providing sufficient flexibility in the system to allow for multiple pathways to reach the target. Flexibility of solutions is central for identifying decarbonization strategies that are robust against multiple uncertainties due, for example, to potential technological failure and the associated risks. An extensive sensitivity analysis was therefore conducted to assess the maximum likelihoods under a range of assumptions for the stringency of emissions reductions. Exact numerical values for the likelihood of meeting the 2°C target differ slightly across the individual GEA-Efficiency, GEA-Mix, and GEA-Supply pathways; however, in principle all pathways stay below the 2°C target with a probability between 50% and 67%.[5]

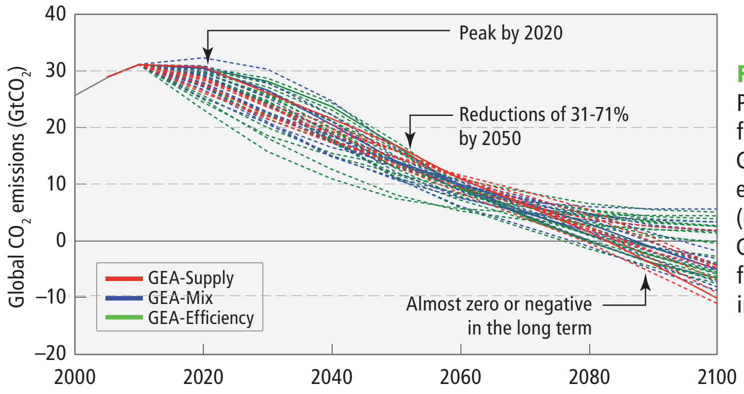


FIGURE 14
Projected global CO_2 emissions from energy and industry in the GEA pathways. Solid lines denote emissions under the three illustrative (unrestricted technology portfolio) GEA pathways, and dashed lines those for individual restricted portfolio pathways in the full set.

Figure 14 compares the total global CO_2 emissions[6] trajectories of all the GEA pathways. As the figure illustrates, emissions may continue to increase for a very short period but eventually have to peak (by about 2020) and decline rapidly thereafter (reductions of about 30–70% by 2050 compared with 2000), reaching almost zero to negative emissions in the long term. The low-emissions pathways of the GEA are compatible with long-term atmospheric CO_2 concentrations below 400 parts per million (ppm). In fact, by the end of the century, most of the GEA pathways bring CO_2 concentrations back down to today's concentration of about 390 ppm. Such low concentrations are the result of achieving globally negative emissions due to enhancements of the terrestrial sink potential (e.g., afforestation and reforestation) in combination with bioenergy with carbon capture and storage (BioCCS) in the late 21st century. Taking into account the direct and indirect effects of non-CO_2 GHG emissions and other radiatively active substances results in long-term concentration levels under the GEA scenarios of 440–450 ppm CO_2-equivalent.

The stringency of the emissions reductions becomes apparent when reviewing the cumulative emissions budgets of the GEA pathways. Given the cumulative nature of climate change, aggregate emissions over the full century represent one of the

[5] The relationship among future GHG emissions, resulting changes in GHG concentrations in the atmosphere, and the ultimate effect in terms of temperature change is subject to large uncertainty. Major reasons for this uncertainty include the limited present understanding of important carbon cycle feedbacks and, in particular, the uncertainty surrounding the so-called climate sensitivity, defined as the increase in global mean temperature resulting from a doubling of the GHG concentration in the atmosphere. Because of these uncertainties, the climate impacts of the sustainable transition pathways are calculated within a probabilistic framework.

[6] This section focuses on CO_2 emissions, as these make up by far the largest share of greenhouse gas emissions from energy and industry. For non-CO_2 emissions of the GEA pathways see the online GEA database: www.iiasa.ac.at/web-apps/ene/geadb.

central boundary conditions for staying below the 2°C target. In the GEA pathways the allowable emissions budget is on average around 1180 $GtCO_2$ between 2010 and 2100 (full range: 940–1460 $GtCO_2$). At today's rate of emissions, this "headroom" would be spent on average in about 38 years (full range: 30–45 years). With continuing growth in emissions in the absence of any new climate policies, the budget would be used up within just 27 years, i.e., by 2037 (full range: 22–32 years).

The relatively wide range of emissions reductions by 2050 reflects uncertainties with respect to emissions reduction potentials in the long and the short term, derived from the comprehensive sensitivity analysis across the transformative GEA pathways. The uncertainties themselves represent both choices and unknowns in regards to policy implementation and technological development on the demand and the supply sides of the energy system (see Table 4). Generally, pathways that have restricted supply-side portfolios (e.g., limited potential for renewables, or no CCS) require more rapid emissions reductions early in the century, to compensate for the loss of mitigation potential in the long term. For example, in the absence of bioenergy and CCS, emissions from the energy sector cannot become negative in the long term and thus need to be reduced comparatively more early in the century.

The bulk of the emissions reductions in the GEA pathways are achieved through decarbonization of supply, reducing the share of energy-related emissions from 50%

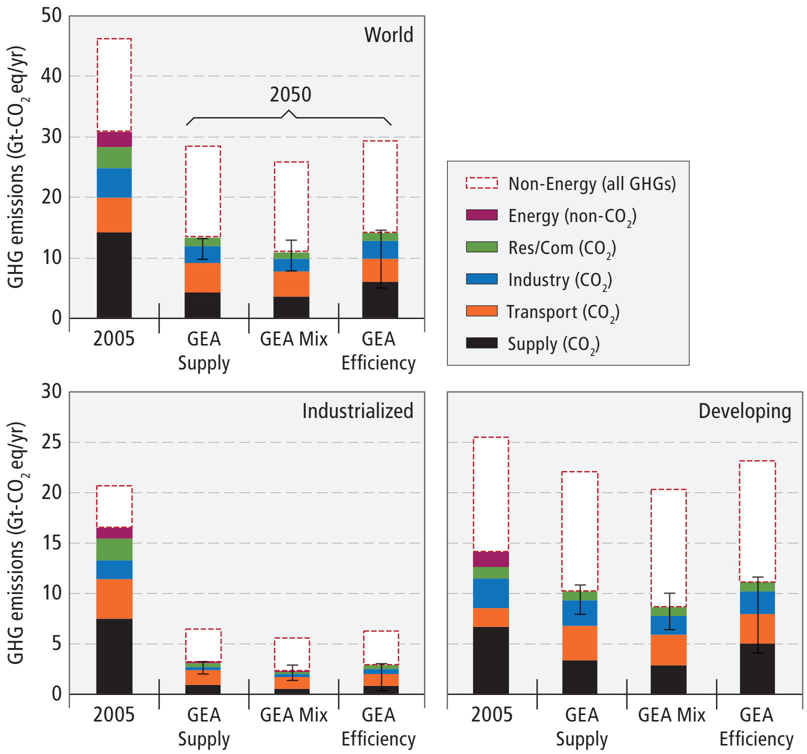


FIGURE 15
GHG emissions from energy supply and demand-side sectors in 2005 and in the three illustrative (unrestricted technology portfolio) GEA pathways in 2050. Dashed lines indicate additional GHG emissions from the non-energy sector. Error bars show the range across all GEA pathways within each pathway group.

