Global Energy Assessment

Toward a Sustainable Future

Key Findings
Summary for Policymakers
Technical Summary

GEA
IIASA

Global Energy Assessment

Toward a Sustainable Future

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Figure 1.2 | Global energy flows of primary to useful energy, including losses, in EJ for 2005.
Source: adapted from Nakicenovic et al., 1998, based on IEA, 2007a; 2007b; 2010.
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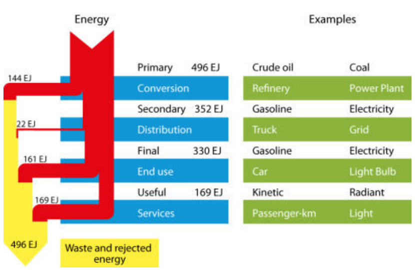

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World Energy Council

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Foreword and Preface

Foreword

Energy is central to addressing major challenges of the 21st Century, challenges like climate change, economic and social development, human well-being, sustainable development, and global security. In 2005, Prof. Bert Bolin, the founding Chair of the Intergovernmental Panel on Climate Change (IPCC), with other eminent scientists and policy-makers, identified that a comprehensive, science-based assessment of the global energy system was needed if these challenges were to be realistically addressed. The Global Energy Assessment (GEA) is the result of this shared vision.

Since the establishment of the GEA in 2006 by governing Council of the International Institute for Applied Systems Analysis (IIASA), 500 independent experts (about 300 authors and 200 anonymous reviewers) from academia, business, government, intergovernmental and non-governmental organizations from all the regions of the world have contributed to GEA in a process similar to that adopted by the IPCC.

The final GEA report examines: (a) the major global challenges and their linkages to energy; (b) the technologies and resources available for providing adequate, modern and affordable forms of energy; (c) the plausible structure of future energy systems most suited to addressing the century's challenges; and (d) the policies and measures, institutions and capacities needed to realize sustainable energy futures.

Undertaking such a massive assessment has required extraordinary leadership, intellectual input, support and coordination. Governance of the Assessment has been overseen by the GEA Council, led by two Co-Presidents, Ged Davis and José Goldemberg and comprising members of supporters and sponsors of the GEA, including international organizations, government agencies, corporations, and foundations and non-governmental organizations. Convening Lead Authors (CLAs) coordinated the 25 Chapters and the contributions of Lead and Contributing Authors. The GEA Executive Committee, led by two Co-Chairs, Thomas B. Johansson and Anand Patwardhan includes all CLAs. Review Editors were appointed by the GEA Council for each Chapter. They in turn appointed anonymous reviewers and guided the rigorous peer-review process.

Completion of GEA has involved dedication and sustained contributions from many colleagues around the world. Our thanks and gratitude go to: Leen Hordijk, the IIASA Director who initiated GEA at IIASA; Sten Nilsson, IIASA Acting Director and Deputy Director; and Detlof von Winterfeldt, the IIASA Director who provided personal and institutional support throughout. The resources and the encouragement they provided helped make GEA a reality. The GEA Organizing Committee and the GEA Council provided wise counsel and guidance throughout. Additionally the GEA Council solicited financial and in-kind resources without which GEA would not have been possible.

We are especially grateful for the contribution and support of the GEA Council, the Executive Committee, the Organizing Committee, the Secretariat, as well as the IIASA Council and management. As host organization for the GEA Secretariat, IIASA has provided substantial in-kind support to GEA over the past seven years.

The Co-Chairs Thomas B. Johansson and Anand Patwardhan of the GEA Executive Committee and the Associate Director, Luis Gomez-Echeverri, coordinated the work of multiple authors and provided intellectual leadership, the vision needed to conduct an assessment of this magnitude, and guidance consistent with the GEA Council resolutions.

It is a pleasure to acknowledge the contribution of the team of editors, Geoff Clarke, Esther Eidinow, Valerie Jones, Susan Guthridge-Gould, Karen Holmes, Gail Karlsson, Wendy Knerr, John Ormiston, Emily Schabacker, Misti Snow, Mark F. Speer, Jon Stacy, Linda Starke, Julia Stewart, Lloyd Timberlake, Michael Treadway, Thomas Woodhatch who patiently edited GEA manuscripts. Thanks to IIASA colleagues who worked with the GEA Secretariat – including Colin Adair, Brigitte Adamik, Marilyn Bernardo, Anita Brachtl, Claire Capate, Elisabeth Clemens, Katalin David, Susanne Deimbacher, Sanja Drinkovic, Linda Foith, Walter Foith, Amy Fox, Bill Godwin-Toby, Amnah Kasman, Martin Gugumuck, Margit Hegenbart, Anka James, Shari Jandl, Elizabeth Lewis, Monica Manchanda, Eri Nagai, Olivia Nilsson, Patrick Nussbaumer,

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Finally we express our sincere gratitude to the GEA authors, whose knowledge and experience has made possible this unique and valuable volume. Behind these people are families who have generously foregone time such that GEA could be completed, we thank them also.

The publication of GEA in June 2012 and the importance of energy at Rio+20 is no coincidence. The UN General Assembly declared 2012 the year of "Sustainable Energy for All" and the UN Secretary General's office initiated a campaign for an Action Agenda to meet the world's energy challenges. The GEA shows that an energy transformation toward a sustainable future is possible with strong political commitment. It is our belief that this assessment will provide policy- and decision-makers around the world, with invaluable new knowledge to inform action and commitment towards achieving these goals and thereby resolving the 21st Century's greatest challenges.

Pavel Kabat
IIASA Director/CEO

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GEA Director

Preface

Today the world of energy has many of the features established in the 20th century:

- Energy consumption grows on average at 2% per year, most of it (80%) originates in fossil fuels
- Energy growth is driven by population growth and economic growth, now predominantly in developing countries and high levels of consumption in the developed countries
- 3 billion people don't have access to basic energy services and have to cook with solid fuels

However, the present path of uninterrupted reliance on fossil fuels poses four challenges to sustainability:

- Soaring greenhouse gas emissions
- Decreasing energy security
- Air pollution at the local and regional levels with resulting health problems
- Lack of universal access to energy services

Most reviews of the energy system needed for the 21st century start with "business as usual" futures and then analyze the effectiveness of specific corrections of course. For many the preferred options are technological fixes such as such as carbon capture and storage (CCS), nuclear energy and even geo-engineering schemes. However, to achieve sustainable development all the needed attributes of energy services, that is availability, affordability, access, security, health, climate and environmental protection, must be met concurrently. The Global Energy Assessment (GEA) accepts this and is unashamedly normative, examining future energy pathways that point to new solutions. The aspirational goals in GEA are defined as:

- Stabilizing global climate change to 2°C above pre-industrial levels to be achieved in the 21st century
- Enhanced energy security by diversification and resilience of energy supply (particularly the dependence on imported oil),
- Eliminating household and ambient air pollution, and
- Universal access to modern energy services by 2030.

GEA's approach is the one adopted by policy planners and governments, that is to take a holistic view of the problems they faced, of which energy supply is only one of them. In such an approach externalities play a big role in determining choice among options. This is what governments do all the time, and is exemplified by the current debates on the future of nuclear energy, shale gas, the building of big dams or a large expansion of biofuels production. None of the preferred options can be established without an understanding of the wider policy agenda. For example, integrated urban planning leads to lower costs than a combination of non-integrated policies in building efficiency, compact layout and decentralized energy production.

The main purpose of GEA has been to establish a state-of-the-art assessment of the science of energy. This work examines not only the major challenges that all face in the 21st Century, and the importance of energy to each, but also the resources that we have available and the various technological options, the integrated nature of the energy system and the various enablers needed, such as policies and capacity development. Central to the integrated analysis of the energy system has been a novel scenario exercise exploring some 40 pathways that satisfy simultaneously the normative social and environmental goals outlined above.

Without question a radical transformation of the present energy system will be required over the coming decades. Common to all pathways will be very strong efforts in energy efficiency improvement for buildings, industry and transportation, offering much-needed flexibility to the energy supply system. But in implementing efficiency options there will be a need to avoid continued lock-in to inefficient energy demand patterns and obsolescent technologies. we will see an increased share of renewables (biomass, hydro, wind, solar and geothermal), which could represent by 2050 over a half of the global energy supply. The foundation is being put in place. For example, half the world's new electric generating capacity added during 2008–10 was renewable, the majority in developing countries. Global 2010 renewable capacity, with additions of ~66 GW, is larger than nuclear power's global installed capacity. In the European Union electric capacity additions have been over 40% renewables in each year between 2006 and 2010, and in Denmark 30% of the electricity produced in 2010 was renewable. Even though China is still building coal plants, its 2010 net capacity additions were 38% renewables.

This will come at a cost, increasing the 2% of global GDP investment currently spent in the energy sector, especially in the next 20 years. However, this should not constrain the drive for universal access, which could be achieved by 2030 for as little as $40 billion per year, less than 3% of overall yearly investment. This would build on successful programs for energy access in a number of developing countries, such as Brazil, Mexico and South Africa. And results have been dramatic. In Brazil, during the ten years prior to September 2011 14 million people were connected to the electricity grid, at a cost of some 10 billion dollars.

Although the required transformation of the energy system is substantial, it is not without precedent. Last century between the 1920's and the 1970's oil replaced coal as the dominant energy source despite the immense available coal reserves. This occurred due to oil, as a liquid, being superior to coal in many respects, particularly for transportation. Similarly energy efficiency and renewables can be an easier way to solve energy security than producing fossil energy at higher costs that usually exacerbate environmental problems.

There are many combinations of energy resources, end-use, and supply technologies that can simultaneously address the multiple sustainability challenges. There will be an increased role of electricity and gases as energy carriers, co-utilization of biomass with fossil fuels in integrated systems, co-production of energy carriers, electricity, and chemicals, and, CCS.

All GEA energy pathways to a more sustainable future represent transformative change from today's energy systems. Large, early, and sustained investments are needed to finance this change, and can be in part achieved through new and innovative polices and institutional mechanisms that should reduce risks and increase the attractiveness of early, upfront investments, that have associated low long-term costs.

The GEA pathways that meet the sustainability goals generate substantial benefits across multiple economic and social objectives. This synergy is advantageous and important, given that measures which lead to local and national benefits, e.g. improved local and immediate health and environment conditions, support the local economy, may be more easily adopted than those measures that are put forward primarily on the grounds of goals that are global and long-term in nature, such as climate mitigation. An approach that emphasizes the local benefits of improved end-use efficiency and increased use of renewable energy would also help address global concerns.

Policies and incentive structures that promote R&D should be key areas for intervention. Rationalizing and reallocating subsidies, including subsidies to fossil fuels and nuclear energy can create new opportunities for investment. A major acceleration of publicly financed R&D and its reorientation towards energy efficiency and renewable energy technologies is required. And to bring new technologies to market an integrated approach towards energy for sustainable development is needed; with policies in sectors such as industry, buildings, urbanization, transport, health, environment, climate, security, and others made mutually supportive.

The transition from coal to oil occurred without significant government regulations although subsidies played a role. However the transformation GEA envisages this century is more fundamental in character, and government policies are a key ingredient needed particularly in changing buildings codes, fuel efficiency standards for transportation and mandates for the introduction of renewables. A new found appreciation by policy-makers of the multiple benefits of sustainability options and their appropriate valuation will be critical for the transformation to occur.

The Global Energy Assessment's report establishes a benchmark for current understanding of the options for building a sustainable future for the energy system. But the Assessment consists more than just a report. Analytical tools have been developed to help translate the Assessment into actionable findings. Tools for decision making, that include global and regional scenarios, can be used to develop policy choices to address country-specific problems.

An important contribution to knowledge is the massive data base that is at the disposal of research and scientific community for their own use, and eventually analysis will be made available to the public at large.

Outreach has already started with the presentation of the early findings of GEA at the Vienna Energy Forum in June 2011. Importantly at that forum a Ministerial declaration, supported by the UNIDO leadership, endorsed the solutions offered by GEA, particularly:

- Ensure universal access to moderns forms of energy for all by 2030
- Reduce global energy intensity by 40% by 2030
- Increase the share of renewables 30% by 2030

These three objectives are reflected in the Action Agenda of the UN Secretary General's High-Level Group on "Sustainable Energy for All".

The aim going forward is to ensure the widest dissemination of GEA's work that is possible, including both national and regional policy dialogues.

This opportunity to layout a new approach to the design and implementation of sustainable energy pathways would not be possible without the extraordinary effort of the 500 or so contributors, be they authors from various disciplines and walks of life, reviewers, editors or members of the secretariat, executive team and council. We thank you all.

Ged Davis and José Goldemberg
GEA Co-Presidents

Key Findings

The Global Energy Challenge

Since before the Industrial Revolution, societies have relied on increasing supplies of energy to meet their need for goods and services. Major changes in current trends are required if future energy systems are to be affordable, safe, secure, and environmentally sound. There is an urgent need for a sustained and comprehensive strategy to help resolve the following challenges:

- *providing affordable energy services for the well-being of the 7 billion people today and the 9 billion people projected by 2050;*
- *improving living conditions and enhancing economic opportunities, particularly for the 3 billion people who cook with solid fuels today and the 1.4 billion people without access to electricity;*
- *increasing energy security for all nations, regions, and communities;*
- *reducing global energy systems greenhouse gas emissions to limit global warming to less than 2°C above pre-industrial levels;*
- *reducing indoor and outdoor air pollution from fuel combustion and its impacts on human health; and*
- *reducing the adverse effects and ancillary risks associated with some energy systems and to increase prosperity.*

Major transformations in energy systems are required to meet these challenges and to increase prosperity.

The Global Energy Assessment (GEA) assessed a broad range of resources, technologies and policy options and identified a number of 'pathways' through which energy systems could be transformed to simultaneously address all of the above challenges

These are the Key Findings:

1. Energy Systems can be Transformed to Support a Sustainable Future: the GEA analysis demonstrates that a sustainable future requires a transformation from today's energy systems to those with: *(i)* radical improvements in energy efficiency, especially in end use, and *(ii)* greater shares of renewable energies and advanced energy systems with carbon capture and storage (CCS) for both fossil fuels and biomass. The analysis ascertained that there are many ways to transform energy systems and many energy portfolio options. Large, early, and sustained investments, combined with supporting policies, are needed to implement and finance change. Many of the investment resources can be found through forward-thinking domestic and local policies and institutional mechanisms that can also support their effective delivery. Some investments are already being made in these options, and should be strengthened and widely applied through new and innovative mechanisms to create a major energy system transformation by 2050.

2. An Effective Transformation Requires Immediate Action: Long infrastructure lifetimes mean that it takes decades to change energy systems; so immediate action is needed to avoid lock-in of invested capital into existing energy systems and associated infrastructure that is not compatible with sustainability goals. For example, by 2050 almost three-quarters of the world population is projected to live in cities. The provision of services and livelihood opportunities to growing urban populations in the years to come presents a major opportunity for transforming energy systems and avoiding lock-in to energy supply and demand patterns that are counterproductive to sustainability goals.

3. Energy Efficiency is an Immediate and Effective Option: Efficiency improvement is proving to be the most cost-effective, near-term option with multiple benefits, such as reducing adverse environmental and health impacts, alleviating poverty, enhancing energy security and flexibility in selecting energy supply options, and creating employment and economic opportunities. Research shows that required improvements in energy efficiency particularly in end-use can be achieved quickly. For example:

- retrofitting buildings can reduce heating and cooling energy requirements by 50–90%;
- new buildings can be designed and built to very high energy performance levels, often using close to zero energy for heating and cooling;
- electrically-powered transportation reduces final energy use by more than a factor of three, as compared to gasoline-powered vehicles;
- a greater integration between spatial planning and travel that emphasizes shorter destinations and enhances opportunities for flexible and diverse choices of travel consolidating a system of collective, motorized, and non-motorized travel options offer major opportunities;
- through a combination of increased energy efficiency and increased use of renewable energy in the industry supply mix, it is possible to produce the increased industrial output needed in 2030 (95% increase over 2005) while maintaining the 2005 level of GHG emissions.

A portfolio of strong, carefully targeted policies is needed to promote energy efficient technologies and address, *inter alia*, direct and indirect costs, benefits, and any rebound effects.

4. Renewable Energies are Abundant, Widely Available, and Increasingly Cost-effective: The share of renewable energy in global primary energy could increase from the current 17% to between 30% to 75%, and in some regions exceed 90%, by 2050. If carefully developed, renewable energies can provide many benefits, including job creation, increased energy security, improved human health, environmental protection, and mitigation of climate change. The major challenges, both technological and economic, are:

- reducing costs through learning and scale-up;
- creating a flexible investment environment that provides the basis for scale-up and diffusion;
- integrating renewable energies into the energy system;
- enhancing research and development to ensure technological advances; and
- assuring the sustainability of the proposed renewable technologies.

While there remain sound economic and technical reasons for more centralized energy supplies, renewable energy technologies are also well-suited for off-grid, distributed energy supplies.

5. Major Changes in Fossil Energy Systems are Essential and Feasible: Transformation toward decarbonized and clean energy systems requires fundamental changes in fossil fuel use, which dominates the current energy landscape. This is feasible with known technologies.

- CO_2 capture and storage (CCS), which is beginning to be used, is key. Expanding CCS will require reducing its costs, supporting scale-up, assuring carbon storage integrity and environmental compatibility, and securing approval of storage sites.

- Growing roles for natural gas, the least carbon-intensive and cleanest fossil fuel, are feasible, including for shale gas, if related environmental issues are properly addressed.

- Co-processing of biomass and coal or natural gas with CCS, using known technologies, is important for co-producing electricity and low-carbon liquid fuels for transportation and for clean cooking. Adding CCS to such coproduction plants is less costly than for plants that make only electricity.

Strong policies, including effective pricing of greenhouse gas emissions, will be needed to fundamentally change the fossil energy system.

6. Universal Access to Modern Energy Carriers and Cleaner Cooking by 2030 is Possible: Universal access to electricity and cleaner cooking fuels and stoves can be achieved by 2030; however, this will require innovative institutions, national and local enabling mechanisms, and targeted policies, including appropriate subsidies and financing. The necessary technologies are available, but resources need to be directed to meet these goals. Universal access is necessary to alleviate poverty, enhance economic prosperity, promote social development, and improve human health and well-being. Enhancing access among poor people, especially poor women, is thus important for increasing their standard of living. Universal access to clean cooking technologies will substantially improve health, prevent millions of premature deaths, and lower household and ambient air pollution levels, as well as the emissions of climate-altering substances.

7. An Integrated Energy System Strategy is Essential: An integrated approach to energy system design for sustainable development is needed – one in which energy policies are coordinated with policies in sectors such as industry, buildings, urbanization, transport, food, health, environment, climate, security, and others, to make them mutually supportive. The use of appropriate policy instruments and institutions can help foster a rapid diffusion and scale-up of advanced technologies in all sectors to simultaneously meet the multiple societal challenges related to energy. The single most important area of action is efficiency improvement in all sectors. This enhances supply side flexibility, allowing the GEA challenges to be met without the need for technologies such as CCS and nuclear.

8. Energy Options for a Sustainable Future bring Substantial Multiple Benefits for Society: Combinations of resources, technologies, and polices that can simultaneously meet global sustainability goals also generate substantial and tangible near-term local and national economic, environmental, and social development benefits. These include, but are not limited to, improved local health and environment conditions, increased employment options, strengthened local economies through new business opportunities, productivity gains, improved social welfare and decreased poverty, more resilient infrastructure, and improved energy security. Synergistic strategies that focus on local and national benefits are more likely to be implemented than measures that are global and long-term in nature. Such an approach emphasizes the local benefits of improved end-use efficiency and increased use of renewable energy, and also helps manage energy-related global challenges. These benefits make the required energy transformations attractive from multiple policy perspectives and at multiple levels of governance.

9. Socio-Cultural Changes as well as Stable Rules and Regulations will be Required: Crucial issues in achieving transformational change toward sustainable future include non-technology drivers such as individual and public awareness, community and societal capacities to adapt to changes, institutions, policies, incentives, strategic spatial planning, social norms, rules and regulations of the marketplace, behavior of market actors, and societies' ability to introduce through the political and institutional systems measures to reflect externalities. Changes in cultures, lifestyles, and values are also required. Effective strategies will need to be adopted and integrated into the fabric of national socio-cultural, political, developmental, and other contextual factors, including recognizing and providing support for the opportunities and needs of all nations and societies.

10. Policy, Regulations, and Stable Investment Regimes will be Essential: A portfolio of policies to enable rapid transformation of energy systems must provide the effective incentive structures and strong signals for the deployment at scale of energy-efficient technologies and energy supply options that contribute to the overall sustainable development. The GEA pathways indicate that global investments in combined energy efficiency and supply will need to increase to between US$1.7–2.2 trillion per year compared to present levels of about US$1.3 trillion per year (about 2% of current world gross domestic product) including end-use components. Policies should encourage integrated approaches across various sectors and promote the development of skills and institutional capacities to improve the investment climate. Examples include applying market-oriented regulations such as vehicle emissions standards and low carbon fuel standards and as well as renewable portfolio standards to accelerate the market penetration of clean energy technologies and fules. Reallocating energy subsidies, especially the large subsidies provided in industrialized countries to fossil fuels without CCS, and nuclear energy, and pricing or regulating GHG emissions and/or GHG-emitting technologies and fules can help support the initial deployment of new energy systems, both end-use and supply, and help make infrastructures energy efficient. Publicly financed research and development needs to accelerate and be reoriented toward energy efficiency, renewable energy and CCS. Current research and development efforts in these areas are grossly inadequate compared with the future potentials and needs.