today to between about 25–45% by 2050 (with exception of pathways assuming limited intermittent renewables). For such dramatic transformations to be realized, however, integration of supply and demand remains an essential task, since one of the main reasons for the comparatively rapid decarbonization of supply is the increasing quality and flexibility of fuels consumed on the demand side (namely electricity). Higher fuel quality requires more elaborate conversion processes and thus permits decarbonization through both fuel switching (e.g., from coal power plants to renewable power) and end-of-pipe solutions (e.g., CCS). The latter option is economic only in large centralized systems and is not applicable in the context of dispersed and heterogeneous demand-side sources (except for some industrial applications, such as CCS from cement production). Efforts to reduce emissions differ significantly across regions and are generally higher in today's industrialized world than in the developing world (Figure 15).

In the context of the Copenhagen Accord, various countries have already made commitments to mitigate their GHG emissions. The compound effect of these pledges is not yet clear, however, owing to numerous uncertainties.[7] Rogelj et al. (2010), for example, estimate that the present pledges are likely to lead to global emissions of 47.9–53.6 $GtCO_2$-eq. by 2020, while UNEP (2010) puts the range at 48.8–51.2 $GtCO_2$-eq. In any case, Figure 16 illustrates that even the most optimistic

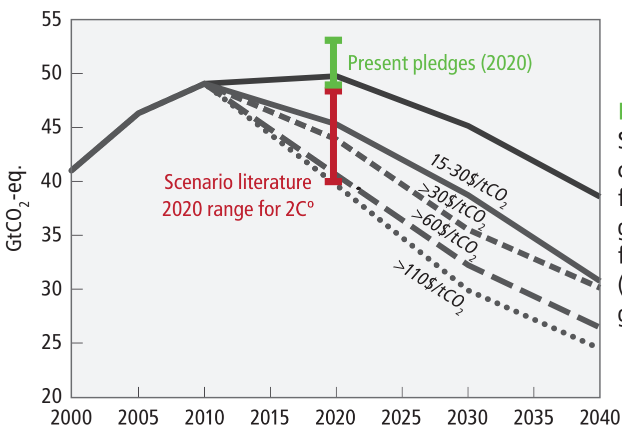


FIGURE 16
Short-term GHG emissions in the GEA pathways compared with the range of emissions resulting from present pledges by 2020. The lower error bar gives the 90th percentile range of 2020 emissions from low-mitigation scenarios in the literature (van Vuuren and Riahi, 2011). The GEA pathways are grouped according to ranges of CO_2 prices by 2020.

assumptions about future implementation of the pledges leads to emissions levels at around the upper bound of the GEA pathways. *Present commitments are therefore not sufficient and thus they are inconsistent with the vast majority of the GEA pathways, which aim at limiting global temperature increase to 2°C compared with preindustrial times* (with a likelihood of above 50%).

[7] Estimates differ between studies that have collated individual country pledges and translated them into global emissions levels because of different assumptions about, for example, the business-as-usual scenario, national actions, the use of offsets included in other countries' targets, particular emissions categories, and the role of land use change.

The gap between the present pledges and the GEA pathways ranges between none (a slight overlap of around 2 $GtCO_2$-eq.) to as large as 11 $GtCO_2$-eq. The pathways with no gap combine the most optimistic assumptions about the emissions reductions resulting from present pledges with the highest emissions estimate from all 41 feasible GEA pathways in 2020. However, as discussed earlier, the GEA pathways with the highest emissions in the short term coincide with those cases that employ the most optimistic assumptions about the future availability of technology, and in which the full portfolio of all mitigation options can expand pervasively and successfully. Any restriction to the portfolio of mitigation options requires greater emissions reductions over the short term, to compensate for the loss of emissions reduction potential in the long term. The gap between present pledges and the GEA pathways is therefore small only if one combines both the most optimistic assumptions about pledges with the most optimistic assumptions for the full portfolio of all mitigation options. The likelihood of the gap actually being small is thus rather low, especially if one considers the history of technology failure as well as the past performance of some countries in terms of emissions reductions.

Figure 16 also shows that, for the different groups of GEA pathways, carbon prices on the order of US$15–45 per tonne of CO_2 would need to be introduced globally by 2020, in order to bring emissions in that year back down to the level between 2005 and 2010. Carbon pricing will need to be complemented by regulation and technology standards, however, to mobilize the required investments and to act against, for example, rebound effects or barriers to implementation. In addition, the stringency of the mitigation policies needs to increase over time, leading to CO_2 prices increasing at about the pace of the discount rate (5%/year in the present analysis). In the most stringent emissions pathways, emissions need to drop to below the level of 2000 by 2020. The global CO_2 price corresponding to such stringent reductions is above US$110 per tonne of CO_2.

Air Pollution and Health

Pollution control is an essential and fundamental component of sustainable development, as good air quality contributes to a healthy society and improves quality of life. Air pollution harms the environment, leads to acidification and eutrophication, and damages vegetation. Both ambient air quality in cities and air quality within rural and urban homes are major contributors to local health. In the developing world in particular, air pollution due to lack of access to modern cooking fuels has serious health consequences; hence, improving the quality of fuels through energy access policies remains a critical challenge. This section examines varying levels of stringency of air quality legislation in combination with a selection of other policies embedded in the GEA pathways, namely those relating to energy access and climate change. The objective is to analyze in detail the implications of different policy packages in terms of their health benefits. Tools used include MESSAGE, which in this analysis is linked to the GAINS (Amann et al., 2008) and TM5 (Dentener et al., 2006) air quality models (see Riahi et al. (2011) for full methodology).[8]

- Through a combination of stringent air pollution, climate change, and energy access policies and measures, the GEA pathways drastically reduce the number of people exposed to harmful levels of air pollutant emissions.
- It is *not* possible to globally attain the World Health Organization guidelines for air quality without ensuring universal access to modern forms of energy.