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The full GEA report is available for download in electronic form at www.globalenergyassessment.org. The website includes an interactive scenario database that documents the GEA pathways.

2 Summaries

SPM

Summary for Policymakers

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Introduction

Energy is essential for human development and energy systems are a crucial entry point for addressing the most pressing global challenges of the 21st century, including sustainable economic and social development, poverty eradication, adequate food production and food security, health for all, climate protection, conservation of ecosystems, peace and security. Yet, more than a decade into the 21st century, current energy systems do not meet these challenges.

A major transformation is therefore required to address these challenges and to avoid potentially catastrophic future consequences for human and planetary systems. The Global Energy Assessment (GEA) demonstrates that energy system change is the key for addressing and resolving these challenges. The GEA identifies strategies that could help resolve the multiple challenges simultaneously and bring multiple benefits. Their successful implementation requires determined, sustained and immediate action.

Transformative change in the energy system may not be internally generated; due to institutional inertia, incumbency and lack of capacity and agility of existing organizations to respond effectively to changing conditions. In such situations clear and consistent external policy signals may be required to initiate and sustain the transformative change needed to meet the sustainability challenges of the 21st century.

The industrial revolution catapulted humanity onto an explosive development path, whereby, reliance on muscle power and traditional biomass was replaced mostly by fossil fuels. In 2005, some 78% of global energy was based on fossil energy sources that provided abundant and ever cheaper energy services to more than half the people in the world. Figure SPM-1 shows this explosive growth of global primary energy with two clear development phases, the first

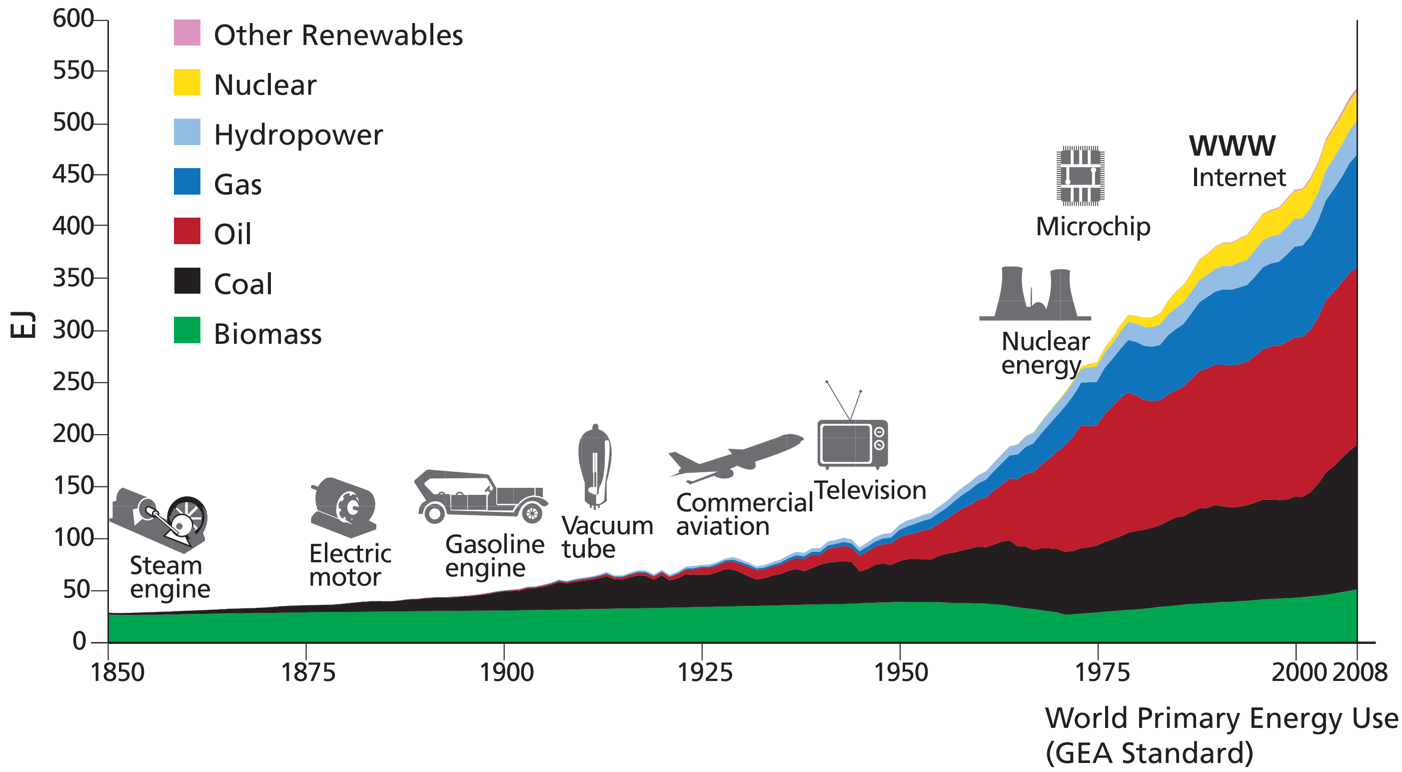

Figure SPM-1. | Evolution of primary energy shown as absolute contributions by different energy sources (EJ). Biomass refers to traditional biomass until the most recent decades, when modern biomass became more prevalent and now accounts for one-quarter of biomass energy. New renewables are discernible in the last few decades. Source: updated from Nakicenovic et al., 1998 and Grubler, 2008, see Chapter 1.[1]

1 **Nakicenovic, N., A. Grubler and A. McDonald (eds.), 1998:** *Global Energy Perspectives*. International Institute for Applied Systems Analysis (IIASA) and World Energy Council (WEC), Cambridge University Press, Cambridge, UK.

Grubler, A., 2008: Energy transitions. In *Encyclopedia of Earth. C. J. Cleveland (ed.), Environmental Information Coalition, National Council* for Science and the Environment, Washington, DC.

characterized by a shift from reliance on traditional energy sources to coal and subsequently to oil and gas. Hydropower, biomass and nuclear energy during the past decades have a combined share of almost 22%. New renewables such as solar and wind are hardly discernible in the figure.

Despite this rapid increase in overall energy use, over three billion people still rely on solid fuels such as traditional biomass, waste, charcoal and coal for household cooking and heating. The resulting air pollution leads to over two million premature deaths per year, mostly of women and children. Furthermore, approximately 20% of the global population has no access to electricity. Addressing these challenges is essential for averting a future with high economic and social costs and adverse environmental impacts on all scales.

An energy system transformation is required to meet these challenges and bring prosperity and well-being to the 9 billion people expected by 2050. The encouraging news is that a beginning of such a transformation can be seen today in the rapidly growing investments in renewable energy sources, high-efficiency technologies, new infrastructures, near zero-energy buildings, electric mobility, 'smart' energy systems, advanced biomass stoves, and many other innovations. The policy challenge is to accelerate, amplify and help make the implementation of these changes possible, widespread and affordable. Initial experience suggests that many of these changes are affordable, although they may be capital intensive and require high upfront investments. However, in general they have lower long-term costs that offset many of the up-front added investment requirements. Many of these innovations also lead to benefits in other areas such as equity and poverty, economic development, energy security, improved health, climate change mitigation, and ecosystem protection.

This Summary for Policymakers expands on the GEA approach and the Key Findings. The Technical Summary provides further support for the key findings.

Goals Used in the Assessment and in the GEA Pathways Analysis

For many of the energy related challenges, different goals have been articulated by the global community, including, in many instances specific quantitative targets. Meeting these goals simultaneously has served as the generic framework for all assessments in the GEA. The GEA pathways illustrate how societies can reach global normative goals of welfare, security, health, and environmental protection outlined below simultaneously with feasible changes in energy systems.

The selection of indicators and the quantitative target levels summarized here is a normative exercise, and the level of ambition has, to the extent possible, been guided by agreements and aspirations expressed through, for example, the United Nations system's actions, resolutions, and from the scientific literature. This, of course, only refers to the necessary changes of the local and global energy systems; much more is required in other sectors of societies for overall sustainability to be realized.

In the GEA pathways analysis, global per capita gross domestic product (GDP) increases by 2% a year on average through 2050, mostly driven by growth in developing countries. This growth rate falls in the middle of existing projections. Global population size is projected to plateau at about 9 billion people by 2050. Energy systems must be able to ***deliver the required energy services*** to support these economic and demographic developments.

To avoid additional complexity, the GEA pathways assume one intermediate population growth pathway that is associated with uncertainty. Given that population growth has significant implications for future energy demand, however, it should be remembered that policies to provide more of the world's men and women the means to make responsible parental decisions (including safe contraception technologies) can significantly reduce the growth in population over the century as well as energy demand and CO_2 emissions. By increasing birth spacing, they would also bring benefits for maternal and child health.

Access to affordable modern energy carriers and end-use conversion devices to improve living conditions and enhancing opportunities for economic development for the 1.4 billion people without access to electricity and the 3 billion who still rely on solid and fossil fuels for cooking is a prerequisite for poverty alleviation and socioeconomic development.

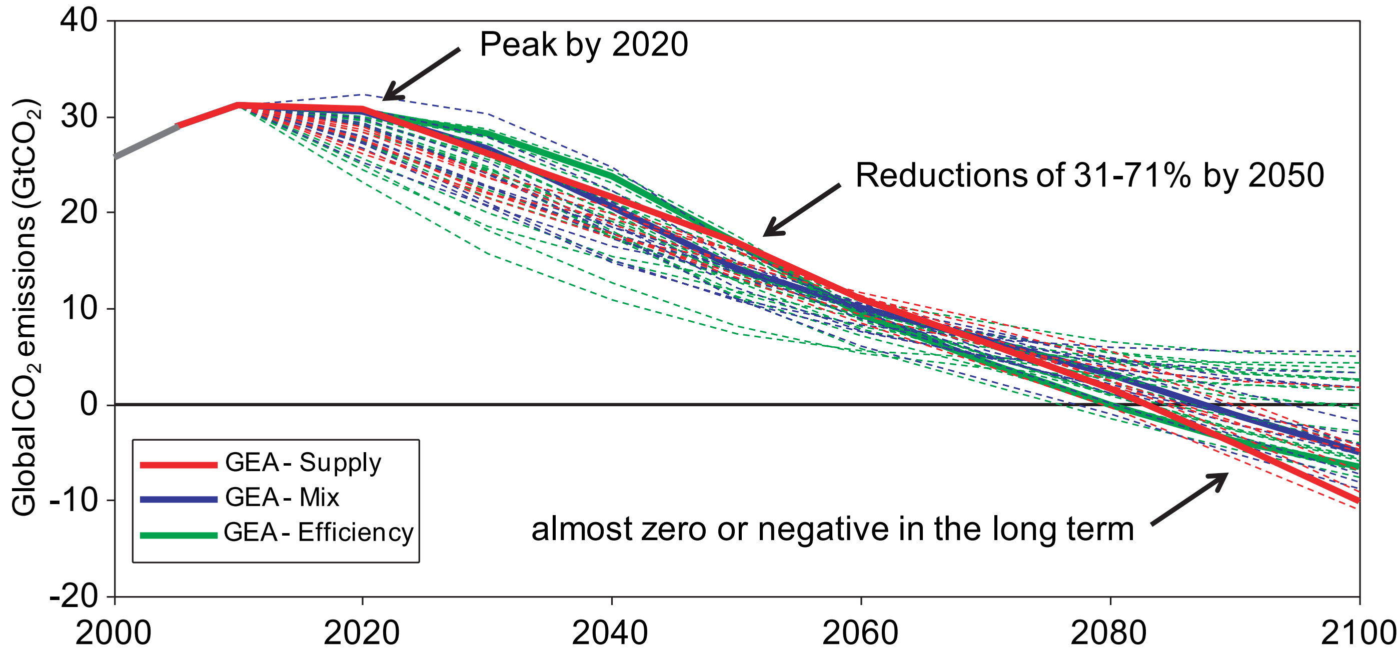

Figure SPM-2. | Development of global CO_2 emissions from energy and industrial sources to limit temperature change to below 2°C (with a success probability of >50%). Shown is that the emissions need to peak by around 2020 (or earlier) and decline toward zero during the following four to five decades. The later the peak occurs, the steeper the decline needs to be and higher the net "negative" emissions. The latter can be achieved through in the energy system through carbon dioxide capture and storage in conjunction with the use of sustainable biomass. Source: Chapter 17. For further details of the GEA pathways see the interactive web-based GEA scenario database hosted by IIASA: www.iiasa.ac.at/web-apps/ene/geadb.

Enhanced energy security for nations and regions is another key element of a sustainable future. Reduced global interdependence via reduced import/export balances, and increased diversity and resilience of energy supply have been adopted as key energy-related metrics. The targets for these goals were assessed ex-post through the GEA pathways analysis (Chapter 17), identifying the need for energy efficiency improvements and deployment of renewables to increase the share of domestic (national or regional) supply in primary energy by a factor of two and thus significantly decrease import dependency (by 2050). At the same time, the share of oil in global energy trade is reduced from the present 75% to below 40% and no other fuel assumes a similarly dominant position in the future.

The ***climate change mitigation*** goal is to contain the global mean temperature increase to less than 2°C above the preindustrial level, with a success probability of at least 50%. This implies global CO_2 emissions reductions from energy and industry to 30–70% of 2000 levels by 2050, and approaching almost zero or net negative emissions in the second half of the century (Figure SPM-2).

Health goals relating to energy systems include controlling household and ambient air pollution. Emissions reductions through the use of advanced fuels and end-use technologies (such as low-emissions biomass cookstoves) for household cooking and heating can significantly reduce human morbidity and mortality due to exposure to household air pollution, as well as help reduce ambient pollution. In the GEA pathways, this is assumed to occur for the vast majority of the world's households by 2030. Similarly, a majority of the world's population is also expected to meet the World Health Organization's (WHO) air quality guidelines (annual PM2.5 concentration < 10 $\mu g/m^3$ by 2030), while remaining populations are expected to stay well within the WHO Tier I-III levels (15–35 $\mu g/m^3$ by 2030). In addition, there needs to be a major expansion of occupational health legislation and enforcement in the energy sector.

Linkages between the energy system and the **environment** are at multiple levels and scales – from local to global. While the local environmental and ecological consequences of resource extraction, processing and energy conversion have been long recognized, attention is increasingly turning towards the growing evidence that humanity has reached a phase when anthropogenic pressures on Earth systems – the climate, oceans, fresh water, and the biosphere – risk irreversible disruption to biophysical processes on the planetary scale. The risk is that systems on Earth may then

Table SPM-1. | Global Burden of Disease, 2000 from Air Pollution and other Energy-related causes. These come from the Comparative Risk Assessment (CRA) published in 2004 by the World Health Organization (WHO). Estimates for 2005 in GEA for outdoor air pollution and household solid fuel use in Chapter 17 are substantially larger, but were not done for all risk pathways shown. Estimates for 2010 in the new CRA by WHO will be released in 2012 and will again include all pathways in a consistent framework.

	Total Premature Deaths – million	Percent of all Deaths	Percent of Global Burden in DALYs	Trend
Direct Effects [except where noted, 100% assigned to energy]				
Household Solid Fuel	1.6	2.9	2.6	Stable
Energy Systems Occupational*	0.2	0.4	0.5	Uncertain
Outdoor Air Pollution	0.8	1.4	0.8	Stable
Climate Change	0.15	0.3	0.4	Rising
Subtotal	2.8	5.0	4.3	
Indirect Effects (100% of each)				
Lead in Vehicle Fuel	0.19	0.3	0.7	Falling
Road Traffic Accidents	0.8	1.4	1.4	Rising
Physical Inactivity	1.9	3.4	1.3	Rising
Subtotal	2.9	5.1	3.4	
Total	5.7	10.1	7.7	

* One-third of global total assigned to energy systems.

Notes: These are not 100% of the totals for each, but represent the difference between what exists now and what might be achieved with feasible policy measures. Thus, for example, they do not assume the infeasible reduction to zero traffic accidents or air pollution levels.

Source: Chapter 4.

reach tipping points, resulting in non-linear, abrupt, and potentially irreversible change, such as destabilization of the Greenland ice sheet or tropical rainforest systems.

There are also a number of other concerns related to how energy systems are designed and operated. For example, activities need to be occupationally safe, a continuing concern as nano- and other new materials are used in energy systems. Other impacts such as oil spills, freshwater contamination and overuse, and releases of radioactive substances must be prevented (ideally) or contained. Waste products must be deposited in acceptable ways to avoid health and environmental impacts. These issues mostly influence local areas, and the regulations and their implementation are typically determined at the national level.

The world is undergoing severe and rapid change involving significant challenges. Although this situation poses a threat, it also offers a unique opportunity – a window of time in which to create a new, more sustainable, more equitable world, provided that the challenges can be addressed promptly and adequately. Energy is a pivotal area for actions to help address the challenges.

The interrelated world brought about by growth and globalization has increased the linkages among the major challenges of the 21st century. We do not have the luxury of being able to rank them in order of priority. As they are closely linked and interdependent, the task of addressing them simultaneously is imperative.

Energy offers a useful entry point into many of the challenges because of its immediate and direct connections with major social, economic, security and development goals of the day. Among many other challenges, energy systems are tightly linked to global economic activities, to freshwater and land resources for energy generation and food production, to biodiversity and air quality through emissions of particulate matter and precursors of tropospheric ozone, and to climate change. Most of all, access to affordable and cleaner energy carriers is a fundamental prerequisite for development, which is why the GEA places great emphasis on the need to integrate energy policy with social, economic, security, development, and environment policies.

Reaching the GEA goals simultaneously requires transformational changes to the energy system, in order to span a broad range of opportunities across urban to rural geographies, from developing to industrial countries, and in transboundary systems. The ingredients of this change are described in the following section.

Key Findings

The Global Energy Assessment (GEA) explored options to transform energy systems that simultaneously address all of the challenges above. A broad range of resources and technologies were assessed, as well as policy options that can be combined to create pathways[2] to energy for a sustainable future. These are the Key Findings:

1. Energy Systems can be Transformed to Support a Sustainable Future: *the GEA analysis demonstrates that a sustainable future requires a transformation from today's energy systems to those with: (i) radical improvements in energy efficiency, especially in end use, and (ii) greater shares of renewable energies and advanced energy systems with carbon capture and storage (CCS) for both fossil fuels and biomass. The analysis ascertained that there are many ways to transform energy systems and many energy portfolio options. Large, early, and sustained investments, combined with supporting policies, are needed to implement and finance change. Many of the investment resources can be found through forward-thinking domestic and local policies and institutional mechanisms that can also support their effective delivery. Some investments are already being made in these options, and should be strengthened and widely applied through new and innovative mechanisms to create a major energy system transformation by 2050.*

Humanity has the capacity, ingenuity, technologies and resources to create a better world. However, the lack of appropriate institutions, coordination mandates, political will and governance structures make the task difficult. Current decision making processes typically aim for short-term, quick results, which may lead to sub-optimal long-term outcomes. The GEA endeavors to make a compelling case for the adoption of a new set of approaches and policies that are essential, urgently required, and achievable.

The GEA highlights essential technology-related requirements for radical energy transformation:

- significantly larger investment in energy efficiency improvements especially end-use across all sectors, with a focus on new investments as well as major retrofits;
- rapid escalation of investments in renewable energies: hydropower, wind, solar energy, modern bioenergy, and geothermal, as well as the smart grids that enable more effective utilization of renewable energies;
- reaching universal access to modern forms of energy and cleaner cooking through micro-financing and subsidies;
- use of fossil fuels and bioenergy at the same facilities for the efficient co-production of multiple energy carriers and chemicals with full-scale deployment of carbon capture and storage; and
- on one extreme nuclear energy could make a significant contribution to global electricity generation, but on the other extreme, it could be phased out.

To meet humanity's need for energy services, comprehensive diffusion of energy and an increased contribution of energy efficiencies are required throughout the energy system – from energy collection and conversion to end use. Rapid diffusion of renewable energy technologies is the second but equally effective option for reaching multiple objectives. Conversion of primary energy to energy carriers such as electricity, hydrogen, liquid fuels and heat along with smart transmission and distribution systems are necessary elements of an energy system meeting sustainability objectives.

2 The GEA developed a range of alternative transformational pathways to explore how to achieve all global energy challenges simultaneously. The results of the GEA pathways are documented in detail at the interactive web-based GEA scenario database hosted by IIASA: www.iiasa.ac.at/web-apps/ene/geadb.

The GEA makes the case that energy system transformation requires an iterative and dynamic transformation of the policy and regulatory landscape, thereby fostering a buildup of skills and institutions that encourage innovation to thrive, create conditions for business to invest, and generate new jobs and livelihood opportunities.

A major finding of the GEA is that some energy options provide multiple benefits. This is particularly true of energy efficiency, renewables, and the coproduction of synthetic transportation fuels, cooking fuels, and electricity with co-gasification of coal and biomass with CCS, which offer advantages in terms of supporting all of the goals related to economic growth, jobs, energy security, local and regional environmental benefits, health, and climate change mitigation. All these advantages imply the creation of value in terms of sustainability. This value should be incorporated into the evaluation of these and other measures and in creating incentives for their use.

One implication of this is that nations and corporations can invest in efficiency and renewable energy for the reasons that are important to them, not just because of a global concern about, for example, climate change mitigation or energy security. But incentives for individual actors to invest in options with large societal values must be strong and effective.