Anthropogenic sources are major contributors to outdoor air pollution. The energy system alone contributes around 60% of all fine particulate matter (PM2.5) emissions (Rao et al., forthcoming). Outdoor air pollution was estimated to result in 2.75 million deaths or 23 million disability adjusted life years (DALYs) lost globally in 2005 (Table 8), of which more than 70% of the burden was felt in Asia. This represents around 5% of all deaths, 2% of all DALYs and around 12% of the total burden that could be attributed to cardiovascular, respiratory and lung cancer in that year. Meanwhile, household air pollution in the developing world (primarily solid fuel combustion in traditional stoves) added another 2.2 million deaths and more than 41.6 million DALYs, with the impacts felt mainly by women and children. Global air pollution control costs amounted to some US$195 billion in 2005, though most of this spending occurred in the industrialized world, as it has over the past several decades (Rao et al., forthcoming).

Future air pollution levels will depend on the continued development of the energy system and the types of policies that are implemented. For this reason, two different scenarios of future air quality are considered here. The first is a business-as-usual (BAU) scenario where all the air quality legislation that currently exists in individual countries throughout the world is enacted and, in addition, all currently planned

[8] The air pollution assessment described here builds upon the MESSAGE energy model as the primary tool for deriving detailed, sector-based estimates of various pollutant gases. In addition, MESSAGE is linked to the GAINS air quality model to represent different levels of air quality legislation until 2030. A number of air pollutants and GHGs have been downscaled to spatially explicit levels for 0.5-degree resolution. To estimate the impacts of the spatially explicit emissions, atmospheric concentrations of particulate matter, aerosols, and ozone were derived using the TM5 model.

legislation actually comes to fruition.[9] The scenario assumes no further progress in terms of either climate or energy access policies. In contrast, the sustainable GEA-Efficiency scenario ensures full achievement of all GEA objectives, including strong climate and universal energy access policies, as well as global implementation of extremely stringent pollution control policies until 2030. The latter pollution policy set – which includes stricter standards for power plants, factories, vehicles, shipping,

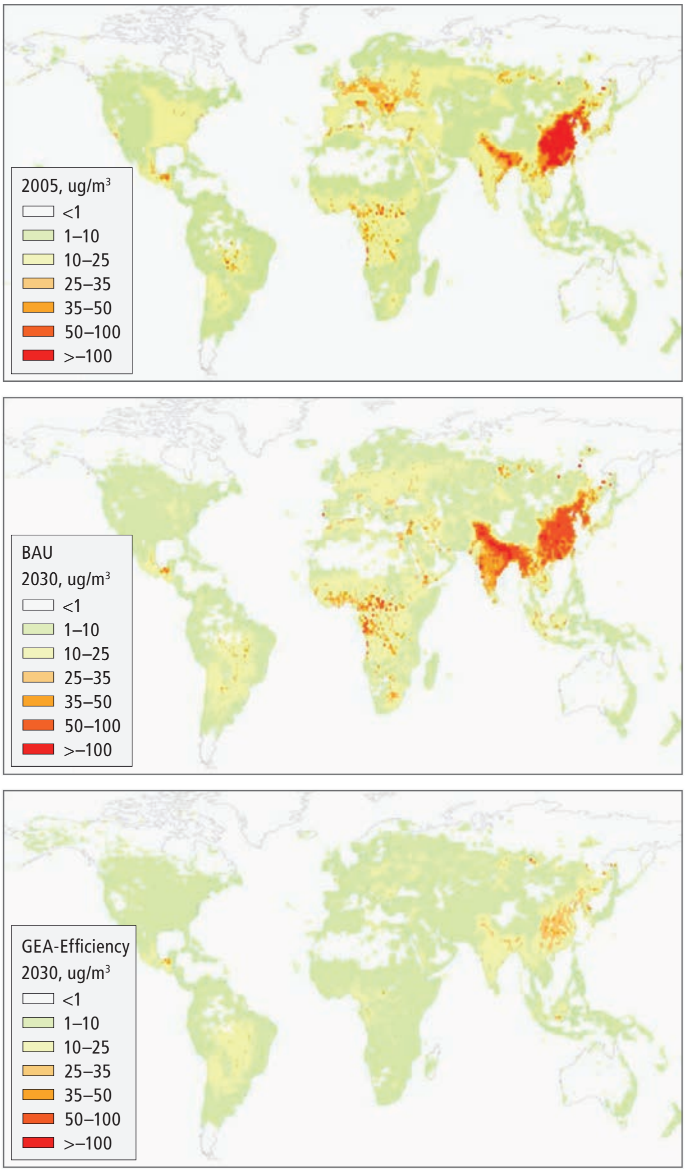


FIGURE 17
Geographic distribution of anthropogenic PM2.5 concentrations in 2005 (*top*) and under alternative policy packages in 2030 (BAU, *middle*; GEA-Efficiency, *bottom*).

[9] The BAU scenario described here is equivalent to the CLE1 scenario in the air pollution section of Chapter 17 of the Global Energy Assessment, whereas the GEA-Efficiency scenario here is synonymous with scenario SLE2 in that same section.

and in agriculture – is much more aggressive than the aggregate of all current and planned legislation but is still less aggressive than the so-called maximum feasible reduction level, which describes the technological frontier in terms of possible air quality control strategies by 2030 (see Amann et al. (2004), Cofala et al. (2007), Kupiainen and Klimont (2004) for specific policies and measures).

Compared to today, the enactment of all current and planned air quality legislation (as in the BAU scenario) is seen to curb the growth of pollutant emissions over the next two decades, especially in OECD countries (Figure 17). Emissions continue to increase in non-OECD countries, however, because of overall high energy demand and very little or nonexistent air quality legislation in many countries (e.g., in Africa). In other words, even if currently legislated air pollution control policies were implemented in all nations where they are now planned, only modest declines in pollutants would be expected, mainly because of increasing growth in emissions in developing countries in spite of the significant technological shifts that can be expected in those countries over the next two decades. The health impacts of outdoor air pollution increase almost 50% by 2030 in the BAU scenario (Table 8), whereas the impacts from household pollution decline by about 50%, thanks to a moderate improvement in the quality of cooking fuels. Due to higher activity levels and the increasing stringency of legislation, a threefold increase in annual air pollution control costs, to around US$600 billion, is required by 2030.

TABLE 8 Outdoor and household health impacts in 2005 and in 2030 for the BAU and GEA-Efficiency scenarios in 2030* (in millions of DALYs).