The GEA explored 60 possible transformation pathways and found that 41 of them satisfy all the GEA goals simultaneously for the same level of economic development and demographic changes, including three groups of illustrative pathways that represent alternative evolutions of the energy system toward sustainable futures.[3] The pathways imply radically changed ways in which humanity uses energy, ranging from much more energy-efficient houses, mobility, products, and industrial processes to a different mix of energy supply – with a much larger proportion of renewable energy and fossil advanced fossil fuel technologies (see Figure SPM-3).

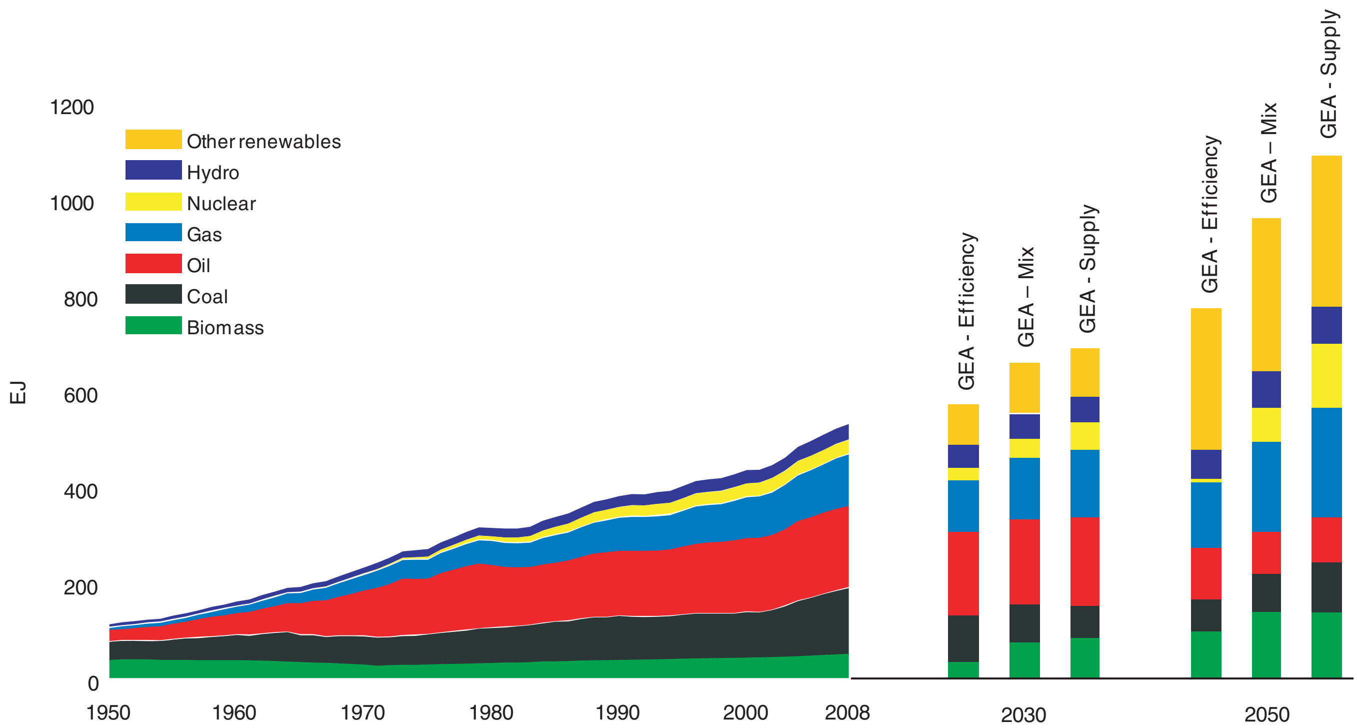

Figure SPM-3. | Development of primary energy to 2008 and in the three illustrative GEA pathways for the years 2030 and 2050. Source: based on Figures TS-24 and 17.13, Chapter 17. For further details of the GEA pathways see the interactive web-based GEA scenario database hosted by IIASA: www.iiasa.ac.at/web-apps/ene/geadb.

3 The pathways encompass eleven world regions, grouped into five GEA regions and energy sectors, including supply and demand, with a full range of associated social, economic, environmental and technological developments.

On the demand side, the three groups of GEA pathways pursue the energy efficiency options to a varying extent. On the supply side, the GEA pathways highlight the broad portfolio of technologies that will be needed to achieve the energy system transformation. Particularly important options are low-carbon energy from renewables, bioenergy, nuclear power, and CCS. In aggregate, at least a 60–80% share of global primary energy will need to come from zero-carbon options by 2050; the electricity sector in particular will need to be almost completely decarbonized by mid-century (low-carbon shares of 75–100%). Getting to that point requires major progress in several critical areas:

- Renewables: Strong renewable energy growth beginning immediately and reaching a global share of 30–75% of primary energy by 2050, with some regions experiencing in the high case almost a complete shift towards renewables by that time;

- Coal: A complete phase-out of coal power without CCS by 2050;

- Natural Gas: Natural gas acting as a bridging or transitional technology in the short to medium term and providing 'virtual' storage for intermittent renewables;

- Energy Storage: Rising requirement for storage technologies and 'virtual' systems (e.g., smart grids and demand-side management) to support system integration of intermittent wind and solar;

- Bioenergy: Strong bioenergy growth in the medium term from 45 EJ in 2005 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, and the co-processing of biomass with coal or natural gas with CCS to make low net GHG-emitting transportation fuels and or electricity;

- Nuclear: Nuclear energy as a choice, not a requirement. The GEA pathways illustrate that it is possible to meet all GEA goals even in the case of a nuclear phase-out. Nuclear energy can play an important role in the supply-side portfolio of some transition pathways; however, its prospects are particularly uncertain because of unresolved challenges surrounding its further deployment, as illustrated by the Fukushima accident and unresolved weapons proliferation risks;

- Carbon Capture and Storage: Fossil CCS as an optional bridging or transitional technology in the medium term unless there is high energy demand, in which case CCS may be essential. CCS technology offers one potentially relatively low-cost pathway to low carbon energy. CCS in conjunction with sustainable biomass is deployed in many pathways to achieve negative emissions and thus help achieve climate stabilization.

New policies would be needed to attract capital flows to predominantly upfront investments with low long-term costs but also low short-term rates of return.

The pathways indicate that the energy transformations need to be initiated without delay, gain momentum rapidly, and be sustained for decades. They will not occur on their own. They require the rapid introduction of policies and fundamental governance changes toward integrating global concerns, such as climate change, into local and national policy priorities, with an emphasis on energy options that contribute to addressing all these concerns simultaneously.

In sum, the GEA finds that there are possible combinations of energy resources and technologies that would enable societies to reach all the GEA goals simultaneously, provided that government interventions accommodate sufficiently strong incentives for rapid investments in energy end-use and supply technologies and systems.

2. An Effective Transformation Requires Immediate Action: *Long infrastructure lifetimes mean that it takes decades to change energy systems; so immediate action is needed to avoid lock-in of invested capital into energy systems and associated infrastructure that is not compatible with sustainability goals. For example, by 2050 almost three-quarters of the world population is projected to live in cities. The provision of services and livelihood opportunities to growing urban populations in the years to come presents a major opportunity for transforming energy systems and avoiding lock-in to energy supply and demand patterns that are counterproductive to sustainability goals.*

Given the longevity of the capital stock of energy systems and of the built environment, rates of change are slow and possible irreversibilities or 'lock-in' effects can have powerful long-lasting effects. Long-term transformations need to be initiated earlier rather than later. Therefore the time for action is *now.* Changes in current policies that are particularly critical in triggering longer-term transformations are technology, and urbanization.

Reflecting economic, social and environmental externalities in the market conditions is therefore a necessary first step to provide appropriate incentives for redirecting private sector investments. Such measures would include removal, or at least substantial reduction, of subsidies to fossil fuels without CCS and nuclear energy, stimulation of development and market entry of new renewable options, and emphasis on energy efficiency in all end-use sectors. According to the GEA pathway analysis, global energy systems investments need to increase to some US$1.7–2.2 trillion annually to 2050, with about US$300–550 billion of that being required for demand-side efficiency. This compares to about US$1 trillion supply-side investments and about $300 billion demand-side investments in energy components per year today. These investments correspond to about 2% of the world gross domestic product in 2005, and would be about 2–3% by 2050, posing a major financing challenge. New policies would be needed to attract such capital flows to predominantly upfront investments with low long-term costs but also low short-term rates of return.

Today about 3.5 billion people, about half the world population live in urban environments. Projections suggest that by 2050 an additional three billion people need to be integrated into the urban fabric. Housing, infrastructure, energy and transport services, and a better urban environment (especially urban air quality) are the key sustainability challenges for urban development.

Urban energy and sustainability policies can harness local decision-making and funding sources to achieve the largest leverage effects in the following areas:

- urban form and density (which are important macro-determinants of urban structures, activity patterns, and hence energy use, particularly for urban transport);
- the quality of the built environment (energy-efficient buildings in particular);
- urban transport policy (in particular the promotion of energy-efficient and 'eco-friendly' public transport and non-motorized mobility options); and
- improvements in urban energy systems through zero-energy building codes, cogeneration or waste-heat recycling schemes, where feasible.

There are important urban size and density thresholds that are useful guides for urban planning and policymaking. The literature review identified a robust density threshold of 50–150 inhabitants per hectare (5,000–15,000 people per square kilometer) below which urban energy use, particularly for transport, increases substantially and which should be avoided. There are also significant potential co-benefits between urban energy policies and environmental policies. However, they require more holistic policy approaches that integrate urban land use, transport, building, and energy policies with the more-traditional air pollution policy frameworks.

Policy coordination at an urban scale is as complex as potentially rewarding in sustainability terms. Institutional and policy learning needs to start early to trigger longer-term changes in urban form and infrastructures. A particular challenge is represented by small to medium sized cities (between 100,000 and 1 million inhabitants), as most urban growth is projected to occur in these centers, primarily in the developing world. In these smaller-scale cities, data and information to guide policy are largely absent, local resources to tackle development challenges are limited, and governance and institutional capacities are insufficient.

3. Energy Efficiency is an Immediate and Effective Option: *Efficiency improvement is proving to be the most cost-effective, near-term option with multiple benefits, such as reducing adverse environmental and health impacts, alleviating poverty, enhancing energy security and flexibility in selecting energy supply options, and creating employment* *and economic opportunities. Research shows that required improvements in energy efficiency particularly in end-use can be achieved quickly. For example:*

- *retrofitting buildings can reduce heating and cooling energy requirements by 50–90%;*
- *new buildings can be designed and built to very high energy performance levels, often using close to zero energy for heating and cooling;*
- *electrically-powered transportation reduces final energy use by more than a factor of three, as compared to gasoline-powered vehicles;*
- *a greater integration between spatial planning and travel that emphasizes shorter destinations and enhances opportunities for flexible and diverse choices of travel consolidating a system of collective, motorized, and non-motorized travel options offers major opportunities;*
- *through a combination of increased enegry efficiency and increased use of renewable energy in the industry supply mix, it is possible to produce the increased industrial output needed in 2030 (95% increase over 2005) while maintaining the 2005 level of GHG emissions.*

A portfolio of strong, carefully targeted policies is needed to promote energy efficient technologies and address, inter alia, direct and indirect costs, benefits, and any rebound effects.

Progress in accelerating the rate of energy efficiency improvement worldwide is critical to an energy system for sustainability. Quickly improving energy efficiency through new investments and retrofits requires focused and aggressive policies that support rapid innovation through more stringent regulations of energy efficiency, fiscal incentives for new technologies, and pricing GHG emissions. Combined with higher energy prices, a culture of conservation among consumers and firms, and an increase in urban density societies can realize a dramatic increase in energy efficiency.

A major challenge is to resolve the issue of split incentives, that is, the situation where those who would be paying for efficiency improvements and other energy investments are more oriented toward short-term rates of return than to the long-term profitability of the investments and, likewise, they are rarely the beneficiaries of reduced energy costs and other public benefits.

Regulations are essential elements of energy policy portfolios to drive an energy transition. Standards for building codes, heating and cooling, appliances, fuel economy, and industrial energy management are one of the most effective policy tools for improving energy efficiency and should be adopted globally. These regulatory policies are most effective when combined with fiscal incentives and attention-attracting measures such as information, awareness, and public leadership programs.

The GEA analysis provides considerable evidence of the ability of such policy packages to deliver major change. However, the results from three decades of experiences with energy efficiency policies in industrial countries also show other effects.

These cost factors and rebound effects mean that subsidies to encourage acquisition of energy-efficient devices are unlikely, on their own, to cause the dramatic energy efficiency gains called for in the GEA analysis. For these gains to be realized, carefully targeted policies are needed. For example, strong efficiency regulations have proven effective. These are updated regularly and have incentives to reward manufacturers who push technology designs toward advanced efficiency by using electricity tariffs that reward efficiency investments and conservation.

In the buildings sector, new and existing technologies as well as non-technological opportunities represent a major opportunity for transformative change of energy use. Passive houses that reduce energy use for heating and cooling by 90% or more, for example, are already found in many countries. Increased investments in a more energy-efficient building shell are in part offset by lower or fully eliminated investments in heating/cooling systems, with energy costs for operation almost avoided, making these new options very attractive. Passive house performance is possible also

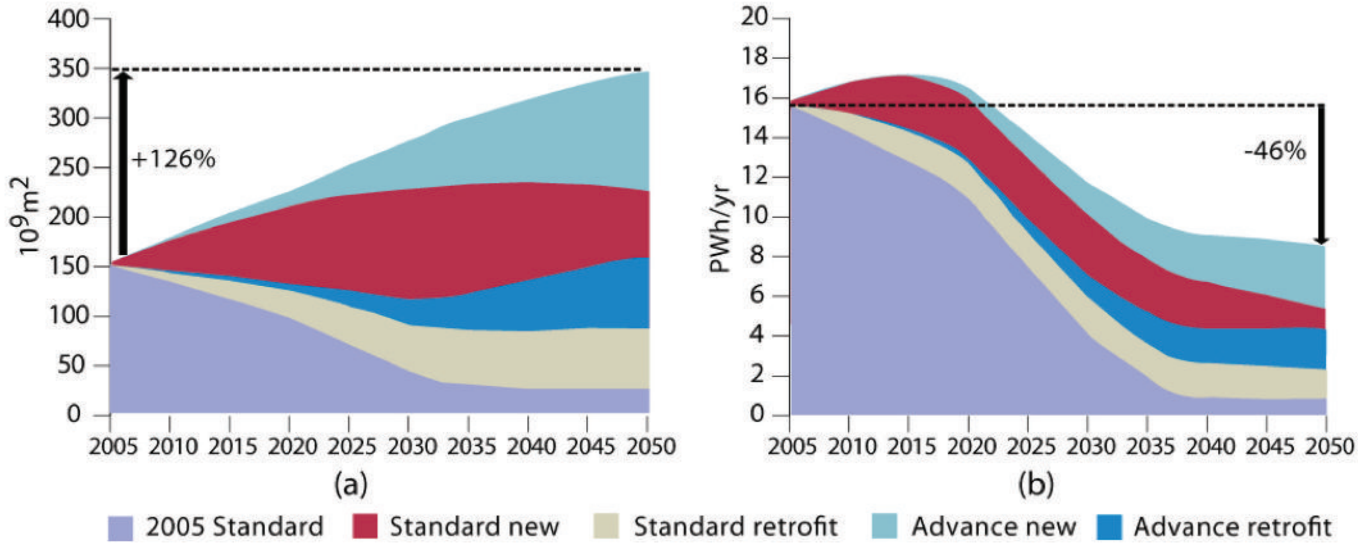

Figure SPM-4. | Global final thermal energy use in buildings (a) and global floor area (b) in the state-of-the-art scenario (corresponding approximately to the "GEA-Efficiency" group of pathways), 2005–2050. Source: Chapter 10.

Key: Explanations of efficiency categories: standard: today's stock; new: new buildings built to today's building code or anticipated new building codes (without additional policies); advance new: new buildings built to today's state-of-the-art performance levels; retrofit: assumes some efficiency gains, typically 35%; advanced retrofit: retrofit built to state-of-the-art levels.

for existing buildings, if it is included as a performance goal when major renovations are done. Energy Plus houses, delivering net energy to the grid over a year, have been constructed even in high latitudes. Building-integrated solar photovoltaics can contribute to meeting the electricity demand in buildings, especially in single-family homes, and solar water heaters can cover all or part of the heat required for hot water demand. However, requiring buildings to be zero-energy or net-energy suppliers may not be the lowest-cost or most sustainable approach in addressing the multiple GEA goals and typically may not be possible, depending on location.

Analysis carried out under the GEA pathway framework demonstrates that a reduction of global final energy use for heating and cooling of about 46% is possible by 2050 compared with 2005 through full use of today's best practices in design, construction, and building operation technology and know-how. This can be obtained even while increasing amenities and comfort and simultaneously accommodating an increase in global floor area of over 126% (Figure SPM-4).

There is, however, a significant risk of lock-in. If stringent building codes are not introduced universally and energy retrofits accelerate but are not subject to state-of-the-art efficiency levels, substantial energy use and corresponding GHG emissions can be 'locked-in' for many decades. This could lead to a 33% increase in global energy use for buildings by 2050 instead of a decrease of 46% (Figure SPM-5).

Wide adoption of the state-of-the-art in the buildings sector would not only contribute significantly to meeting the GEA's multiple goals, such developments would also deliver a wide spectrum of other benefits. A review of quantified multiple benefits showed that productivity gains through reduced incidence of infections from exposure to indoor air pollution score particularly high in industrial countries. Other benefits included increases in productivity, energy security, indoor air quality and health, social welfare, real estate values, and employment. The approximately US$57 trillion cumulative energy cost savings until 2050 in avoided heating and cooling energy costs alone substantially exceeds the estimated US$15 trillion investments that are needed to realize this pathway. The value of the additional benefits has also been shown to be substantial, often exceeding the energy cost savings. In several cases the multiple benefits are so significant, and coincide with other important policy agendas (such as improved energy security, employment, poverty alleviation, competitiveness), that they provide easier and more attractive entry points for local policymaking than climate change or other environmental agendas.

Influencing energy use in the transport sector involves affecting transport needs, infrastructure, and modes, as well as vehicle energy efficiency. Policies for urbanization will have a large impact on transport needs, infrastructure, and

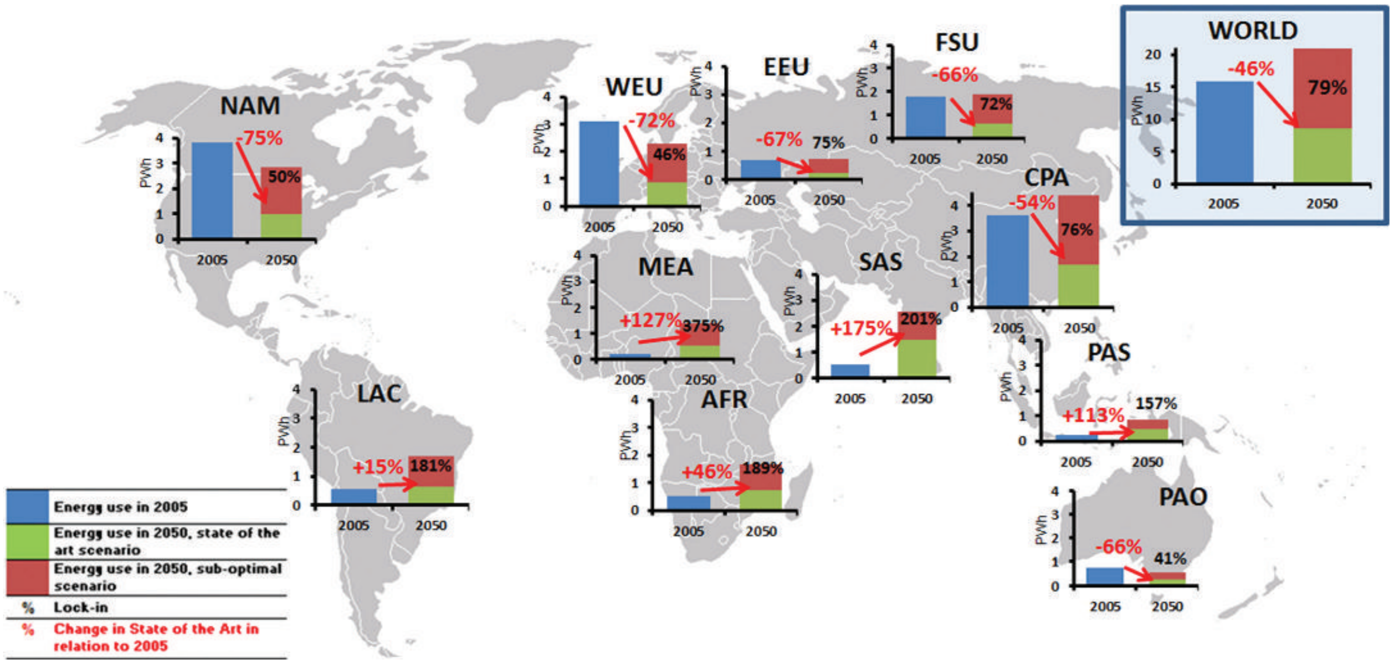

Figure SPM-5. | Final building heating and cooling energy demand scenarios until 2050: state-of-the-art (~corresponding roughly to the GEA-Efficiency set of pathways) and sub-optimal (~corresponding roughly to the GEA-Supply set of pathways scenarios, with the lock-in risk (difference). Note: Green bars, indicated by red arrows and numbers, represent the opportunities through the state-of-the-art scenario, while the red bars with black numbers show the size of the lock-in risk (difference between the two scenarios). Percent figures are relative to 2005 values. Source: Chapter 10.

the viability of different transport modes on the local scale. Both the decision to travel and the choice of how to travel affect fuel consumption. With a focus on urban road transport, a transition to sustainable transport can follow the framework known as 'avoid-shift-improve'. This considers three major principles under which diverse policy instruments are grouped, with interventions assuming different emphasis in industrial and developing countries. They need to focus on technological options, ('improve'), not only with respect to climate mitigation but also with respect to local environmental conditions and social concerns. The other two components – modal shift and avoiding travel influence the level of activity and structural components that link transport to carbon emissions.

A major transformation of transportation is possible over the next 30–40 years and will require improving vehicle designs, infrastructure, fuels and behavior. In the short term improving overall sector energy efficiency, introducing alternative low-carbon fuels and electricity, enhancing the diversification, quantity and quality of public modes of transport is necessary. Medium term goals require reducing travel distances within cities by implementing compact urban design that improves accessibility to jobs and services and facilitates use of non-motorized modes, and replacing and adopting vehicle and engine design (for trucks, airplanes, rail, and ships) following the best available technological opportunities for increasing efficiency and societal acceptability.

Transport policy goals for urbanization and equity include the adoption of measures for increasing accessibility and the affordable provision of urban mobility services and infrastructure that facilitates the widespread use of non-motorized options Cities can be planned to be more compact with less urban sprawl and a greater mix of land uses and strategic siting of local markets to improve logistics and reduces the distances that passengers and goods need to travel. Urban form and street design and layout can facilitate walking, cycling, and their integration within a network of public transport modes. Employers in many sectors can enhance the job-housing balance of employees through their decisions on where to be located and can provide incentives for replacing some non-essential journeys for work purposes with the use of information technologies and communication.

Modal share could move to modes that are less energy-intensive, both for passenger and freight transport. In cities, a combination of push and pull measures through traffic demand management can induce shifts from cars to public transit and cycling and can realize multiple social and health benefits. In particular, non-motorized transportation could be promoted everywhere as there is wide agreement about its benefits to transportation and people's health. Parking policies and extensive car pooling and car sharing, combined with information technology options can become key policies to reduce the use of cars. Efficient road capacity utilization, energy use and infrastructure costs for different modes could be considered when transport choices are made.

There are still many opportunities to improve conventional vehicle technologies. The combination of introducing incremental efficiency technologies, increasing the efficiency of converting the fuel energy to work by improving drive train efficiency, and recapturing energy losses and reducing loads (weight, rolling, air resistance, and accessory loads) on the vehicle has the potential to approximately double the fuel efficiency of 'new' light-duty vehicles from 7.5 liters per 100 km in 2010 to 3.0 liters per 100 km by 2050.

The emergence of electric drive technologies such as plug-in hybrid electric vehicles allows for zero tailpipe emissions for low driving ranges, up to around 50 kilometers in urban conditions. All-electric battery vehicles can achieve a very high efficiency (more than 90%, four times the efficiency of an internal combustion engine vehicle but excluding the generation and transmission of the electricity), but they have a low driving range and short battery life. If existing fuel saving and hybrid technologies are deployed on a broad scale, fleet-average specific fuel savings of a factor of two can be obtained in the next decade.

The aggregate energy intensity in the industrial sector in different countries has shown steady declines due to improvements in energy efficiency and a change in the structure of the industrial output. In the EU-27, for instance, the final energy use by industry has remained almost constant (13.4 EJ) at 1990 levels; 30% of the reduction in energy intensity is due to structural changes, with the remainder due to energy efficiency improvements.

In different industrial sectors, adopting the best achievable technology can result in savings of 10–30% below the current average. An analysis of cost-cutting measures in 2005 indicated energy savings potentials of 2.2 EJ for motors and 3.3 EJ for steam systems. The economic payback period for these measures ranges from less than nine months to four years. A systematic analysis of materials and energy flows indicates significant potential for process integration, heat pumps, and cogeneration.

Nevertheless, such a transformation has multiple benefits. Improved energy efficiency in industry results in significant energy productivity gains as a result, for example, in improved motor systems; compressed air systems; ventilation, heat recovery, and air conditioning systems; and improvements in comfort and the working environment through better lighting, thermal comfort, and reduced indoor air pollution from improved ventilation systems, and, in turn, improved productivity boosts corporate competitiveness.

4. Renewable Energies are Abundant, Widely Available, and Increasingly Cost-effective: *The share of renewable energy in global primary energy could increase from the current 17% to between 30% to 75%, and in some regions exceed 90%, by 2050. If carefully developed, renewable energies can provide many benefits, including job creation, increased energy security, improved human health, environmental protection, and mitigation of climate change. The major challenges, both technological and economic, are:*

- *reducing costs through learning and scale-up;*
- *creating a flexible investment environment that provides the basis for scale-up and diffusion;*
- *integrating renewable energies into the energy system;*
- *enhancing research and development to ensure technological advances; and*
- *assuring the sustainability of the proposed renewable technologies.*

While there remain sound economic and technical reasons for more centralized energy supplies, renewable energy technologies are also well-suited for off-grid, distributed energy supplies.

The GEA pathways show that renewable energies can exceed 90% of projected energy demand for specific regions. The GEA pathways analysis indicates that a significant increase in renewable energy supplies is technically feasible and necessary in order to meet the GEA goals.

Table SPM-2. | Renewable energy flows, potential, and utilization in EJ of energy inputs provided by nature.[a]

	Primary Energy 2005[b] [EJ]	Direct Input 2005 [EJ]	Technical potential [EJ/yr]	Annual flows [EJ/yr]
Biomass, MSW, etc.	46.3	46.3	160–270	2200
Geothermal	0.78	2.3	810–1545	1500
Hydro	30.1	11.7	50–60	200
Solar	0.39	0.5	62,000–280,000	3,900,000
Wind	1.1	1.3	1250–2250	110,000
Ocean	-	-	3240–10,500	1,000,000

[a] The data are direct energy-input data, not primary energy substitution equivalent shown in the first column. Considering technology-specific conversion factors greatly reduces the output potentials. For example, the technical 3150 EJ/yr of ocean energy in ocean thermal energy conversion (OTEC) would result in an electricity output of about 100 EJ/yr.

[b] Calculated using the GEA substitution method (see Chapter 1, Appendix 1.A.3).

Source: Chapter 7.

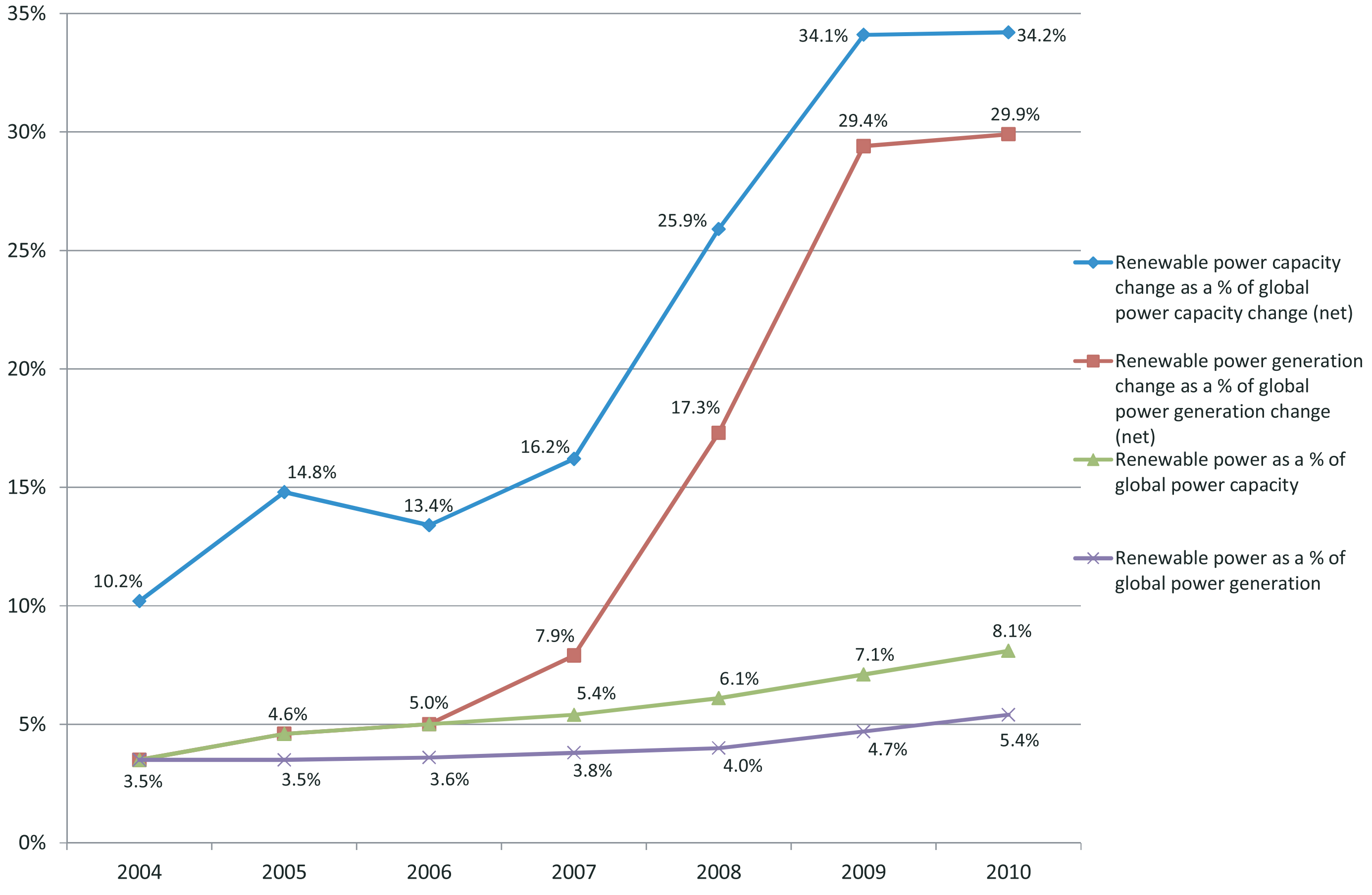

Figure SPM-6. | Renewable power capacity and generation (excluding large hydro) as a percentage of global capacity and generation, respectively, and their rates of change also in percent; 2004–2010. Source: UNEP and BNEF, 2011, see Chapter 11.[4]

The resource base is sufficient to provide full coverage of human energy demand at several times the present level and potentially more than 10 times this level (see Table SPM-2). Starting in 2007 renewable power generating capacity has grown fast in the world (see Figure SPM-6), and is now over 30% of total capacity expansion, excluding large scale hydropower. Figure SPM-7 shows a regional breakdown of the investments.

4 **UNEP and BNEF, 2011:** *Global Trends in Renewable Energy Investment 2011: Analysis of Trends and Issues in the Financing of Renewable Energy*. United Nations Environment Programme (UNEP), Nairobi, Kenya and Bloomberg New Energy Finance (BNEF), London, UK.

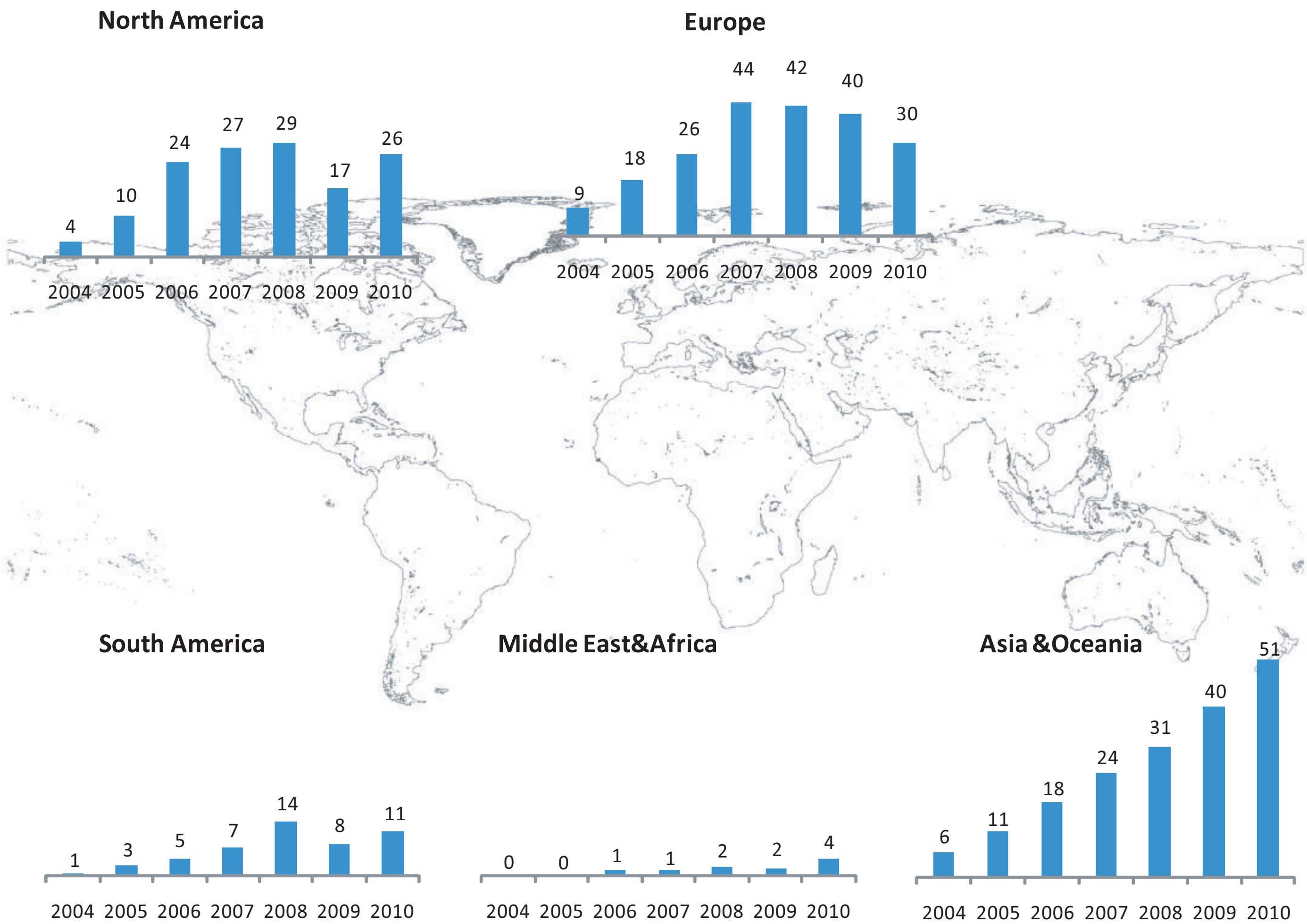

Figure SPM-7. | New financial investments in renewable energy, by region, 2004–2010 (US$$_{2005}$bn). New investment volume adjusts for reinvested equity; total values include estimates for undisclosed deals. This comparison does not include small-scale distributed energy projects or large-scale hydropower investments. Source: Chapter 11.

The rapid expansion in renewables, which has largely taken place in only a few countries, has usually been supported by incentives of different types or driven by quota requirements. Especially successful have been the feed-in tariffs used in the majority of EU countries, China, and elsewhere. Global investments in 2009 were slightly lower as a result of the financial crises (although with less reduction than for most other energy technologies), and in 2010 they rebounded. Both wind and solar PV electricity are nowadays cost-competitive in some markets and are projected to become so in many markets in the next 5–10 years without any public subsidy. However, renewables face resistance due to lock-in to conventional energies and substantial market barriers in the majority of markets.

The intermittent and variable generation of wind, solar and wave power must be handled within an electricity system that was not designed to accommodate it, and in which traditional base load-power from nuclear, geothermal and fossil power stations with restricted flexibility limit the system's ability to follow load variations. Energy systems have historically been designed to handle loads that vary over seconds, days, weeks, and years with high reliability. These systems are becoming increasingly able to accommodate increased quantities of variable generation through use of so-called smart systems with advanced sensing and control capabilities. With support from accurate and timely load forecasting, capacity management, and overall intelligent load and demand-side management, experience has shown that at least 20%, perhaps up to 50%, of variable renewable generation can be accommodated in most existing systems at low costs and that it is feasible to accommodate additional intermittent generation with additional investment in grid flexibility, low capital cost fuel-based generation, storage, and demand-side management (smart grids).

Safe and reliable improvements of interconnections between nations and across geographical regions will facilitate the compensation due to fluctuations in electricity generation from rapidly increasing shares of variable renewable energies in the system. Wind and solar PV and most hydrokinetic or ocean thermal technologies offer the unique additional attribute of virtually complete elimination of additional water requirements for power generation. Other renewable options, including bio-based options, geothermal, concentrating solar, and hydropower on a life-cycle basis, still require water for cooling of a steam turbine or are associated with large amounts of evaporation.

The development of high-voltage direct current (HVDC) transmission cables may allow the use of remote resources of wind and solar at costs projected to be affordable. Such cables have been installed for many years in sub-marine and on-shore locations, and demand is increasing (in the North Sea, for example). This is significant, as some of the best renewable energy resources are located far from load centers. In conjunction with energy storage at the generation location, such transmission cables can be used to provide base load electricity supply.

The GEA pathways analysis indicates that a significant increase in renewable energy supplies is technically feasible and necessary in order to meet the GEA objectives.

5. Major Changes in Fossil Energy Systems are Essential and Feasible: *Transformation toward decarbonized and clean energy systems requires fundamental changes in fossil fuel use, which dominates the current energy landscape. This is feasible with known technologies.*

- *CO_2 capture and storage (CCS), which is beginning to be used, is key. Expanding CCS will require reducing its costs, supporting scale-up, assuring carbon storage integrity and environmental compatibility, and securing approval of storage sites.*

- *Growing roles for natural gas, the least carbon-intensive and cleanest fossil fuel, are feasible, including for shale gas, if related environmental issues are properly addressed.*

- *Co-processing of biomass and coal or natural gas with CCS, using known technologies, is important for co-producing electricity and low-carbon liquid fuels for transportation and for clean cooking. Adding CCS to such coproduction plants is less costly than for plants that make only electricity.*

Strong policies, including effective pricing of greenhouse gas emissions, will be needed to fundamentally change the fossil energy system.

Table SPM-3. | Fossil and uranium reserves, resources, and occurrences.[a]

	Historical production through 2005 [EJ]	Production 2005 [EJ]	Reserves [EJ]	Resources [EJ]	Additional occurrences [EJ]
Conventional oil	6069	147.9	4900–7610	4170–6150	
Unconventional oil	513	20.2	3750–5600	11,280–14,800	> 40,000
Conventional gas	3087	89.8	5000–7100	7200–8900	
Unconventional gas	113	9.6	20,100–67,100	40,200–121,900	> 1,000,000
Coal	6712	123.8	17,300–21,000	291,000–435,000	
Conventional uranium[b]	1218	24.7	2400	7400	
Unconventional uranium	34	n.a.		7100	> 2,600,000

[a] The data reflect the ranges found in the literature; the distinction between reserves and resources is based on current (exploration and production) technology and market conditions. Resource data are not cumulative and do not include reserves.

[b] Reserves, resources, and occurrences of uranium are based on a once-through fuel cycle operation. Closed fuel cycles and breeding technology would increase the uranium resource dimension 50–60 fold. Thorium-based fuel cycles would enlarge the fissile-resource base further.

Source: Chapter 7.