	2005		2030			
			BAU		GEA-Efficiency	
Region	Outdoor	Household	Outdoor	Household	Outdoor	Household
World	*23.1*	*41.6*	*33.6*	*>20*	*12.4*	*0*
OECD	2.4	0	1.2	0	0.2	0
REFS**	1.9	0	0.9	0	0.2	0
Middle East and North Africa	0.6	0	1.4	0	0.2	0
South Asia	7.3	13.8	13	8	5.8	0
Pacific Asia	1.1	3.9	1.8	3.5	0.4	0
Sub-Saharan Africa	0.9	18.6	1.9	10	0.1	0
Centrally Planned Asia	8.6	4.6	13.2	<2.6	5.4	0
Latin America and the Caribbean	0.3	0.8	0.1	<0.4	0.1	0

*Some fractions of the population are exposed to both outdoor and household air pollution and given possible non-linearity of dose response functions at higher concentrations, impacts cannot be combined.
**Reformed economies of Eastern Europe and the Former Soviet Union

The GEA-Efficiency scenario, in contrast, illustrates just how far pollutant emissions, and their corresponding impacts on human health, can be reduced when stringent air quality policies are combined with strong policies on climate change, energy access, and energy efficiency (Table 8, Figure 17). The scenario results in an overall emissions reduction (across all pollutants) of at least 50% in 2030 compared with 2005 levels (Figure 18) and ensures that 100% of the world's population breathes air that meets the WHO-mandated Tier I concentration level of 35 μg/m^3 for PM2.5, which is the global target of the GEA pathways for the environmental and health objective (see Table 1). Such improved air quality throughout the world yields enormous health benefits by 2030: just 1.2 million deaths and only 12.4 million DALYs, reducing the pollution-related burden to less than 2% of total deaths, 1% of total DALYs and around 5% of deaths and DALYs that can be attributed to cardiovascular, respiratory and lung cancer. Importantly, as a result of policies driving universal access to clean cooking fuels by 2030, the GEA-Efficiency scenario sees the health impacts related to household air pollution disappear within just two decades.

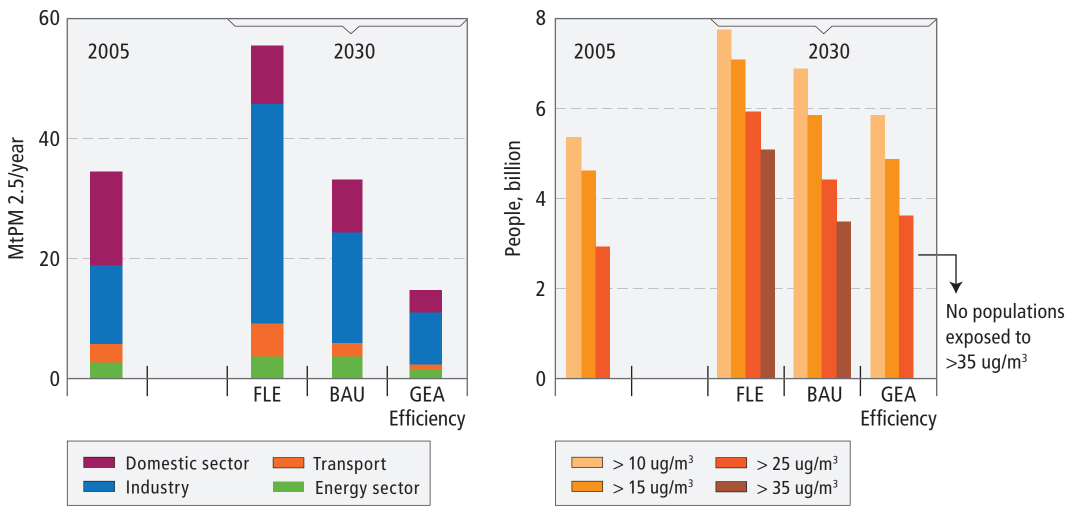


FIGURE 18
Global energy-related PM2.5 emissions by sector in 2005 and under alternative policy packages in 2030 (*left figure*). Global population exposed to fine particulate matter concentrations exceeding WHO air quality targets in 2005 and under alternative policy packages in 2030 (*right figure*). FLE refers to a scenario in which the stringency of pollution control legislation is forever frozen at today's levels.

How the Pathways Enhance Energy Security

Energy security has been a major concern for national and international energy systems for decades, and for this reason it remains an important sustainability objective to address in the GEA pathways. The challenge is that the concept of energy security has multiple dimensions. The following list summarizes some of the main energy security concerns today:

- ***Oil*** Volatility in the global oil market coupled with the geographic concentration of oil production; rapidly increasing demand under potentially constrained production capacities; growing dependence of an increasing number of countries on imported oil from ever fewer producing countries, with low-income countries often facing unaffordable costs of imports; and the dominance of oil in the transportation sector, where easily available substitutes are lacking
- ***Natural gas*** Dependence of a number of countries on imported natural gas, often procured from a single supplier and delivered through a limited number of potentially vulnerable routes and infrastructures
- ***Electricity*** Vulnerability of electricity systems associated with low diversity of power generation options, aging infrastructure, inadequate generation capacity, and rapid demand growth
- ***Energy export revenue*** Volatility and uncertain sustainability of energy export revenue ("energy demand" security) in countries where energy resource extraction is a vital economic sector
- ***Combined energy supply vulnerabilities*** Overall energy vulnerability of a number of individual countries that face several of the above concerns simultaneously.

The chapters focusing on energy security in the Global Energy Assessment establish a framework for analyzing the energy security-related vulnerabilities of energy systems associated with specific fuels, particular end-use sectors (including electricity as an energy carrier), and individual countries. In short, for each of these three subsystems, three dimensions of energy security concerns are identified: sovereignty (the degree of control that national governments have over energy systems), resilience (the ability of energy systems to respond to disruptions), and robustness (the risks related to the physical state of energy resources and infrastructure). The energy security analysis of the GEA pathways adopts a similar framework[10] but considers different energy subsystems to reflect game-changing

[10] Specifically, the energy security analysis of the GEA pathways relates to sovereignty and resilience concerns. Robustness concerns could not be addressed at the aggregated level of world regions.

developments in the transition pathways.[11] Moreover, the analysis focuses not only on the globally traded fuels that dominate today (oil, gas, and coal) but also on the potential energy carriers of the future (electricity, biofuels and hydrogen). The main energy end-use sectors (transportation, industry, residential and commercial) and electricity generation are also analyzed in turn.