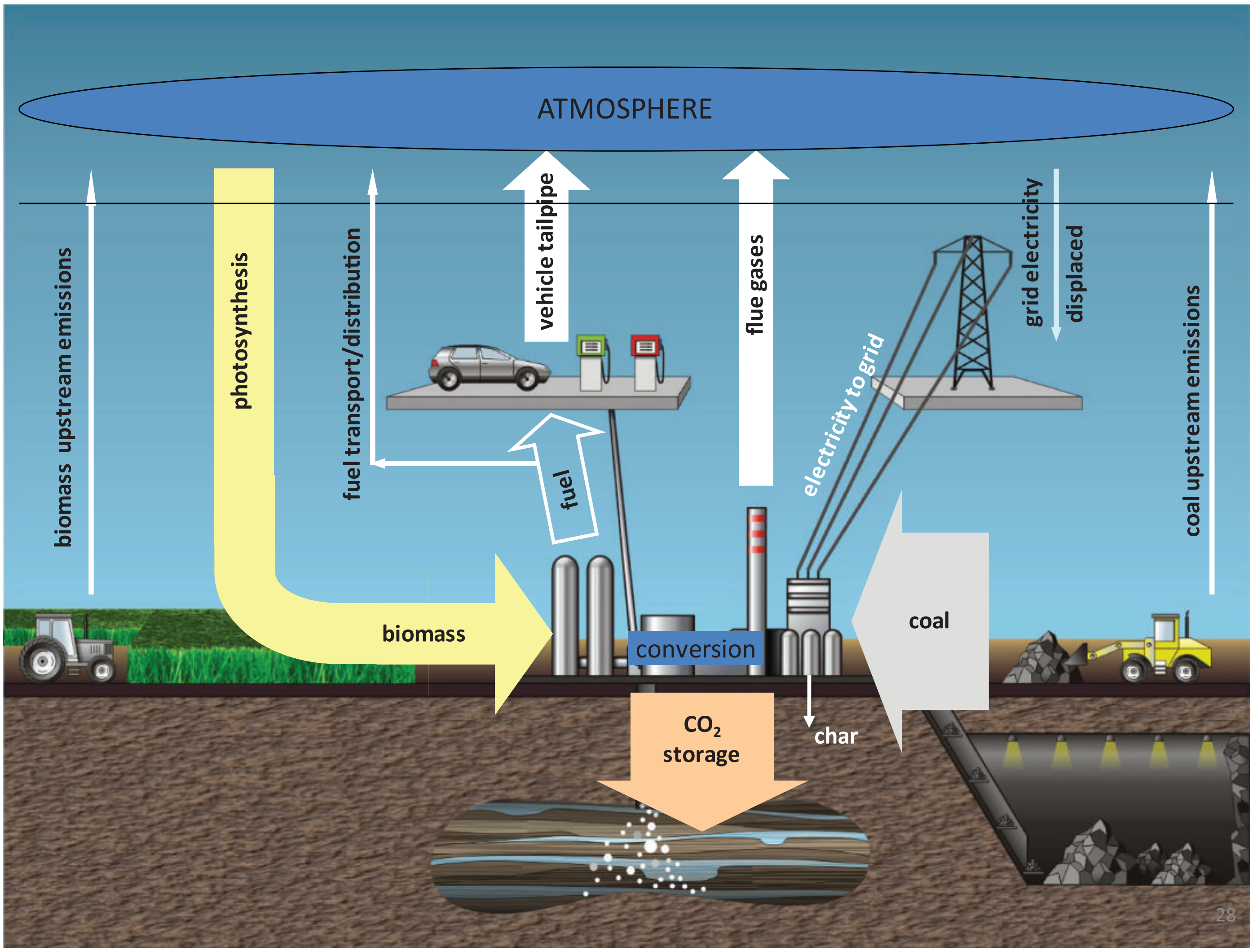

Figure SPM-8. | Carbon flows for conversion of coal and biomass to liquid fuels and electricity. For this system, when biomass is approximately 30% of the feedstock input (on a higher heating value basis), the net fuel cycle GHG emissions associated with the produced liquid fuels and electricity would be less than 10% of the emissions for the displaced fossil energy. Source: Larson et al., 2010, see Chapter 12.[5]

Continued use of coal and other fossil fuels in a carbon-constrained world requires strategies that deal with this reality. For industrial and developing countries, these strategies would differ in the short term but converge in the long term. For developing countries, the emphasis could be on increasing access to energy services based on clean energy carriers, building new manufacturing and energy infrastructures that anticipate the evolution to low-carbon energy systems, and exploiting the rapid growth in these infrastructures to facilitate introduction of the advanced energy technologies needed to meet sustainability goals. In industrial countries, where energy infrastructures are largely already in place, a high priority could be overhauling existing coal power plant sites to add additional capabilities (such as co-production of power and fuels) and CCS. Simply switching from coal to natural gas power generation without CCS will not achieve the needed carbon emission reductions.

Among the technologies that use fossil fuels, co-production strategies using coal plus biomass and CCS have the greatest ability to address all the major energy-related societal challenges. In the long term, hydrogen made from fossil fuels with CCS is an energy option, but infrastructure challenges are likely to limit this option in the near

5 **Larson, E. D., G. Fiorese, G. Liu, R. H. Williams, T. G. Kreutz and S. Consonni, 2010:** Co-production of Decarbonized Synfuels and Electricity from Coal + Biomass with CO_2 Capture and Storage: an Illinois Case Study. *Energy – Environmental Science*, **3**(1):28–42.

term. Co-production with CCS of electricity and carbon-based synthetic transportation fuels such as gasoline, diesel and jet fuel represent low-cost approaches for simultaneously greatly reducing carbon emissions for both electricity and transportation fuels and providing multiple benefits (Figure SPM 8): enhancing energy supply security, providing transportation fuels that are less polluting than petroleum-derived fuels in terms of conventional air pollutants, providing super-clean synthetic cooking fuels as alternatives to cooking with biomass and coal (critically important for developing countries), and greatly reducing the severe health damage costs due to air pollution from conventional coal power plants.

No technological breakthroughs are needed to get started with co-production strategies, but there are formidable institutional hurdles created by the need to manage two disparate feedstock supply chains (for coal and biomass) and provide simultaneously three products (liquid fuels, electricity, and CO_2) serving three different commodity markets.

6. Universal Access to Modern Energy Carriers and Cleaner Cooking by 2030 is Possible: *Universal access to electricity and cleaner cooking fuels and stoves can be achieved by 2030; however, this will require innovative institutions, national and local enabling mechanisms, and targeted policies, including appropriate subsidies and financing. The necessary technologies are available, but resources need to be directed to meet these goals. Universal access is necessary to alleviate poverty, enhance economic prosperity, promote social development, and improve human health and well-being. Enhancing access among poor people, especially poor women, is thus important for increasing their standard of living. Universal access to clean cooking technologies will substantially improve health, prevent millions of premature deaths, and lower household and ambient air pollution levels, as well as the emissions of climate-altering substances.*

Access to affordable modern energy carriers and cleaner cooking, improves well-being and enables people to alleviate poverty and expand their local economies. Enhanced access to modern energy carriers and cleaner cooking can become an effective tool for improving health for example, by reducing air pollution and can also help combat hunger by increasing food productivity and reducing post-harvest losses. Modern energy carriers and end-use conversion devices could improve education and school attendance by providing better lighting, heating, and cooling services. Electrifying rural health centers enables medical services to be provided at night, medicines to be preserved and more-advanced medical equipment to be used. Reduction of the proportional cost of energy services, particularly for rural poor people who spend a significant part of their time and disposable income on energy, is also important. This can liberate financial and human, especially women's, resources for other important activities or expenses, such as education, purchasing more and better-quality food, and expanding income-generating activities.

Several challenges exist to improving access to modern forms of energy and cleaner cooking. These include low income levels, unequal income distribution, inequitable distribution of modern forms of energy, a lack of financial resources to build the necessary infrastructure, weak institutional and legal frameworks, and a lack of political commitment to scaling up access. Even among households that have physical access to electricity and modern fuels, a lack of affordability and unreliable supplies limit their ability to use these resources, particularly for productive purposes. In addition to access to modern forms of energy, there must be access to end-use devices that provide the desired energy services. Those who can afford modern energy carriers may still not be able to afford the upfront costs of connections or the conversion technology or equipment that makes that energy useful.

While the scale of the challenge is tremendous, access to energy for all, electricity for all, and modern fuels or stoves for all by 2030 is achievable. This will require global investments of US$36–41 billion annually – a small fraction of total energy infrastructural investments required by 2030. It is expected that as households with public sector support gain access to modern energy and end-use devices and start earning incomes, their standard of living and ability to pay for the energy services utilized would successively expand.

Between 1990 and 2008 almost two billion people gained access to electricity, more than the corresponding population increase of 1.4 billion people over that time period (see Figure SPM-9). By 2030, the 1.4 billion people currently without access to electricity plus the projected population increase to 2030 of 1.5 billion people need to be connected to meet the GEA goal on electricity access (see Figure SPM-10). To achieve this, a multitrack approach is needed, combing grid extension with microgrids and household systems. Grid extension is currently the lowest cost per kWh delivered and also the preferred delivery form by most customers because of the capacity to deliver larger quantities of power for

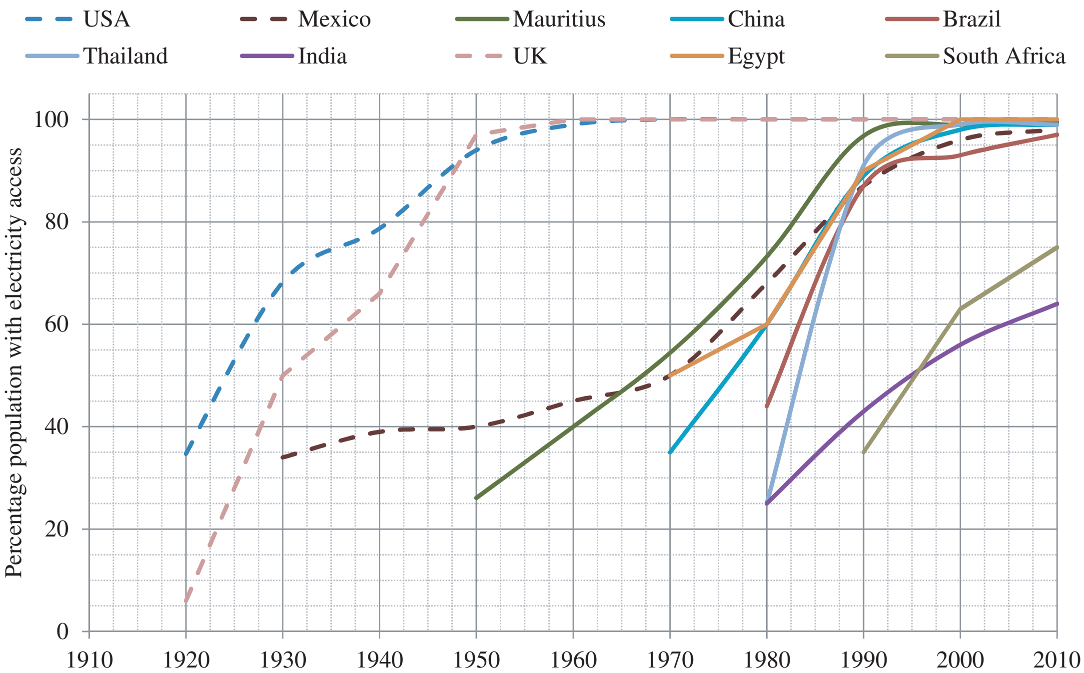

Figure SPM-9. | Historical experience with household electrification in select countries. Source: Chapter 19.

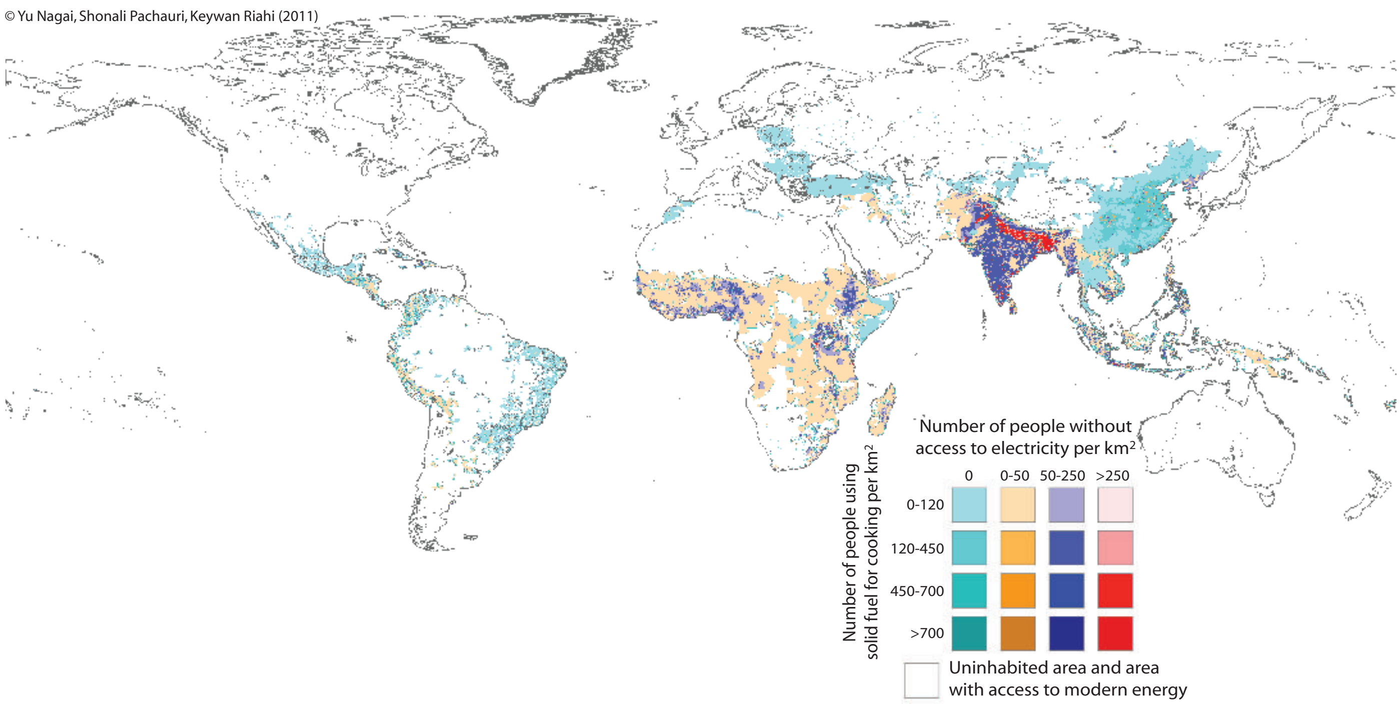

Figure SPM-10. | Density of population lacking access to modern energy carriers in 2005. Colored areas show people per km² without access to electricity and those that use solid fuels for cooking, e.g., dark blue and red areas show where people do not have access to electricity and cook predominately using solid fuels. Source: Chapters 17 and 19.

productive purposes. For many remote populations grid extension by 2030 will be highly unlikely and microgrids offer an alternative, based on local renewable energies or imported fossil fuels. An interesting approach to providing modern energy and development in remote villages is the multifunctional platform beginning to gain hold in West Africa. Household electrification is expanding rapidly in some countries, based on solar PV that are financed by micro-credits that has been done without increasing household expenses for energy (replacing candles and kerosene).

About 3 billion people rely entirely, or to a large degree, on traditional biomass or coal for cooking and heating. This number has not changed appreciably over the last decades, particularly among households in rural areas. Indeed, more people rely on these fuels today than any time in human history. Improving the cooking experience for these populations will require access to cleaner liquid or gaseous fuels, especially biogas, liquid petroleum gas (LPG), and ethanol, or alternatively access to advanced biomass stoves with efficiency and pollutants emissions similar to those of gas stoves. Transitioning to such fuels or stoves is not likely to have negative implications for climatic change. This is because transitioning to modern fuels (even in the case that these are fossil based) will displace large quantities of traditional biomass use. Current technologies that use traditional biomass are a factor 4–5 times less efficient than cooking with modern fuels such as LPG, and are associated with significant emissions of non-CO_2 Kyoto gases (e.g., CH_4, N_2O) and aerosols (e.g., BC, OC) due to incomplete combustion.

Providing universal and affordable access to electricity and cleaner cooking is possible if timely and adequate policies are put in place. Overall, and on the basis of successful experiences of increasing access to modern energy, no single approach can be recommended above the others. What is clear, however, is that the current institutional arrangements and policies have met with mixed success, at best. Reforms are needed, at global and country level, to strengthen the feasibility of energy projects for poor people, expand the range of players involved, open up the regulatory system, and allow for innovation. In the specific case of access to cleaner cooking, fuel subsidies alone will be neither sufficient nor cost-effective in terms of achieving ambitious energy access objectives (see Figure SPM-11). Financial mechanisms, such as micro-credit, will need to complement subsidies to make critical end-use devices such as cleaner cookstoves affordable for poor people.

A paradigm shift is needed in the approach to energy planning and policy implementation in order to facilitate access to modern forms of energy and cleaner cooking. Current supply-side approaches that simply take as their starting point the provision of electricity, petroleum, or gas, or of equipment of a particular type (solar technology, improved cookstoves, biogas, and other forms of bioenergy) are unable to reap the full potential of social and economic improvements that

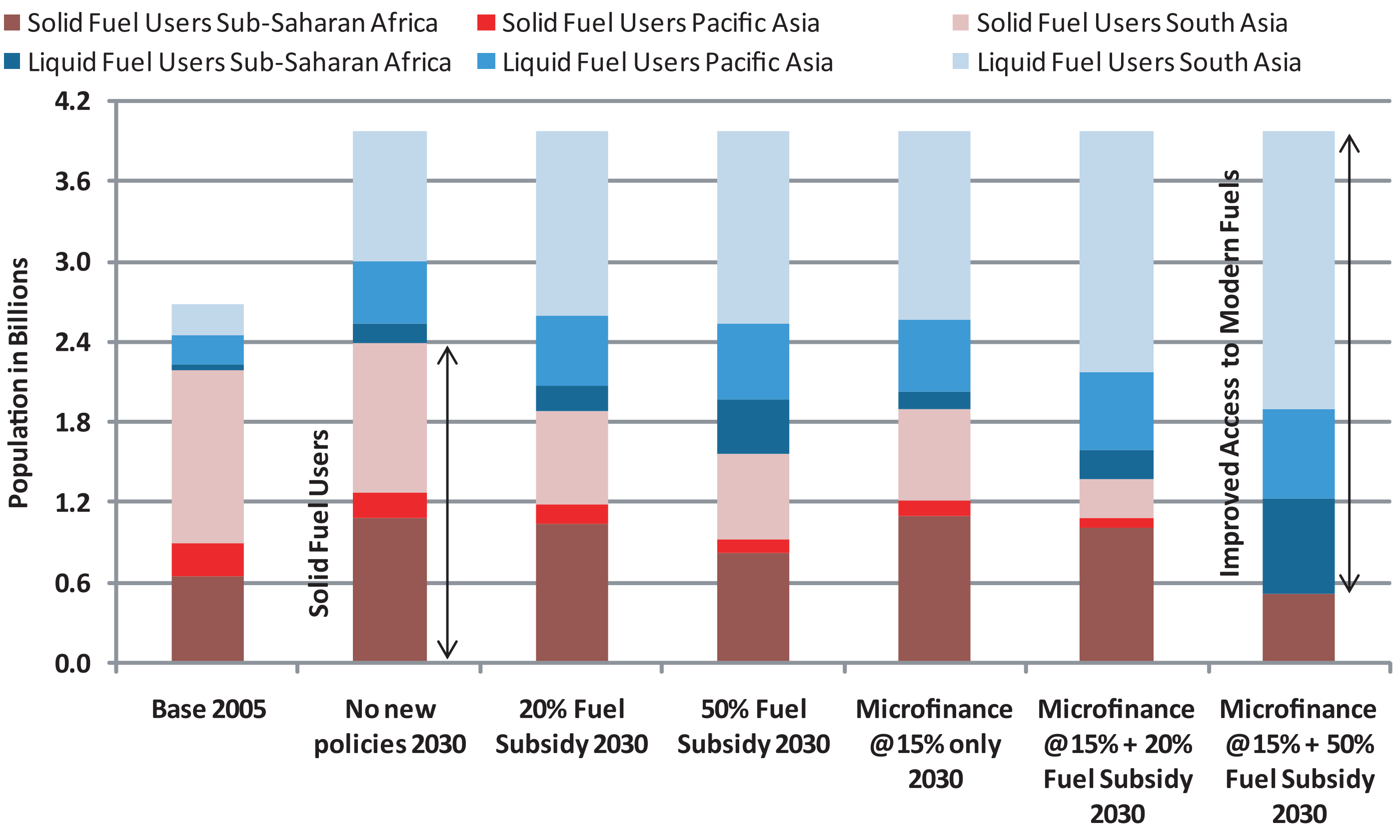

Figure SPM-11. | Impact of alternative policy scenarios on access to cleaner cooking fuels in three developing regions. Subsidies are relative to consumer price levels and are additional to existing subsidies. Source: Chapter 17.

follow from improved energy access and cleaner cooking. Leveraging funding and access to capital from public and private sources – for needed investments at the macro level and, at the micro level, for meeting costs for low-income households – is crucial in efforts to expand access to energy services for the poorest people. Creative financing mechanisms and transparent cost and price structures will be critical to achieving the required scale-up and quick roll-out of solutions to improve access.

Policy recommendations in the form of general ideas or guidelines are provided below. Regional and national contexts should be considered in defining strategies, instruments, and measures.

- A better understanding and a clearer diagnosis of the structure and functioning of energy systems, along with the needs (energy services) to be supplied, is needed. It has often been absent in the discussion of proposals and the role of public policies. Good policies need good diagnoses. Support and funds for diagnosis and information should be part of the strategies.

- Subsidies are generally justified as a response to inequality and social expectations in energy provision. However, their net effect can be positive or negative depending on the intended goals of the subsidy, and the way a subsidy is implemented. An effective tariff and subsidy regime has to be transparent and minimize administrative costs to avoid gaming of the system and to maximize the benefits that accrue to the intended recipients. Subsidies to energy should be complemented with funds toward solving the first-cost capital financing problem since up-front costs of equipment are, usually, the key barrier.

- Financing mechanisms are needed for every scale of energy intervention. Mobilizing affordable and genuine international, regional, national, and local funds is crucial.

- Energy access policy is part of a wider development policy and should be aligned with other sector policies and objectives. If these policies are misaligned, they can reduce the effectiveness of any given policy. Policy misalignments can occur when different energy policies work at cross-purposes or when government priorities that could benefit from an effective energy policy are not aligned. In particular, there is a need to link rural and peri-urban energy supply more closely with rural development. This would shift the focus from minimal household supply to a more comprehensive approach to energy that includes productive activities and other welfare-enhancing uses of energy. Ideally, the linkages between energy and other policy priorities, such as health, education, gender equality and poverty alleviation, should be recognized explicitly and local solutions that address these needs be encouraged and supported.

- Capacity development is needed, especially for the design and implementation of public policies oriented to poor people.

7. An Integrated Energy System Strategy is Essential: *An integrated approach to energy system design for sustainable development is needed – one in which energy policies are coordinated with policies in sectors such as industry, buildings, urbanization, transport, food, health, environment, climate, security, and others, to make them mutually supportive. The use of appropriate policy instruments and institutions can help foster a rapid diffusion and scale-up of advanced technologies in all sectors to simultaneously meet the multiple societal challenges related to energy. The single most important area of action is efficiency improvement in all sectors. This enhances supply side flexibility, allowing the GEA challenges to be met without the need for technologies such as CCS and nuclear.*

Energy-focused policies must be coordinated and integrated with policies addressing socioeconomic development and environmental protection in other sectors. Effective policy portfolios will require a combination of instruments, including regulatory frameworks and investment policies, as well as measures for strengthening capacity development, which stimulate innovation.

The main conclusion from the GEA pathways analysis is that energy efficiency improvements are the most important option to increase the flexibility of regional and sectoral energy end use and supply systems. In pathways with high rates of efficiency improvements, it was possible to achieve the GEA normative goals under any of the assumed supply portfolio restrictions and even without including nuclear energy and CCS technologies.

Energy systems differ between regions, between major economies, and between developing and industrial countries. Approaches to the necessary transitions to create energy systems for a sustainable future therefore vary, and policies that work successfully in one region may fail in another. Nevertheless, there are lessons to be learned from shared experiences. The evolution of energy systems will depend on how well technologies are implemented and how well policies are instituted to bring about the required changes.

Prevailing market and institutional structures in the energy sector have a significant influence on investments in different end-use and supply-side options. In countries with well-developed energy markets, spot-market energy trading is common and long-term contracts are becoming less frequent; and it is now more difficult to ensure long-term returns on large-scale investments. This is the main impediment to financing of large capital-intensive energy-supply projects.

Governments must recognize that policies promoting competition in the electricity sector must also prevent the short-term exercise of market power that results in unjustified excessive profits for some producers and speculators as well as price volatility for consumers, requiring continued regulation and public sector involvement in energy system planning and long-term contracting.

A regulatory framework is essential as it facilitates the creation and modernization of physical infrastructure and capital investments in energy end-use and supply systems. It is also necessary for economic development and poverty reduction.

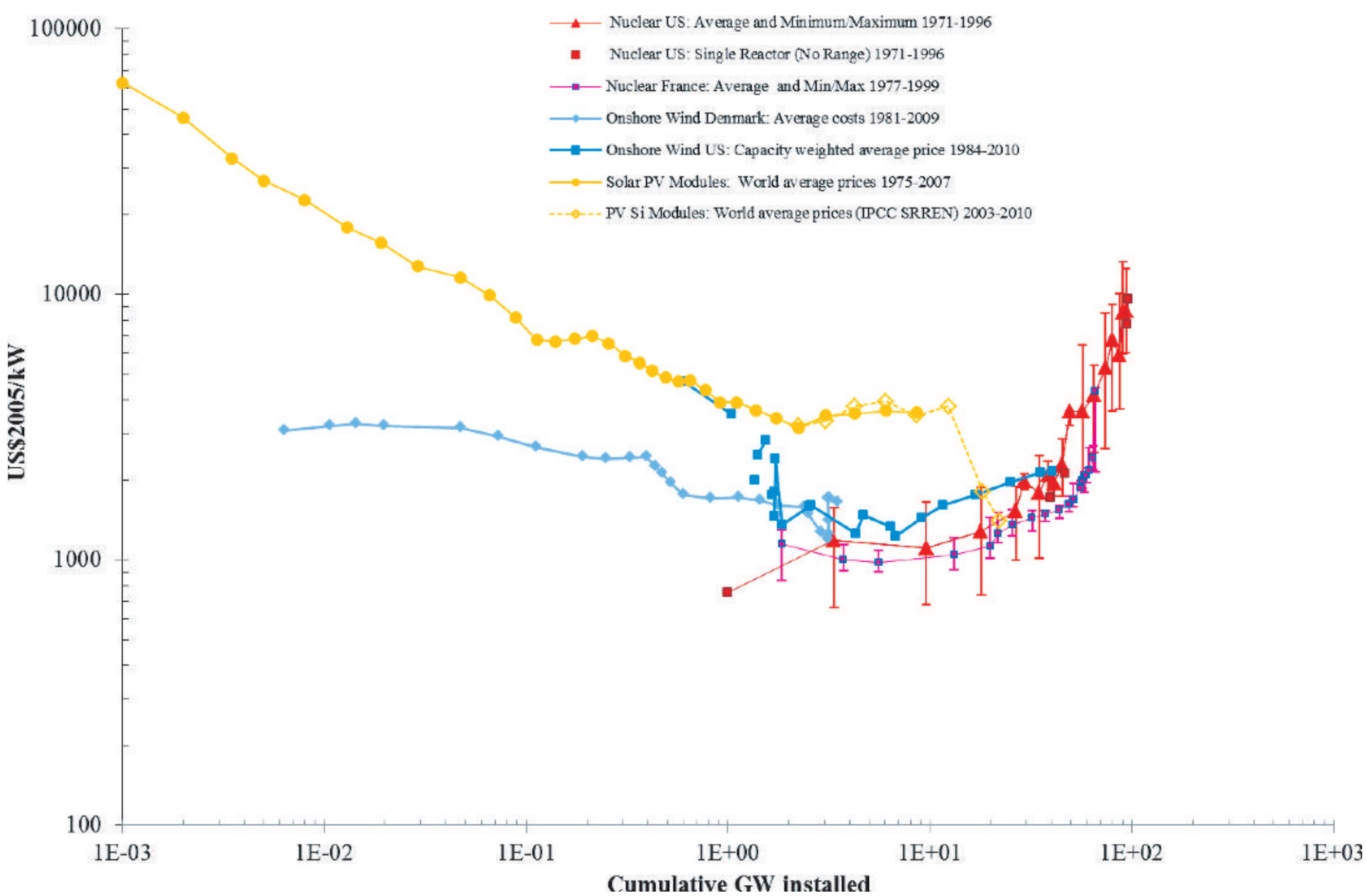

Figure SPM-12. | Cost trends of selected non-fossil energy technologies (US$2005/kW installed capacity) versus cumulative deployment (cumulative GW installed) Chapter 24 data have been updated with most recent cost trends (2010) available in the literature for PV Si Modules and US onshore wind turbines. Note that the summary illustrates comparative cost trends only and is not suitable for direct economic comparison of different energy technologies due to important differences between the economics of technology components (e.g. PV modules versus total systems installed), cost versus price data, and also differences in load factors across technologies (e.g., nuclear's electricity output per kW installed is three to four times larger than that of PV or wind turbine systems). Source: Chapter 24.

Success will depend on the implementation of robust public and private partnerships that can achieve unprecedented cooperation and integration between and among the public and private sectors, civil society, and academia.

A multiplicity of policies is required to address the potential impacts of the energy system on human health and the environment. A mix of regulations, information programs, and subsidies are needed, for example, to stimulate the rapid adoption of household energy-using devices that have virtually zero indoor emissions. Ambient air quality requires regulations on emissions from fuel combustion. Similarly, regional air quality must be protected by technology and emissions regulations or by direct emissions pricing.

Policies to foster energy from biomass should seek to minimize the trade-offs between biomass for food and biomass for fuel by encouraging the use of biomass residues and sustainable feedstocks as well as efficient conversion processes. Many developing countries import all or most of their current liquid fuels (in the form of oil and diesel) at increasingly higher costs and have at the same time large areas that are off-grid.

Greenhouse gas pricing policies will be essential in shifting energy systems toward low-carbon emission technologies, fuels, and activities. While there is disagreement on which pricing method is best – carbon taxes or cap and trade – the two approaches can be designed so that their effects are quite similar. The price certainty of a carbon tax can be approximated with cap and trade by setting a price floor and ceiling for permit prices. The revenues generated by a carbon tax can also be obtained by auctioning permits in the cap and trade approach

It is important to complement GHG pricing with a portfolio of other regulatory and market mechanisms. This is because different instruments are more effective in different sectors, geographic and cultural regions, as well as for different options. For instance, due to the magnitude and diversity of market barriers prevailing in the building sector, different regulatory and market-based instruments and their packages needed to be tailored to overcome specific barriers.

Strategic alliances and strong coordination among various policy fields will be able to lead to the realization of a larger share of technological potential by improving the economics of efficiency investments through the addition of further benefits to cost-efficiency considerations, such as security, employment, social welfare, and regional development. For example, policies for urban planning that encourage high density development with investments in public transport are likely to lead to lower long-term energy demand. Similarly, policies for renewable energy technologies could emphasize positive spillover effects on new venture and job creation. By actively seeking opportunities for such cross-sectoral integration; the required changes in the energy system may be accelerated. For example, a shift to clean cooking may be regarded as much a required change in the energy system, as an intervention to improve maternal and child health.

8. Energy Options for a Sustainable Future bring Substantial, Multiple Benefits for Society: *Combinations of resources, technologies, and polices that can simultaneously meet global sustainability goals also generate substantial economic, environmental, and social development benefits. These include, but are not limited to, improved local health and environment conditions, increased employment options, strengthened local economies through new business opportunities, productivity gains, improved social welfare and decreased poverty, more resilient infrastructure, and improved energy security. Synergistic strategies that focus on local and national benefits are more likely to be implemented than measures that are global and long-term in nature. Such an approach emphasizes the local benefits of improved end-use efficiency and increased use of renewable energy, and also helps manage energy-related global challenges. These benefits make the required energy transformations attractive from multiple policy perpectives and at multiple levels of governance.*

The energy systems illustrated by the GEA pathways meet the sustainability goals by design while generating substantial economic, environmental, and social benefits. For example, achieving near-term pollution and health objectives is furthered by investing in the same energy technologies that would be used to limit climate change. Policies to control emissions of greenhouse gases, or to increase access to cleaner cooking fuels could, in turn, bring significant improvements in pollution related health impacts. For example as the GEA pathways indicate, a saving of 20 million disability adjusted life years (DALYs) from outdoor air pollution and more than 24 million DALYs from household air pollution. In addition, universal access to electricity and cleaner cooking fuels opens up opportunities for education, for income generating activities, and significantly improved well-being.

This synergy is crucial and advantageous, given that measures which lead to local and national benefits (e.g., improved health and environment) may be more easily adopted than those measures that are put forward solely on the grounds of global goals. Many energy efficiency and renewable energy options enjoy such synergies and generate benefits across multiple objectives. Some of these advantages can be so substantial for certain investments and measures that they may offer more attractive entry points into policymaking than the climate or social targets alone. This is particularly the case where benefits are local rather than global. Seeking local benefits and receiving global benefits as a bonus is very attractive, and this is often the case for investments in energy efficiency and renewable sources of energy.

Therefore, even if some of these multiple benefits cannot be easily monetized, identifying and considering them explicitly may be important for decision-making. Cost-effectiveness (or cost-benefit) analyses evaluating energy options may fare differently when multiple benefits are considered.

The enhancement of end-use efficiency in buildings, transport and industry offers many examples of benefits across multiple environmental, social, and economic objectives:

- *inter alia* improved social welfare as a result of very high efficiency and thus very low fuel-cost buildings;
- reduced need for public funds spent on energy price subsidies for people living in poverty; health benefits through significantly reduced indoor and outdoor air pollution, often translating into commendable productivity gains;
- productivity gains and general improvements in operational efficiency in industry translate into strengthened competitiveness; and
- enhancing efficiency by increasing the rate of building retrofits can in addition be a source of employment and know-how.

Other benefits that are difficult to quantify include improved comfort and well-being, reduced congestion, new business opportunities, and better and more durable capital stock.

Rapid decarbonization of the energy system for climate protection also reduces the need for subsidies presently given to carbon-intensive petroleum products and coal. Subsidies for these fuels amount to approximately US$132–240 billion per year, and only 15% of this total is spent directly towards those with limited access to clean energy. However, GHG mitigation in the GEA pathways would, at the same time, reduce consumption of carbon-intensive fossil fuels, leading to a reduction in the need for subsidies for petroleum products and coal in the order of US$70–130 billion per year by 2050 compared to today.

Whether an impact is a benefit or a liability depends on the baseline and specific local situation. For example, while LPG causes major environmental and climate impacts in itself, it still has major advantages in many areas when it replaces traditional biomass as a fuel. Thus a unique novelty of the analysis is that it provides a new, additional framework for a well-founded assessment for individual decisions to choose among various energy alternatives, which complement financial appraisals. For example, in regions where access to modern forms of energy is a major energy policy goal, evaluations of "energy security" will play an essential role in ranking the different options available at comparable costs. In other areas, access or employment may be key secondary objectives of energy policy and these can play an important role in additional prioritization of options with comparable local costs.

There is a broad array of different benefits in the spectrum of policy target areas, which represent many potential entry points into policy-making. However, some options can have a wider range of multiple benefits than others, in particular renewable energies and improved energy end-use efficiency.

9. Socio-Cultural Changes as well as Stable Rules and Regulations will be Required: *Crucial issues in achieving transformational change toward sustainable future include non-technology drivers such as individual and public awareness, community and societal capacities to adapt to changes, institutions, policies, incentives, strategic spatial planning, social norms, rules and regulations of the marketplace, behavior of market actors, and societies' ability to introduce through the political and institutional system, measures to reflect externalities. Changes in cultures, lifestyles, and values are also required. Effective strategies will need to be adopted and integrated into the fabric of national socio-cultural, political, developmental, and other contextual factors, including recognizing and providing support for the opportunities and needs of all nations and societies.*

The complexity, magnitude, and speed of the changes envisaged in this transformation will necessitate a major shift in the way that societies analyze and define the concept of 'capacities' and the way in which they go about the important task of developing these capacities to meet the challenges of energy transitions. Different from some of the linear approaches to capacity development and to technology transfer and deployment used today, which often fail to appreciate the complexity of change processes, the concept of capacity development advanced by the GEA is intimately linked to the energy transitions perspective based on multilayered processes of system change.

In these processes, special attention is paid to the informal institutions that arise out of historically shaped habits, practices, and vested interests of players in the system already in place and to the tendency for path dependence, where past choices constrain present options. They are given special attention because they constitute potential impediments to needed change. In the transitions perspective, both learning and unlearning such habits, practices, and norms in the course of change are important.

Traditional habits, practices, and norms also shape the styles of communication in societies. Evidence shows that the more successful change processes take place in environments that tend to move away from top-down communication and consultation to more active and continuous dialogue practices. Capacity development has an important role to play in building mechanisms of support and capacities for interactive feedback, flexibility, and adaptive management and change. And because these traditional habits, practices, and norms are embedded in a broader social context, building capacities for dialogue at the local level is essential.

Market development and the role of feedback and flexibility at the local and project level are also essential in support of the diffusion of new energy technologies, but they are usually ignored in the design of capacity building initiatives. Also important is the need to build and strengthen capacities for local manufacture, repair, and distribution of new energy-related technologies, whether related to improved cookstoves, solar home systems, or other forms of early energy access initiatives, or to the introduction of more modern and decentralized forms of energy. Successful examples of energy technology development and diffusion also point to the need to develop and strengthen local research capacities, participating in collaborative research and development efforts and coordinating across sectors and disciplines.

But these new and emerging forms of knowledge networking, coupled with new and innovative forms of finance and technology research collaboration and development, require new and enhanced capacities for effective participation on the international level that many countries, particularly developing ones, do not have or are not well developed today. The increasingly complex and fast-paced world of energy and climate change finance is a good example of an area where present capacities fall far short of the need. The recent climate change negotiations alone have generated pledges of fast-start finance up to 2012 of some US$30 billion and promises to work collaboratively so that this funding can grow to some US$100 billion by 2020.

This is only a small part of the overall investment projections needed to meet the high growth in energy demand – some US$1.7–2.2 trillion per year are needed to 2050. The world of energy finance has always been a large and complex market. The difference today is that it is becoming even more complex, with new and innovative instruments of finance, including the carbon market, and with countries demanding more attention to the need to develop, introduce, and diffuse new technologies. Under these conditions, a multi-goal approach can both speed the diffusion of new energy technologies as well as stimulate the development and energy transition processes in developing countries.

10. Policies, Regulations, and Stable Investment Regimes will be Essential: *A portfolio of policies to enable rapid transformation of energy systems must provide the effective incentive structures and strong signals for the deployment at scale of energy-efficient technologies and energy supply options that contribute to the overall sustainable development. The GEA pathways indicate that global investments in combined energy efficiency and supply will need to increase to between US$1.7–2.2 trillion per year compared to present levels of about US$1.3 trillion per year (about 2% of current world gross domestic product) including end-use components. Policies should encourage integrated approaches across various sectors and promote the development of skills and institutional capacities to improve the investment climate. Examples include applying market-oriented regulations such as vehicle emissions standards and low carbon fuel standards and as well as renewable portfolio standards to accelerate the market penetration of clean energy technologies and fuels. Reallocating energy subsidies, especially the large subsidies provided in industrialized countries to fossil fuels without CCS, and nuclear energy, and pricing or regulating GHG emissions and/or GHG-emitting technologies and fuels can help support the initial deployment of new energy systems, both end-use and supply, and help make infrastructures energy efficient. Publicly financed research and development needs to accelerate and be reoriented toward energy efficiency, renewable energy and CCS. Current research and development efforts in these areas are grossly inadequate compared with the future potentials and needs.*

The GEA analysis has identified pronounced asymmetries in current incentive structures for the development, early deployment, and the widespread diffusion of energy end-use and supply technologies that need rebalancing. Current technology policy frameworks are also often fragmented and contradictory instead of integrated and aligned. Nowhere is this more apparent that in the continued subsidies for fossil fuels that amount to close to US$500 billion and are in direct contradiction with policy initiatives that promote increasing energy end-use efficiency and deployment of renewables. This assessment has also identified a marked mismatch between the critical needs for vastly improved energy efficiency and the under-representation of energy efficiency in publicly funded energy research and development and deployment (RD&D) and incentives for early market deployment of new technologies which are presently characterized by a distinct supply-side over-emphasis.

A first, even if incomplete, assessment of the entire global investments into energy technologies – both supply and demand-side technologies – across different innovation stages suggests RD&D investments of some US$50 billion, market formation investments (which rely on directed public policy support) of some US$150 billion, and an estimated range of US$1–5 trillion investments in mature energy supply and end-use technologies (technology diffusion). The GEA pathways estimate the current annual energy investments at about US$1.3 trillion per year. The difference to the estimated range up to US$5 trillion is related mostly to the magnitude of demand-side investments that is not included in the pathways. Demand-side investments are of critical importance, particularly because the lifetimes of end-use technologies can be considerably shorter than those on the supply side. Demand-side investments might thus play an important role in achieving pervasive and rapid improvements in the energy system.

Major developing economies have become significant players in global energy technology RD&D, with public- and private-sector investments approaching some US$20 billion – in other words, almost half of global innovation investments – which are significantly above OECD public-sector energy RD&D investments (US$13 billion).

Policies now need to move toward a more integrated approach, stimulating simultaneously the development as well as the adoption of efficient and cleaner energy technologies and measures. RD&D initiatives without simultaneous incentives for consumers to adopt the outcomes of innovation efforts risk not only being ineffective but also precluding the market feedbacks and learning that are critical for continued improvements in technologies.

Another area of near-term technology policy focus is the domain of enhancing the international cooperation in energy technology research and development as well as in the domains of technology standards. Through dynamic standard setting and international harmonization, predictable and long-term signals are provided to innovation players and markets. Ambitious efficiency standards are of particular urgency for long-lived capital assets such as buildings. Other end-use technologies such as vehicles or appliances turn over much more quickly, offering the possibility of more gradually phased in technology standards as long as clear long-term signals are provided.

Table SPM-4. | Energy investments needed between 2010 and 2050 to achieve GEA sustainability goals and illustrative policy mechanisms for mobilizing financial resources. GEA pathways indicate that global investments in combined energy efficiency and supply have to increase to about US$1.7–2.2 trillion per year compared with the present level of some US$1.3 trillion (2% of current gross world product). Given projected economic growth, this would be an approximately constant fraction of GDP in 2050.

Times	Investment (billions of US$/year)		Policy mechanisms			
		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* (feed-in tariff and renewable portfolio standards can complement GHG pricing)	*Essential* (GHG pricing is key to rapid development of renewables)	*Complement* (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 to electricity and cleaner Cooking[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, micro-financing for appliances, subsidies for clean cookstoves)	*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 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 a).

[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 almost universal access by 2030 (including electricity grid connections and fuel subsidies for cleaner cooking fuels).

Some of the policies for energy for sustainability described above simply involve an improvement of existing policies, such as better management of the electricity sector or more responsible use of fossil fuel resource rents. But the dominant message of the GEA is that the global energy system must be rapidly modified and expanded to provide energy access to those who have none, and must quickly transform to an energy system more supportive of sustainable development. This transition will require considerable investments over the coming decades. Table SPM-4 indicates the necessary investments to achieve this as estimated by the GEA, and links these to the types of policies needed. It also assesses these policies in terms of their necessity and their ability to complement or substitute for each other. Although considerable, these investment levels can be compared to estimates of global fossil fuel subsidy levels on the order of US$500 billion a year, of which an estimated US$100 billion goes to producers.

Table SPM-4 compares the costs and policies for different technology options to those of promoting energy access. Different types of technologies and objectives will require different combinations of policy mechanisms to attract the necessary investments. Thus, the Table identifies 'essential' policy mechanisms that must be included for a specific option to achieve the rapid energy system transformation, 'desired' policy mechanisms that would help but are not a necessary condition, 'uncertain' policy mechanisms in which the outcome will depend on the policy emphasis and thus might favor or disfavor a specific option, and policies that are inadequate on their own but could 'complement' other essential policies.

GEA findings indicate that global investments in combined energy efficiency and supplies have to increase to about US$1.7–2.2 trillion per year compared with the present level of some US$1.3 trillion (2% of current gross world product). Given projected economic growth, this would be an approximately constant fraction of GDP in 2050.