- Under the GEA pathways, energy security improves in the world as a whole and in the majority of regions. The diversity of energy sources increases whereas both trade volumes and trade intensities (the share of traded energy in overall energy use) decline in most pathways.
- Individual end-use sectors generally use a more diverse mix of energy sources than today. The transportation sector, presently associated with major energy security concerns, achieves a diversity level similar to that in other end-use sectors.
- No individual fuel is likely to cause energy security concerns similar to those caused by oil today.

In all the GEA pathways, oil is phased out in the long term, accounting for between 9% and 15% of global primary energy supply by 2050 and declining to less than 1% by the end of the century (compared to 36% today). As a result, trade volumes of oil for all pathways peak at about 100 EJ (compared with approximately 83 EJ today) between 2020 and 2030 and decline thereafter. Present energy security concerns associated with oil drastically diminish in the transition pathways because of comparatively modest demand growth due to efficiency improvements and a more diversified supply mix. Moreover, no "new oil" emerges in the global energy arena, and no other fuel comes to assume a dominant role similar to that which oil plays today. Biofuels, hydrogen, and electricity[12] are traded in much smaller volumes and with greater geographic diversity of producers than is the case with oil at present. The only exception is natural gas, which by 2050 accounts for about 20% of primary energy globally and 36–51 EJ of trade per year across the range of GEA pathways. In terms of the geographic concentration of supply, gas production remains at its current level until about 2050, thus comparable to the

[11] Energy diversity is represented in the GEA pathways analysis by (1) a simple Shannon-Wiener diversity index, SWDI (Shannon and Weaver, 1963), and (2) a compound SWDI that simultaneously measures global energy trade (reflecting sovereignty concerns) and diversity (reflecting resilience concerns) (Jansen et al., 2004).

[12] Although electricity comes to dominate final energy consumption, it is not, strictly speaking, a "fuel" as it is produced from a variety of sources. Moreover, global trade in electricity is minimal in all pathways, never accounting for more than 2% of total electricity supply.

current concentration of oil production. And although gas production becomes even more concentrated later in the century, future energy security concerns for gas are not likely to be as severe as they are for oil, given that the overall diversity and resilience of national and regional energy systems will dramatically improve over time in the GEA pathways.

All regions of the world generally follow the global trend toward improved energy security in the GEA pathways (Table 9). Some experience a more rapid and pronounced increase in diversity and self-sufficiency of their energy systems, whereas others – particularly those with more limited energy options – could experience continued reliance on particular fuels (primarily natural gas) in specific sectors (transportation and electricity generation) under certain pathways. The flip side of the decrease in energy imports is a fall in energy exports for certain regions. Energy exports provide vital revenue for a number of countries,

TABLE 9 Regional trends in diversity and import dependency, 2005 and 2050.

	Import Dependency*		Diversity						Compound diversity index	
			Electricity		Transport		Primay Energy Supply			
Region	2005	2050	2005	2050	2005	2050	2005	2050	2005	2050
AFR	-8%	-0.07	1.01	1.64-1.89	0.07	1.24-1.73	1.40	1.66-1.83	1.4	1.51-1.73
CPA	4%	8%-14%	0.74	1.72-1.85	0.21	1.06-1.77	1.17	1.87-1.97	1.05	1.56-1.73
EEU	36%	28%-34%	1.2	1.43-1.60	0.16	1.38-1.76	1.53	1.86-1.94	0.99	1.32-1.50
FSU	-54%	-0.56	1.4	1.34-1.51	0.42	1.36-1.70	1.37	1.68-1.97	1.37	1.68-1.97
LAM	-34%	-0.13	1.26	1.38-1.68	0.31	1.41-1.73	1.44	1.71-1.94	1.44	1.71-1.94
MEA	-187%	-0.46	1	1.12-1.47	0.03	1.09-1.23	0.95	1.22-1.56	0.87	1.17-1.49
NAM	21%	2%-8%	1.46	1.55-1.80	0.08	1.28-1.76	1.54	1.87-2.04	1.34	1.71-1.91
PAO	41%	-0.22	1.55	1.64-1.95	0.09	1.46-1.79	1.48	1.87-2.07	0.99	1.70-1.81
PAS	28%	10%-28%	1.47	1.53-1.88	0.02	1.28-1.72	1.50	1.96-2.04	1.2	1.45-1.74
SAS	20%	29%-32%	1.22	1.68-1.82	0.11	0.92-1.55	1.46	1.69-1.84	1.16	1.03-1.25
WEU	40%	31%-36%	1.64	1.52-1.73	0.16	1.48-1.75	1.61	1.84-1.93	1.1	1.27-1.34
World	20%	13%-16%	1.54	1.79-1.92	0.15	1.38-1.77	1.62	1.94-2.05	1.36	1.64-1.77

LEGEND	Import Dependency*	Diversity	Compound diversity
	low (<16%)	High (>1.5)	High (>1.5)
	medium (16-34%)	Medium (1.0-1.5)	Medium (1.0-1.5)
	high (>34%)	Low (<1.0)	Low (<1.0)

*Import dependency values are reported as negative if a region is a net energy exporter. World import dependency is the portion of global primary energy that is traded.

-The higher the diversity index, the greater the diversity and resilience of the energy resource portfolio.

AFR = sub-Saharan Africa; CPA = China and Centrally Planned Asia; EEU = Eastern Europe; FSU = Former Soviet Union; LAM = Latin America and the Caribbean; MEA = Middle East and North Africa; NAM = North America; PAO = Pacific OECD; PAS = Pacific Asia; SAS = South Asia; WEU = Western Europe and rapid and profound declines in such revenue could adversely affect energy-exporting regions. This drop in export volumes may be partly mitigated, however, by rising energy prices. The Middle East is poised to experience the largest decline in energy export volumes of all world regions because of the declining share of oil in the global energy mix. In contrast, the major export "winner" under all GEA pathways appears to be the countries of the former Soviet Union, which experience a dramatic rise in their energy exports due to the increasing demand for natural gas.

In terms of the evolving energy security landscape under the GEA pathways, certain commonalities exist between particular world regions. The first group includes such industrialized regions as the Pacific OECD countries, parts of Latin America and the Caribbean, North America, and Western Europe, which generally follow the global trends with respect to fuels and end-use sectors. Transitions in their energy systems are primarily driven by global factors: the switch away from fossil fuels, increases in efficiency, and diversification of transport technologies. Since all these transitions generally improve energy security by increasing resilience and sovereignty, energy security in these regions also improves significantly. The second group includes sub-Saharan Africa and Centrally Planned Asia, in which the global energy transitions provide a context for massive growth in regional energy systems. The expansion of energy systems in sub-Saharan Africa to extend energy access to all, and in Centrally Planned Asia and China to keep up with rapidly growing economies, results in dramatically altered configurations of energy systems, leapfrogging the inherited energy systems inertia of the currently industrialized world. As a result, many energy security indicators in these regions improve much more rapidly and dramatically than in the rest of the world, as their energy systems become more diverse and more reliant on regional rather than global resources. The third group includes those regions which because of their geography and either fossil fuel resource endowments (the Former Soviet Union, the Middle East and North Africa) or resource scarcity (Eastern Europe and South Asia), have more limited options for radical systemic change. The diversity of energy supply, especially in specific sectors in these regions, could remain below the global average. For example, their transportation and electricity sectors may become dominated by natural gas by the middle of the century.

Conclusion: Harnessing Synergies between Multiple Energy Objectives

The energy system of the future could potentially develop in a number of different directions, depending on how society and its decision makers prioritize various worthwhile energy objectives, including, but not limited to, climate change mitigation, improved air quality and health, universal energy access, and enhanced energy security. The GEA transition pathways show that achieving these objectives simultaneously is technically possible, but it would require a dramatic transformation of the global energy system over the next several decades. And while transitions of this kind would generate enormous synergies, understanding these dynamic relationships requires a more integrated, holistic perspective than is typically taken by decision makers at the present time (McCollum et al., 2011). For this reason the synergies between the multiple energy objectives are often overlooked, or they are simply not understood. Compounding the problem is that in many countries separate policy institutions are responsible for dealing with each of the objectives. Moreover, the objectives often find themselves competing for attention in the policy world.

- Climate change mitigation can be an important entry point for achieving society's pollution/health and energy security goals.
- Decarbonization of the energy system will lead to improved air quality and, thus, lower health impacts worldwide: globally aggregated DALYs can be reduced by up to 22 million in 2030.
- Decarbonization can help to further the energy security goals of individual countries and regions by promoting a more dependable, resilient, and diversified energy portfolio that sees an increased utilization of domestically available renewable energy sources.
- An integrated, holistic approach to energy policy and planning is badly needed: the combined costs of climate change mitigation, energy security, and air pollution control come at a significantly reduced total energy bill if the multiple benefits of each are properly accounted for in the calculation of total energy *system* costs.
- Added costs of pollution control are cut by up to US$500 billion annually in 2030 under stringent climate policy.
- Added costs of energy security are cut by up to US$130 billion annually in 2030 under stringent climate policy.

This section views the major energy challenges facing society through an integrated, holistic lens. It attempts to illuminate the major synergies and, to a lesser extent, the trade-offs among the various energy objectives and the requisite policy choices and outcomes. In so doing, the analysis takes a slightly different approach from the GEA pathways described so far in the report. Here the illustrative GEA-Mix pathway is used as a starting point for generating several hundred alternate scenarios that attempt to cover a large portion of the full scenario space across several different dimensions.[13] (For instance, some scenarios push climate change mitigation while ignoring security and air pollution.) Within this space, many of the scenarios are unsustainable by GEA standards, as each meets (or fails to meet) the GEA targets for energy sustainability to varying degrees. The analysis uses these less stringent scenarios as counterfactuals and for comparison purposes, in order to show how certain objectives and policy choices push in the same direction, while in certain instances they could be in conflict.

TABLE 10 Indicators for climate change, pollution and health, and energy security and levels of satisfaction within the Weak–Intermediate–Stringent framework.

Fulfillment	Climate Change [probability of staying within 2°C warming limit]	Pollution and Health [million DALYs, 2030]	Energy security [compound diversity indicator, 2030]
Weak	<20%	>33	<1.40
Intermediate	20–50%	15–33	1.40–1.50
Stringent	>50%	<15	>1.50

Because the fulfillment of each of the individual GEA objectives can be measured in its own unique way, this section adopts a simple framework to describe the scenario space across all three objectives (Table 10). The framework defines three levels of satisfaction – Weak, Intermediate, and Stringent – for each of the three energy objectives, and specific numerical ranges are given for what constitutes each of these levels in terms of the relevant indicators. Note that the minimum allowable indicator values corresponding to the Stringent level derive directly from the official GEA targets for sustainability (Table 1).

The individual scenarios of the large ensemble vary greatly along the dimensions of climate change, pollution and health, and energy security, and for this reason the energy-related costs of the scenarios span a fairly wide range as well. This is illustrated in Figure 19, where each bar represents the cumulative costs of a single scenario, and the scenarios are sorted in order of increasing costs. If one thinks of the multiple energy objectives as societal targets that the energy system should attempt to satisfy (i.e., scenario inputs), then total costs are an embodiment (i.e., scenario outputs) of the system-wide transformations that must take place in order to meet those objectives

[13] Notably, the energy access objective is taken as given in this analysis. This simplification was made because energy access, compared with the other objectives, has the lowest impacts on energy use and GHG emissions.

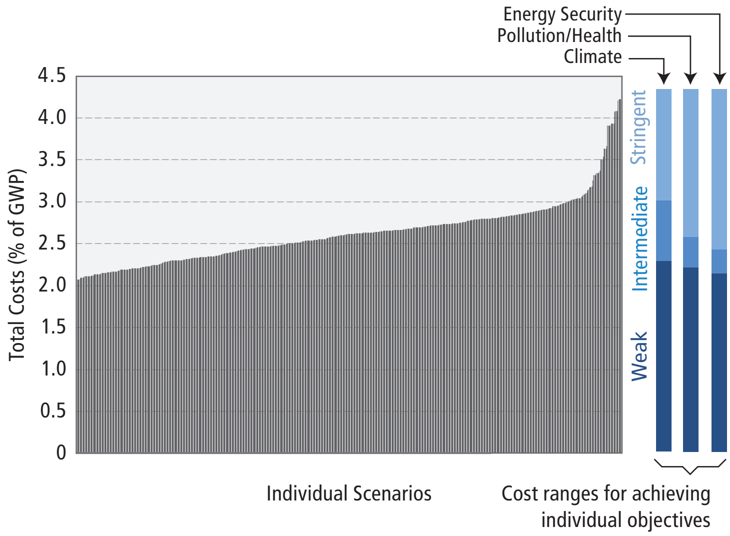


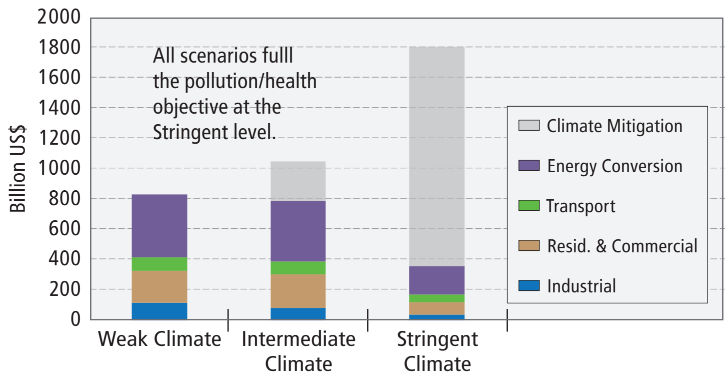
FIGURE 19
Cumulative discounted total energy system costs as a share of cumulative GDP for all scenarios in the full ensemble (2010–2050). Includes energy system investments (supply and demand technologies, as well as climate change mitigation, energy security, and pollution control investments), operation and maintenance, fuel, and nonenergy mitigation costs. Bars at right illustrate the ranges of total cost that correspond to Weak, Intermediate, and Stringent fulfillment of the climate, pollution and health, and energy security objectives.