For some objectives, such as energy access, future investment needs are comparatively modest. However, a variety of different policy mechanisms – including subsidies and regulation as well as capacity building programs – need to be in place. Regulations and standards are also essential for almost all other options listed in the Table, while externality pricing might be necessary for capital-intensive technologies to achieve rapid deployment (such as a carbon tax to promote diffusion of renewables, CCS, or efficiency). The GEA estimates that the investment requirements to transform energy systems are in the range of US$1.7–2.2 trillion per year through 2020. Capital requirements for energy infrastructure are only a small part of the overall investment projections, but among the highest priorities of the options listed. A multi-goal approach can both speed the diffusion of new energy technologies as well as stimulate the development and energy transition processes in developing countries.

Increasing investments 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, adequate institutions to promote and support them, and innovative financial instruments to facilitate them The portfolio needs to include regulations and technology standards in sectors with, for example, relatively low price elasticity in combination with externality pricing to avoid rebound effects, as well as targeted subsidies to promote specific 'no-regret' options while addressing affordability. In addition, focus needs to be given to capacity development to create an enabling technical, institutional, legal, and financial environment to complement traditional deployment policies (particularly in the developing world).

In sum, the GEA finds that attainment of a sustainable future for all is predicated on resolving energy challenges. This requires the creation of market conditions, via government interventions, that invite and stimulate investments in energy options that provide incentives for rapid investments in energy end-use and supply technologies and systems.

TS

Technical Summary

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Contents

1 Introduction

Energy is essential for human development and energy systems are a crucial entry point for addressing the most pressing global challenges of the 21st century, including sustainable economic, and social development, poverty eradication, adequate food production and food security, health for all, climate protection, conservation of ecosystems, peace, and security. Yet, more than a decade into the 21st century, current energy systems do not meet these challenges.

In this context, two considerations are important. The first is the capacity and agility of the players within the energy system to seize opportunities in response to these challenges. The second is the response capacity of the energy system itself, as the investments are long-term and tend to follow standard financial patterns, mainly avoiding risks and price instabilities. This traditional approach does not embrace the transformation needed to respond properly to the economic, environmental, and social sustainability challenges of the 21st century.

A major transformation is required to address these challenges and to avoid potentially catastrophic consequences for human and planetary systems. The GEA identifies strategies that could help resolve the multiple challenges simultaneously and bring multiple benefits. Their successful implementation requires determined, sustained, and immediate action.

The industrial revolution catapulted humanity onto an explosive development path, whereby reliance on muscle power and traditional biomass was replaced mostly by fossil fuels. In 2005, approximately 78% of global energy was based on fossil energy sources that provided abundant and ever cheaper energy services to more than half the world's population. Figure TS-1 shows two clear development phases in this explosive growth of global primary energy: the first characterized by a shift from reliance on traditional energy sources to coal and subsequently to oil and gas. During the past decades, hydropower, biomass, and nuclear energy have a combined share of almost 12%, while new renewables, such as solar and wind, are hardly discernible in Figure TS-1. These major transitions are also illustrated in Figure TS-2, which shows the shares of global primary energy and their changes over the period from 1850 to 2008. The dominance of biomass in the 1800s was overtaken by coal in the first half of the 20th century, giving way to oil around 1970. Oil still retains the largest share of global primary energy.[2]

Despite this rapid increase in overall energy use, over three billion people still rely on solid fuels such as traditional biomass, waste,

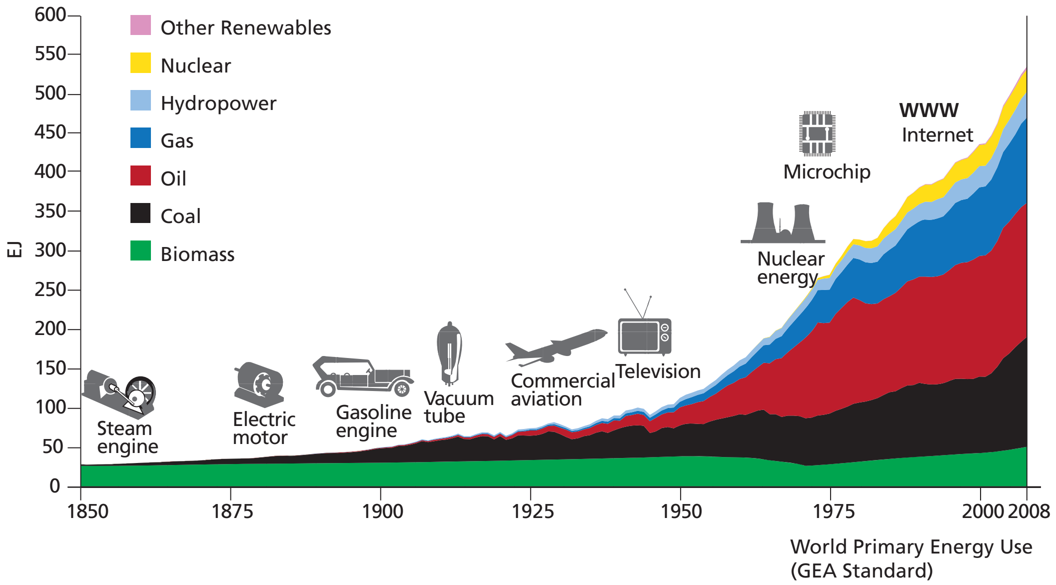


Figure TS-1 | Evolution of primary energy shown as absolute contributions by different energy sources (EJ). Biomass refers to traditional biomass until the most recent decades, when modern biomass became more prevalent and now accounts for one-quarter of biomass energy. New renewables have emerged in the last few decades. Source: updated from Nakicenovic et al., 1998 and Grubler, 2008, see Chapter 1.[1]

1 **Nakicenovic, N., A. Grubler and A. McDonald (eds.), 1998:** *Global Energy Perspectives.* International Institute for Applied Systems Analysis (IIASA) and World Energy Council (WEC), Cambridge University Press, Cambridge, UK.
Grubler, A., 2008: Energy transitions. In *Encyclopedia of Earth*. C. J. Cleveland (ed.), Environmental Information Coalition, National Council for Science and the Environment, Washington, DC.

2 GEA convention on primary energy using primary energy substitution equivalent (see Chapter 1.A.3) is used throughout.

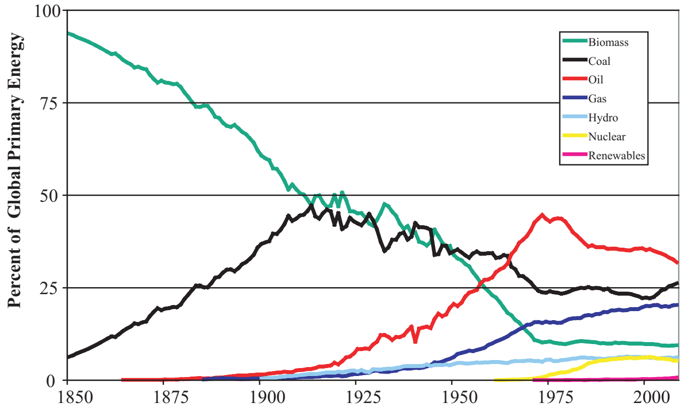


Figure TS-2 | Evolution of primary energy shown as shares of different energy sources. Source: updated from Nakicenovic et al., 1998 and Grubler, 2008; see Chapter 1.[3]

charcoal, and coal for household cooking and heating. The resulting air pollution leads to over two million premature deaths per year, mostly of women and children. Furthermore, approximately 20% of the global population has no access to electricity, making it difficult for children to study after sunset and impossible, for example, to keep vaccines cold, provide mechanical energy for agriculture and irrigation, and power the most simple machines for manufacturing and commerce. This situation undermines economic development and energy security, and causes indoor and outdoor air pollution and climate change. Addressing these challenges is essential to averting a future with high economic and social costs and adverse environmental impacts on all scales.

An energy system transformation is required to meet these challenges and bring prosperity and well-being to the nine billion people expected by 2050. The encouraging news is that the beginnings of such a transformation can be seen today, in the rapidly growing investments in renewable energy sources, high-efficiency technologies, new infrastructure, near zero-energy buildings, electric mobility, 'smart' energy systems, advanced biomass stoves, and many other innovations. The policy challenge is to accelerate, amplify, and help make the implementation of these changes possible, widespread, and affordable. Initial experience suggests that many of these changes are affordable, although they may be capital intensive and require high upfront investments. However, in general, they have lower long-term costs that offset many of the upfront added-investment requirements. Many of these innovations also lead to benefits in other areas such as equity and poverty, economic development, energy security, improved health, climate change mitigation, and ecosystem protection.

3 **Nakicenovic, N., A. Grubler and A. McDonald (eds.), 1998:** *Global Energy Perspectives.* International Institute for Applied Systems Analysis (IIASA) and World Energy Council (WEC), Cambridge University Press, Cambridge, UK.
Grubler, A., 2008: Energy transitions. In *Encyclopedia of Earth*. C. J. Cleveland (ed.), Environmental Information Coalition, National Council for Science and the Environment, Washington, DC.

At the same time, the beginning of this grand transformation is, to a large extent, obscured by business-as-usual (BAU) thinking and behavior. Also, it tends to be blocked by current decision-making processes, institutions, consumption patterns, capital vintages, interests, and investment patterns that show a lock-in to old development pathways. However, there are excellent examples in many countries of transformational changes showing the opportunities available. The transition from the 'pervasive old' to the 'emerging new' will require continuous and major enhancements in awareness, knowledge, and skills, as well as new institutions, policies, and strategies.

GEA shows that while the local, regional, and global challenges, and their demands on energy systems, are enormous, they can all be met in a timely manner, effectively, and simultaneously – if societies want to do so. The assessment shows that a transformation toward energy systems supportive of sustainable development is possible. However, it will require decision makers to approach energy systems in an innovative and integrated way, to significantly strengthen their efforts domestically, and to coordinate their activities internationally.

GEA explored 60 alternative energy transformation pathways toward a sustainable future that simultaneously satisfy all the normative social and scientifically based environmental goals: continued economic development, universal access to modern energy carriers, climate and environment protection, improved human health, and better energy security.

The 60 pathways were grouped into three different approaches toward achieving the normative goals: GEA-Supply, GEA-Mix, and GEA-Efficiency. They were selected to represent three alternative evolutions of the energy system toward a sustainable future (details are in Section TS-4). A major conclusion is that many of these pathways satisfy all the GEA goals (see Sections TS-2.6 and TS-4).

This Technical Summary synthesizes and integrates the main findings from the individual chapters in the GEA report. It is structured as follows. Section TS-2 outlines the magnitude and orientation of the energy system change that is required, and forms the basis for specific goals expressed in terms of qualitative and quantitative indicators. Section TS-3 presents the building blocks of the transformation, such as energy resources, energy end-use and supply technologies, infrastructures, and systems. Section TS-4 describes the energy pathways for sustainable development and their implications. Section TS-5 presents policy tools and interventions to implement energy pathways that deliver on the goals for sustainable development.

2 The Need for Change

This section summarizes the major global challenges of the 21st century that require actions on energy systems in order to be resolved. GEA has developed energy-related indicators of sustainability that are discussed in this section, and used in Section TS-4 in the development of pathways toward a sustainable future.

2.1 Economic and Population Growth[4]

Energy access is fundamental to the growth and development of modern economies. Energy use is rising rapidly, driven by worldwide population growth, increased economic prosperity, an expanding middle class, and the lifestyles of the richest 1–2 billion people, as well as by the burgeoning use of ever more energy-intensive technologies in homes and workplaces around the world. This explosive growth in energy use is illustrated in TS-1. Even as the total energy use has increased rapidly, there is wide variation on a per capita basis (up to a factor of 10) in the final energy use among major world regions (see Figure TS-3).

On an individual basis, this variation is of the same order of magnitude as the disparity in global income distribution. Particularly striking on the regional level is how the sectoral shares in final energy vary from about equal percentage allocations at the higher levels of energy use to almost all energy being used in the residential (and commercial) sector at the lowest levels – meaning that almost no energy services are available to support production and development.

Several historic shifts are likely to fundamentally alter the global economy over the coming decades. First, as developing nations move from poverty to relative affluence, there will be a shift from agriculture to more energy-intensive commercial enterprises. Greater affluence has historically also been associated with an increase in meat consumption and other protein-rich diets, which multiply the stresses on the global environment due to the elevated need for water and land and increased greenhouse gas (GHG) emissions.

Currently, the process of industrialization is energy-intensive, as it requires high levels for material transformations. Rising incomes are expected to generate higher demands for private transport as well as for space and water heating, space cooling, and power-hungry household appliances. Demand for freight transport also implies increasing demand for energy transport services. It is unclear to what extent these demands are subject to saturation at higher income levels.

Second, for the first time in human history half the world population now lives in cities, and this urban fraction is growing faster than the overall population growth. The largest and fastest-growing urban centers are found in the world's poorer regions, where lack of energy access is most prevalent.

Access to affordable and sustainable energy services is fundamental to human development and economic growth. Economies lacking proper access to modern forms of energy (particularly electricity and other forms of mechanical energy for productive purposes, and also cleaner household combustion) cannot develop and contribute to improvements in well-being.

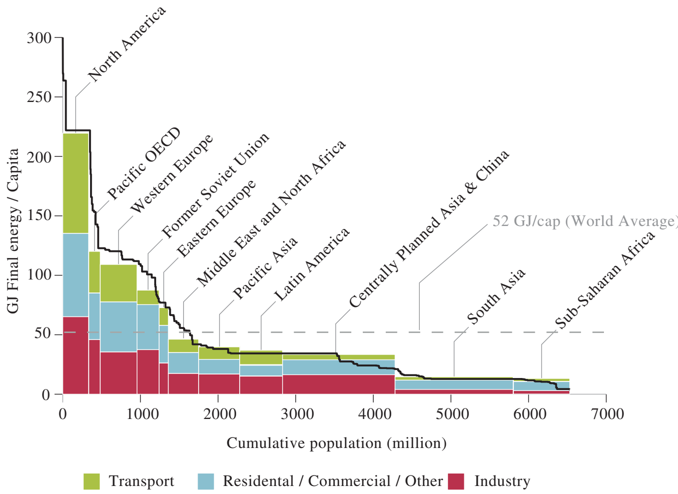


Figure TS-3 | Final energy (GJ) per capita versus cumulative population for 11 world regions sorted by declining per capita energy use (with final energy use disaggregated by sector and total, color bars) and final energy per capita for 137 countries in 2005 (black, solid line). Dashed horizontal line shows the average final energy per capita, which indicates that approximately 1.5 billion people are above and 5.5 billion below that level. Source: Chapters 1 and 19.

Energy for sustainable development must concurrently meet, without compromise, all dimensions of energy service requirements. These include availability, affordability, accessibility, security, health, climate, and environmental protection. The approach in GEA focuses on the energy options that deliver benefits for many, if not all, of these dimensions to avoid costly lock-in effects from a focus on a single dimension.

Being a multiplier of consumption, population growth remains a major driver of global impacts. Given the absolute limits of the planet, as illustrated by the need to limit concentrations of climate-altering pollutants, reductions in population growth trends can provide valuable additional decades to help resolve energy and other problems before reaching planetary limits. There is no coercion implied here, as studies show that hundreds of millions of women wish to control their family size but do not have access to modern contraceptive technologies. Models show, for example, that by providing such services, CO_2 emissions from energy use could be reduced by 30% in 2100 over what is otherwise projected. Providing reproductive health services to these women is also an equity issue – all women, not just those in rich countries, ought to have access to such services. It is also an important health issue, as spacing births, which, along with reducing the total number of births, is an effect of giving women access to contraception, has major benefits for child and maternal health.

2.2 Energy Access, Poverty, and Development[5]

Poverty is the most critical social challenge that faces developing and industrialized countries globally. Approximately three billion people live

4 Section TS-2.1 is based on Chapter 6.

5 Section TS-2.2 is based on Chapters 2 and 19.

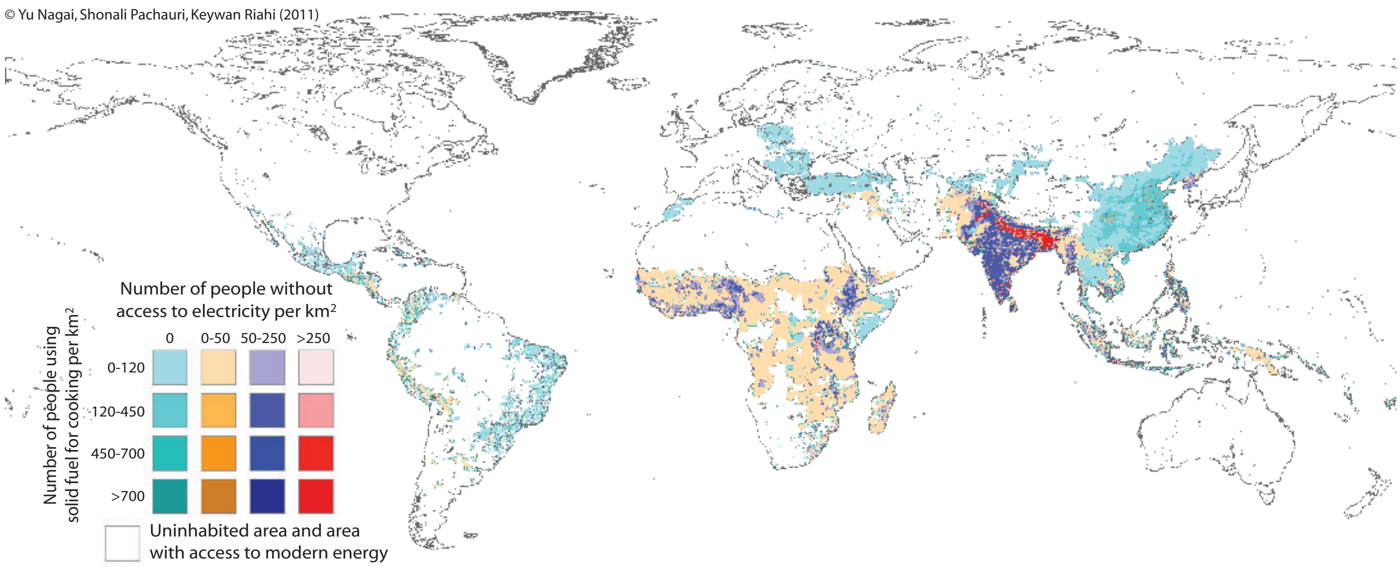


Figure TS-4 | Density of population lacking access to modern energy carriers in 2005. Colored areas show people per km² without access to electricity and those that use solid fuels for cooking, e.g., dark blue and red areas show where people do not have access to electricity and cook predominately using solid fuels. Source: Chapters 17 and 19.

on less than US$2 a day, with about 1.4 billion living in extreme poverty, on less than US$1.25 a day. The number of people with no access to electricity is 1.4 billion. Around 2.7 billion people rely on traditional biomass, such as fuel wood, charcoal, and agricultural residues (including animal dung), for cooking and heating, and another 400 million cook and/or heat with coal, making a total of around three billion people who rely on solid fuels for cooking and heating (see Figure TS-4).

Providing access to modern energy carriers and end-use conversion devices, such as cleaner cookstoves, is a major step to enable people living in poverty to improve their lives and reach the United Nations Millennium Development Goals and beyond.

Enhanced access to electricity, fuels and cleaner cooking systems can be an effective tool for improving health, for example by reducing air pollution, and can combat extreme hunger by increasing food productivity and reducing post-harvest losses. The energy technologies needed are relatively affordable, can often be produced locally, and in many cases do not require large-scale centralized energy supply options or costly infrastructure. Modern energy carriers, such as electricity and cleaner burning fuels, and end-use conversion devices can also improve education and school attendance by providing better energy services, such as lighting, heating, and cooling services. Electrifying rural health centers enables medical services to be provided at night, medicines to be preserved, and more-advanced medical equipment to be used.

Modern carriers and end-use conversion devices also encourage investments in capital goods that use electricity, which, in turn, allows the establishment of advanced agro-processing industries in rural areas, such as sugar production, milk cooling, grain milling, and food preservation. Processing will help make more food edible for longer, keep more money in local communities if the processing is done locally, and, in some cases, help farmers retain control of sales. These not only enhance rural incomes through increased sales and better prices, they also increase food production, and thereby contribute to reducing extreme hunger. Enhancing access among poor people, especially poor women, Is thus important for increasing their standard of living. Reducing the proportional cost of energy services is also important, particularly for the rural poor, who spend a significant part of their time and disposable income on energy. This can liberate financial and human resources for other important activities or expenses, such as education, purchasing more and better-quality food, and expanding income-generating activities.

2.3 Energy Security[6]

Energy security, that is, the uninterrupted provision of vital energy services, is critical for every nation. For many industrial countries, the key energy security challenges are dependence on imported fossil fuels and reliability of infrastructure. Many emerging economies have additional vulnerabilities, such as insufficient power generation capacity, high energy intensity, and rapid demand growth. In many low-income countries, multiple vulnerabilities of energy systems overlap, making them especially insecure.

Oil is at the center of contemporary energy-security concerns for most nations, regions, and communities. Oil products provide over 90% of transport energy in almost all countries. Thus, disruptions of oil supplies may have catastrophic effects, not only on personal mobility, but also on food production and distribution, medical care, national security, manufacturing, and other vital functions of modern societies. At the same time, conventional oil resources are increasingly concentrated in just a few

6 Section TS-2.3 is based on Chapter 5.

regions. The concerns over political stability affecting resource extraction and transport add to uncertainty. Moreover, the global production capacity of conventional oil is widely perceived as limited (see Section TS-3.1.1). Furthermore, the demand for transport fuels is steadily rising, especially rapidly in emerging Asian economies. Thus, for most countries, an ever higher share of their oil, or even all of it, must be imported. More than three billion people live in countries that import more than 75% of the oil and petroleum products they use (see Figure TS-5). An additional 1.7 billion people living in countries with limited domestic oil resources (including China) are likely to experience similarly high levels of import dependence in the coming decades.