(e.g., increased utilization of advanced technologies and alternative fuels). The resulting total cost of a given scenario thus depends entirely on how far it goes toward satisfying each individual objective, illustrated on the right side of the figure by the ranges of scenarios, from a cost perspective, that correspond to Weak, Intermediate, and Stringent fulfillment of the climate, pollution and health, and energy security objectives. The least costly scenarios – those making little or no improvement progress toward sustainability, such as the baseline – lie within the Weak region, whereas scenarios that achieve one or all of the objectives at the Intermediate or the Stringent level obviously incur costs in the middle or the upper end of the range, respectively. Notably, total costs range from 3.1% to 4.2% of globally-aggregated GDP (i.e., gross world product) for the class of scenarios that achieves stringent fulfillment of all three objectives simultaneously. By comparison, energy system costs in the counterfactual baseline are about 2.1% of GWP over the same time period. Hence, the combined costs of all climate, pollution, security, and access policies amount to just 1.0% to 2.1% of GWP over this first part of the century.[14]

There are enormous co-benefits between pollution and climate policy. Thus, achieving society's pollution and health objectives through climate change mitigation as an entry point has the potential to significantly reduce the added costs of pollution control. A closer look at three select scenarios of the large ensemble illustrates this point quite clearly. Each scenario in Figure 20 fulfills the pollution and health objective at the Stringent level; however, each does it by vastly different means, pursuing the climate objective to a greater or lesser degree. The Weak Climate scenario, for instance,

[14] An important caveat to the cost analysis shown here is that it performs only a partial economic accounting. The analysis attempts to capture multiple benefits in terms of avoided or reduced costs for climate change mitigation, energy security, and pollution control. However, given the inherent difficulties in valuing human life in the economic sense, and given the vast uncertainties with respect to the economic valuation of, for example, climate-related damages, the analysis does not attempt to value other benefits of pursuing these three objectives. Hence, the conclusions on multiple economic benefits presented in this section relate to "mitigation" costs only; they would become larger if other benefits were assigned an economic value as well.

FIGURE 20
Global annual pollution control and climate change mitigation costs for Weak, Intermediate, and Stringent climate policy scenarios in 2030. The Stringent Climate scenario achieves the 2°C target with a comparatively high probability of >60% and thus represents an upper-bound estimate for climate change mitigation costs and pollution control co-benefits across the GEA pathways.



represents a business-as-usual energy future, where climate change gains essentially no further traction throughout the world but in which decision makers recognize air pollution as a major problem requiring an immediate solution. As a result of the substantially more advanced end-of-pipe pollution controls that would be required in such a future, these pollution-only policies would add a significant US$830 billion to total annual energy system costs in 2030 (compared with US$1630 billion for the rest of the energy system). However, as the stringency of climate policy increases, the added costs of pollution control decrease significantly, especially in the Stringent Climate scenario, where control costs are US$470 billion less than in the Weak Climate scenario, a 57% reduction.[15] This striking result illustrates that a significant portion of climate change mitigation costs can be compensated for by reduced pollution control requirements, a synergistic relationship that often gets overlooked by policy makers. The primary driver of these enormous synergies is investment in low-carbon energy technologies (e.g., nuclear and renewables), which have the co-benefit that they are also pollution-free. As the energy system is decarbonized, there is less air pollution generated and less of a need for end-of-pipe pollution control technologies at fossil power plants and factories and on vehicles.

It is also important to note that reducing air pollutant emissions can have potentially advantageous impacts on the global climate as well. The synergies between the two, however, are not likely to be as massive as those coming from the opposite direction (climate mitigation on pollution control). While reducing the quantity of key air pollutants emitted to the atmosphere – namely those that cause warming (black carbon and the ozone precursors methane, nitrogen oxides, carbon monoxide, and volatile organic compounds) – certainly could play a modest role in mitigating climate change (Cofala et al., 2009; Ramanathan and Xu, 2010), the climate feedbacks of air pollution are rather complex, and policy makers must be careful to ensure that control strategies reduce some specific pollutants proportionally more than others

[15] Generally, pollution control costs of scenarios reaching the Stringent fulfillment level are on the order of US$200 to US$350 billion in 2030.

(e.g., warming components reduced more than the main cooling components, sulfur dioxide and organic carbon), in an effort to preserve the overall cooling effect of aerosols and, thus, to produce a net gain for the climate, or to at least remain radiant energy–neutral.

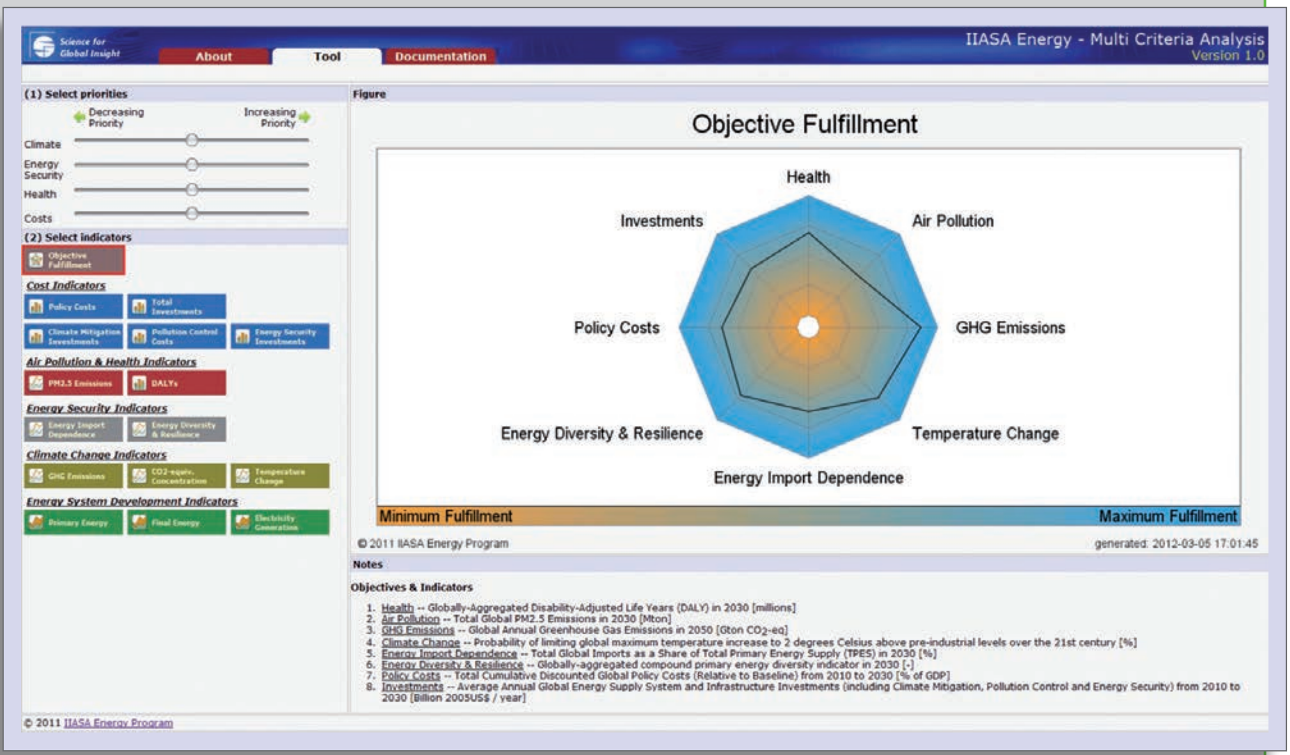
Stringent climate policies can also help to achieve near-term energy security goals. As countries and regions invest more heavily in renewables in an effort to decarbonize their economies, they will by extension reduce their need to import globally traded fossil energy commodities such as coal, oil, and natural gas. Because renewables

BOX 4 The IIASA Energy—Multi Criteria Analysis Policy Tool (ENE-MCA)

An interactive Web-based scenario analysis tool allowing the concurrent assessment of multiple energy objectives

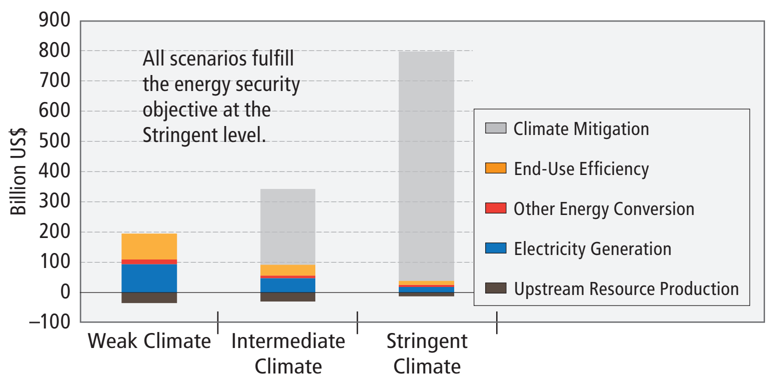
URL: **www.iiasa.ac.at/web-apps/ene/GeaMCA**

The ENE-MCA policy tool allows energy decision makers and planners to conduct a comprehensive and integrated assessment of the major energy challenges of the 21st century and, in so doing, to make more informed choices about the sustainable energy development pathways on which they will embark in the future. The ENE-MCA tool provides a comprehensive and interactive overview of the various synergies and trade-offs involved in attaching priorities to four of the main energy sustainability objectives – climate change, energy security, air pollution and health, and affordability. As not all objectives are given the same priority by different policymakers, ENE-MCA allows users to see how alternative worldviews can lead to qualitatively different energy system futures. It also permits users to visualize the complex, and not always obvious, relationships among the different policy choices they are considering making. The ENE-MCA policy tool was developed at IIASA in support of the Global Energy Assessment.



(biomass, hydro, wind, solar, and geothermal) can potentially be produced almost entirely domestically (or at least regionally within a cluster of like-minded countries), they are from a dependency perspective inherently secure resources. At the same time, increased utilization of renewables tends to diversify the energy resource mix away from one that relies so heavily on fossil energy. Thus, decarbonization of the energy system can simultaneously reduce import dependence and increase energy diversity, both of which are key indicators of a more secure energy supply.

FIGURE 21
Global annual energy security investment and climate change mitigation costs for Weak, Intermediate, and Stringent climate policy scenarios in 2030. Note that the cost accounting for climate mitigation is more comprehensive than that shown for security, which captures only investments.



Similar to the relationship between climate mitigation and pollution control, the costs of enhancing energy security are significantly reduced at higher levels of decarbonization. Figure 21 illustrates these co-benefits by summarizing energy security costs under three alternative climate policy regimes. When climate policies are weak or nonexistent, the security cost premium, in terms of globally-aggregated annual energy system investments, is estimated at approximately US$160 billion in 2030. By comparison, under an Intermediate or a Stringent Climate regime, the added costs of security decline significantly, to just US$64 billion and US$28 billion/year, respectively (reductions of 61% and 84% compared with the Weak Climate case). The figure shows that security policy (applied at the level of individual countries and groups of countries) primarily spurs additional investments in end-use efficiency and electricity generation, while at the same time lowering the investment requirements for upstream energy extraction (coal mining and oil production). The security co-benefits that stem from climate change mitigation are then largely attributed to the reduced need for extra "security investments," since climate policy already promotes substantial investments in energy efficiency and conservation and the increased utilization of domestically produced, low-carbon energy sources.

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David McCollum is a Research Scholar with the Energy Program at the International Institute for Applied Systems Analysis. He received his doctorate in transportation technology & policy from the University of California, Davis (USA), Institute of Transportation Studies in 2011, following the completion of an MSc in agricultural & resource economics from the same institution, and a BSc in chemical engineering from the University of Tennessee (USA).

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He has been appointed a Lead Author of the recently published IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, a Lead Author of the Global Energy Assessment (GEA), and a Lead Author of the IPCC 5th Assessment Report which is scheduled for publication in 2014. Since 2010 he is an Associate Deputy Editor of the interdisciplinary journal Climatic Change. Dr. Krey also teaches in an MSc program on "Renewable Energy in Central and Eastern Europe" at the Vienna University of Technology.

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