The increasing concentration of conventional oil production, and the rapidly shifting global demand patterns, make some analysts and politicians fear a 'scramble for energy' or even 'resource wars'. These factors result in rising and volatile oil prices that affect all economies, especially low-income countries, almost all of which import over 80% of their oil supplies. The costs of energy imports (primarily oil products) exceed 20% of the export earnings in 35 countries that together are home to 2.5 billion people.

Import dependence is also common in countries that extensively use natural gas. Almost 650 million people live in countries that import over 75% of their gas. Most of these countries rely on a very limited number of gas suppliers (in many cases just one) and import routes. The risks of supply disruptions and price fluctuations are often the most serious energy security issues in such countries. The potential of recent shale gas technology developments to alleviate these concerns is at present uncertain.

Electricity systems in many low- and middle-income countries have inadequate generation capacity, low diversity of generation options, and low reliability of transmission and distribution systems. In over two-thirds of low-income countries, electricity supply is interrupted for at least one hour each day. Over 700 million people live in countries that derive a significant proportion of their electricity from only one or two major dams. Hydroelectric power production may also become insecure due to increased stress on global water supplies through increased population, agriculture, energy production, and climate change, which may affect seasonal water availability.

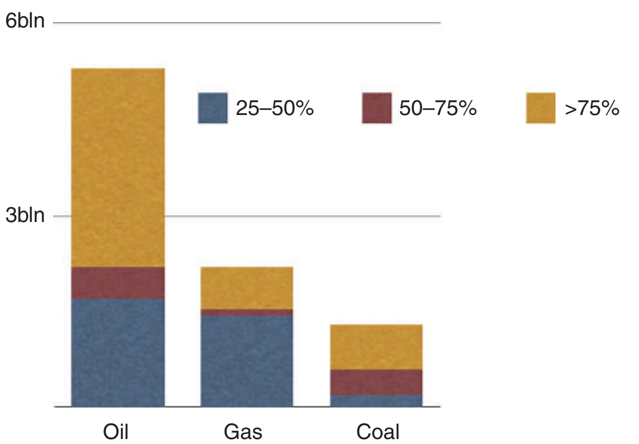


Figure TS-5 | Number of people in countries that are dependent on imported oil, gas and coal. Source: data from Chapter 5.

Many countries using nuclear power are experiencing an aging of the reactor fleet and workforce, as well as problems obtaining the capital and technologies to renew or expand nuclear programs. Twenty-one out of 29 countries with nuclear power plants have not started to build a new reactor in the last 20 years, and in 19 of these countries the average age of nuclear power plants is over 25 years. Large-scale enrichment, reactor manufacturing, and reprocessing technologies are currently concentrated in just a few countries (see Figure 5.5 in Chapter 5). The spread of enrichment or reprocessing to a larger number of countries is opposed by concerns over nuclear weapons proliferation – one of the main controversies – and the risks and costs associated with nuclear energy.

Another energy security issue is 'demand security'. Vital energy export revenues play a major part in the economies of some 15–20 mainly low- or middle-income countries. In many cases these revenues are not expected to last for more than one generation, and in several cases they may cease in less than a decade. In addition, poor energy-exporting nations are at a high risk of the 'resource curse': economic and political instability eventually affecting human development and security. The present economic and social importance of energy export revenues should be recognized in international arrangements, while diversifying the economies of countries excessively dependent on energy exports is also a high priority in dealing with 'demand security'.

2.4 Environment[7]

Linkages between the energy system and the environment are seen on multiple levels and scales – from local to global. While the local environmental and ecological consequences of resource extraction, processing, and energy conversion have been long recognized, attention is increasingly turning toward the growing evidence that humanity has reached a phase when anthropogenic pressures on Earth systems – the climate, oceans, freshwater, and the biosphere – risk irreversible disruption to biophysical processes on the planetary scale. The risk is that systems on Earth may then reach tipping points, resulting in non-linear, abrupt, and potentially irreversible change, such as destabilization of the Greenland ice sheet or tropical rainforest systems.

The challenges are illustrated in Figure TS-6, showing planetary boundaries for nine Earth system processes, which together define a safe operating space for humanity (indicated by the green area), within which human development stands a good chance of proceeding without large-scale deleterious change. Estimates indicate that the safe levels are being approached or, in some cases, transgressed. Energy systems contribute to humanity's approach to many of the planetary boundaries,

7 Section TS-2.4 is based on Chapters 3 and 17.

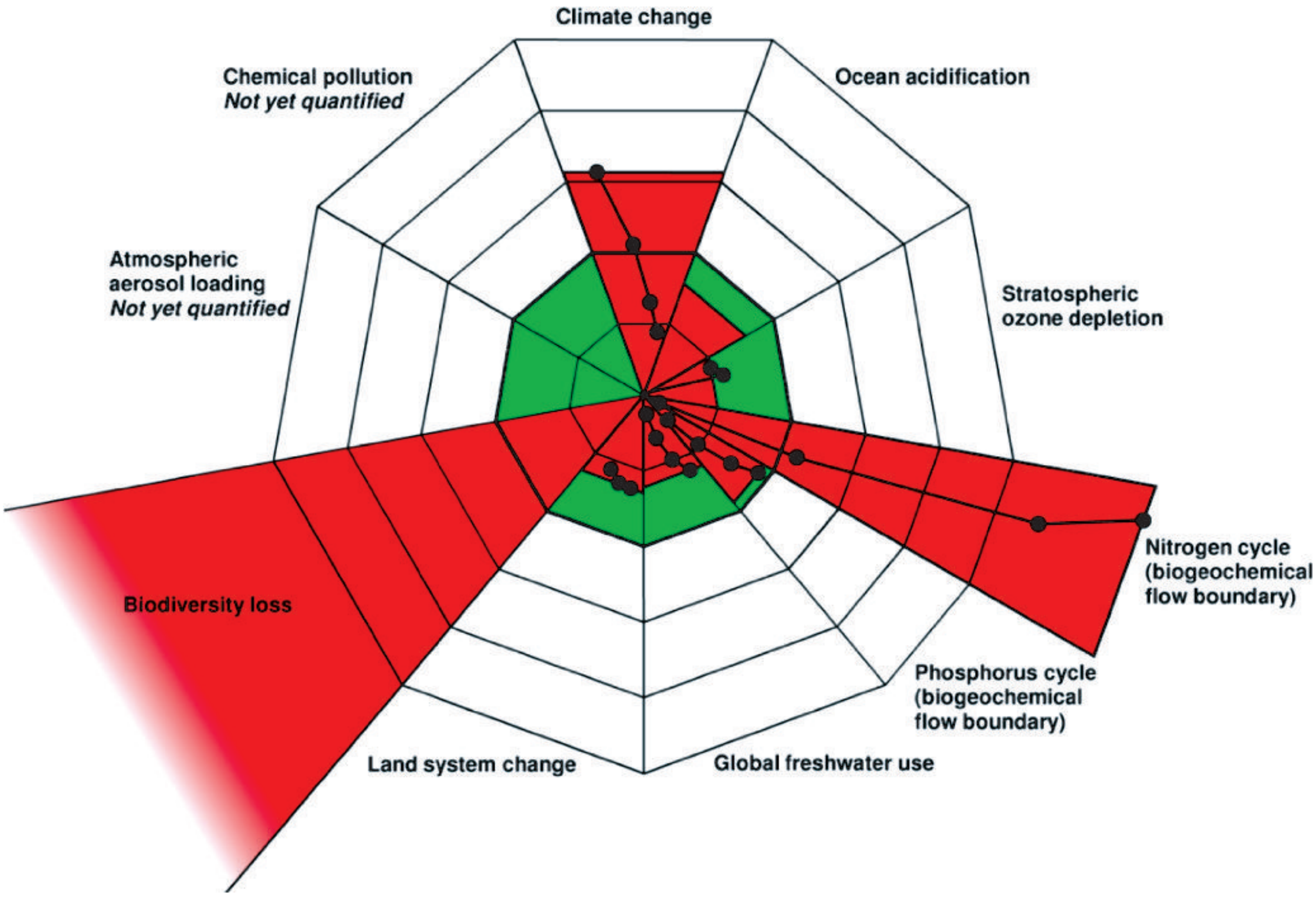


Figure TS-6 | Current global state of the world for the 10 proposed planetary boundaries. The green area denotes a "safe operating space" for human development, and red indicates the current position for each boundary process. The dots indicate evolution by decade from the 1950s. Source: Chapter 3.

and in particular climate change, aerosol loading, ocean acidification, biodiversity loss, chemical pollution, land system change, the nitrogen cycle, and fresh water use.

In 2005, energy supply and use contributed around 80% of CO_2 emissions and 30% of methane emissions (Chapter 1), as well as large fractions of other substances, such as black carbon, organic carbon, and aerosols that can either warm or cool the atmosphere, depending on their composition. Energy systems are furthermore tightly linked to land and freshwater use through dependence on water and land resources for energy generation. They are also linked to ecosystem services and air quality through emissions of particulate matter and atmospheric pollutants, such as nitrogen and sulfur oxides, and precursors of tropospheric ozone that can lead to acidification, eutrophication, and reduced net primary productivity. Consequently, the energy system has a critical part to play in achieving global sustainability.

One of the areas of concern most influenced by energy systems is climate change. Threats to agriculture, biodiversity, ecosystems, water supply in some areas and floods in others, sea levels, and many other environmental aspects will continue to worsen unless climate change is curbed significantly. Moreover, degradation of land, biodiversity, and freshwater resources, which are closely related to energy generation and use, has accelerated climate change. In response to this challenge, the global community decided to take actions to limit anthropogenic warming to less than 2°C above pre-industrialized levels (UNFCC, Decision 1/CP.16). This stabilization target is the normative goal adopted by GEA and is reflected in all pathways toward a more sustainable future (see Section TS-4). GEA recognizes however, that even a 2°C target may lead to large adverse effects, including risks of reaching tipping points, thus highlighting the need for an even more ambitious target.

Limiting global temperature increase to less than 2°C above pre-industrial levels (with a probability of greater than 50%) requires rapid reductions of global CO_2 emissions from the energy sector with a peak around 2020 and a decline thereafter to 30–70% below 2000 emissions levels by 2050, finally reaching almost zero or even negative CO_2 emissions in the second half of the century (see Figure TS-7). Given that even a 2°C target will likely lead to significant impacts, assuring only a 50% chance of success is a rather low bar to set. A higher probability of meeting the 2°C target, or a lower temperature-increase target, would require higher emission reductions by 2050 and beyond. In particular, the later

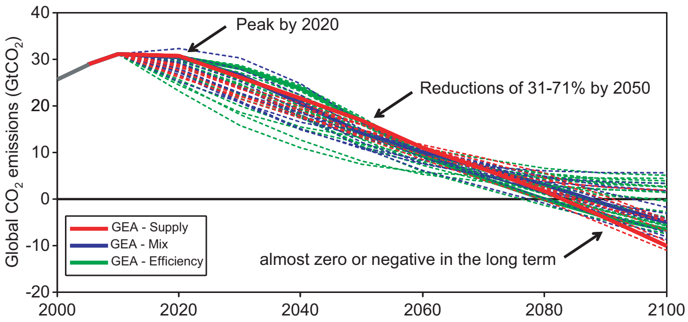


Figure TS-7 | Development of global CO_2 emissions from energy and industrial sources to limit temperature change to below 2°C (with a probability of >50%). Shown is that the emissions need to peak by around 2020 (or earlier) and decline toward zero during the following four to five decades. The later the peak occurs, the steeper the decline needs to be and higher the net 'negative' emissions. The latter can be achieved in the energy system through CCS in conjunction with the use of sustainable biomass. Source: Chapter 17. For further details of the GEA pathways see the interactive web-based GEA scenario database hosted by IIASA: www.iiasa.ac.at/web-apps/ene/geadb.

the emissions peak, the higher the need for net 'negative' emissions in the second half of the century, for example, by using biomass together with carbon capture and storage (CCS) (see Section TS-3.3.2.2).

Reducing emissions of both long-lived GHGs, such as CO_2, and short-lived climate forcers, such as ozone precursors and black carbon (both emitted, for example, from the combustion of diesel fuel and household biomass fuel), is essential. Reducing short-lived climate forcers is critical to slow the rate of near-term climate change and provides a far greater likelihood of achieving the 2°C target when coupled with aggressive measures to also bring down long-lived GHG emissions.

The focus on planetary-scale impacts does not reduce the importance of addressing local and regional environmental and ecological impacts. Atmospheric pollutants may limit the net primary productivity of ecosystems, and lead to the acidification and eutrophication of land and seascapes. Land is affected through loss or damage to ecosystems from land-use change and contamination from energy-related waste arising from activities such as mining, drilling, and the transport of fossil fuels. In addition, disaster mitigation systems need to be continually developed and implemented to avert energy-related environmental disasters, for example, from nuclear accidents, oil rig explosions, oil tanker spills, flooding from hydroelectric dam bursts, and so on.

Differences in energy provisioning systems around the world cause variability in the environmental challenges. Reducing such problems requires policy implementation targeted at the most threatening environmental effects specific to a nation and region. Problems may arise when the impacts considered a priority at the regional scale differs from those at the global scale.

In such situations, international cooperative approaches may be required to provide economic and social infrastructural support to address both national and regionally perceived priorities, and more internationally driven concerns over environmental threats and the ability to remain within the safe operating limits of planetary boundaries.

2.5 Health[8]

Energy systems are currently responsible for a large proportion of the global burden of disease, which is in the order of five million premature deaths annually from air pollution and other energy-related causes and more than 8% of all ill health (lost healthy life years from both morbidity and premature mortality) (see Table TS-1).

Air pollution from incomplete combustion of fuels and biomass burning is a major contributor to ill health. As cooking fuel is the greatest source of household indoor air pollution, and a significant source of outdoor pollution, access to cleaner cooking (see Section TS-2.2) would provide significant improvement. Outdoor air pollution in both urban and rural areas accounted for 2.7 million premature deaths globally in 2005, while about 2.2 million premature deaths are estimated to occur annually from exposure to indoor air pollution in developing countries, mainly among women, the elderly, and young children. Other sources of outdoor air pollution include the transportation sector, industry, power plants, and space conditioning.

Occupational health impacts, particularly from harvesting/mining and processing biomass and coal, are currently the next most important impact on health from energy systems. Miners are exposed to collapsing mine shafts, fire and explosion risks, toxic gases (carbon monoxide), lung-damaging dusts (coal and silica), and hot work environments, as well as injury and ergonomics hazards. Oil and gas workers face injury risks, particularly during drilling, emergency situations, and work on offshore platforms, as well as exposure to toxic materials at refineries.

Unlike biomass and fossil fuels, nuclear power systems are not a significant source of routine health impacts, although they often garner considerable public and policy concern. Average radiation doses to workers in nuclear power industries have generally declined over the past two decades. For nuclear power facilities, as with large hydroelectric facilities, the major health risks lie mostly with high-consequence but low-probability accidents.

Climate change is beginning to have an important impact on health, causing an estimated 150,000 premature deaths in 2000, with more than 90% of these occurring among the poorest populations in the world. Both the direct health burden and the share of climate change impacts due to energy systems are expected to rise under current projections of GHG emissions and changing background health conditions in vulnerable populations. By 2010, this impact may have doubled.

8 Section TS-2.5 is based on Chapter 4.

Table TS-1 | Global burden of disease in 2000 from air pollution and other energy-related causes. These come from the Comparative Risk Assessment (CRA) published in 2004 by the World Health Organisation. GEA estimates for 2005 of outdoor air pollution and household solid fuel use in Chapter 17 are substantially larger, but were not done for all CRA risk pathways shown. Estimates for 2010 in the new CRA will be released in 2012 and will again include all pathways in a consistent framework.

	Total Premature Deaths – million	Percent of all Deaths	Percent of Global Burden in DALYs	Trend
Direct Effects [except where noted, 100% assigned to energy]				
Household Solid Fuel	1.6	2.9	2.6	Stable
Energy Systems Occupational*	0.2	0.4	0.5	Uncertain
Outdoor Air Pollution	0.8	1.4	0.8	Stable
Climate Change	0.15	0.3	0.4	Rising
Subtotal	2.8	5.0	4.3	
Indirect Effects (100% of each)				
Lead in vehicle Fuel	0.19	0.3	0.7	Falling
Road Traffic Accidents	0.8	1.4	1.4	Rising
Physical Inactivity	1.9	3.4	1.3	Rising
Subtotal	2.9	5.1	3.4	
Total	5.7	10.1	7.7	

* One-third of global total assigned to energy systems.

Notes: These are not 100% of the totals for each, but represent the difference between what exists now and what might be achieved with feasible policy measures. Thus, for example, they do not assume the infeasible reduction to zero traffic accidents or air pollution levels. DALYS = disability adjusted life years.

Source: Chapter 4

2.6 Goals Used in the Assessment and in the GEA Pathways Analysis

For many of the energy-related challenges different goals have been articulated by the global community, in many instances including specific quantitative targets. This sub-section summarizes the concrete goals in major areas that require changes to energy systems, based on Section TS-2. Meeting these goals simultaneously has served as the generic framework for all assessments in GEA. The GEA pathways, described and elaborated in Section TS-4, illustrate how societies can reach the global normative goals of welfare, security, health, and environmental protection outlined below, simultaneously with feasible changes in energy systems.

The selection of indicators and quantitative target levels summarized here is a normative exercise, and the level of ambition has, to the extent possible, been guided by agreements and aspirations expressed through, for example, the United Nations system's actions and resolutions, and from the scientific literature. This, of course, only refers to the necessary changes of the local and global energy systems; much more is required in other sectors of societies for overall sustainability to be realized.

In the GEA pathways analysis, the global per capita gross domestic product (GDP) increases on average by 2% per year through 2050, mostly driven by growth in developing countries. This growth rate declines in the middle of existing projections. Global population size is projected to plateau at about nine billion people by 2050. Energy systems must be able to ***deliver the required energy services*** to support these economic and demographic developments.

Universal access to affordable modern energy carriers and end-use conversion (especially electricity and cleaner cooking)[9] by 2030 for the 1.4 billion people without access to electricity and the three billion people who still rely on solid and fossil fuels for cooking is a prerequisite for poverty alleviation and socioeconomic development.

Enhanced energy security for nations and regions is another key element of a sustainable future. Reduced global interdependence via reduced import/export balances and increased diversity and resilience of energy supply have been adopted as key energy-related metrics. The targets for these goals were assessed ex-post through the GEA pathways analysis (Chapter 17), identifying the need for energy efficiency improvements and deployment of renewables to increase the share of domestic (national or regional) supply in primary energy by a factor of two, and thus significantly decrease import dependency (by 2050). At the same time, the share of oil in global energy trade is reduced from the present 75% to below 40% and no other fuel assumes a similarly dominant position in the future.

9 See Chapter 2.2.

The ***climate change mitigation*** goal is to, at a minimum, contain the global mean temperature increase to less than 2°C above the pre-industrial level, with a probability of at least 50%. This implies global CO_2 emissions reductions from energy and industry to 30–70% of 2000 levels by 2050, and approaching almost zero or net negative emissions in the second half of the century.

Health and environment goals include controlling household and ambient air pollution, ocean acidification, and deforestation. Emissions reductions through the use of advanced fuels and end-use technologies for household cooking and heating can significantly reduce human morbidity and mortality due to exposure to household air pollution, as well as help reduce ambient pollution. In the GEA pathways, this is assumed to occur for the vast majority of the world's households by 2030. Similarly, a majority of the world's population is also expected to meet WHO air-quality guidelines (annual PM2.5 concentration[10] <10 μg/m^3), while the remaining population is expected to stay well within the WHO Tier I-III levels (15–35 μg/m^3) by 2030. In addition, there needs to be a major expansion of occupational health legislation and enforcement in the energy sector.

There are also a number of other concerns related to how energy systems are designed and operated. For example, activities need to be occupationally safe, a continuing concern as nano-technologies and other new materials are used in energy systems. Other impacts such as oil spills, freshwater contamination and overuse, and releases of radioactive substances must be prevented (ideally) or contained. Waste products must be deposited in acceptable ways to avoid health and environmental impacts. These issues mostly influence local areas, and the regulations and their implementation are typically determined at the national level. The analysis of indicators and pathways to sustainability in Section TS-4 assumes that such concerns and impacts are under control.

Reaching these goals simultaneously requires transformational changes to the energy system in order to span a broad range of opportunities across urban to rural geographies, from developing to industrial countries, and in transboundary systems. The ingredients of this change are described in the Section TS-3.

3 Options for Resources and Technologies

This section assesses the building blocks that can be used for transforming energy systems toward a sustainable future, including the available resources, whether fossil fuels, fissile material, or renewable energy flows. It assesses technology options on the demand and supply sides and concludes with some insights from a comparative evaluation of options. We begin with a brief description of current global and regional energy systems.

The ultimate purpose of energy systems is to deliver energy that either directly or indirectly provides goods and services to meet people's needs and aspirations. The *energy system* includes all steps in the chain – from primary energy resources to energy services (see Figure TS-8). The *energy sector* refers to the steps in the chain, from the extraction of primary energy resources through to the delivery of final energy carriers for use in end-use technologies that produce energy services or goods. In economic terms, the energy sector includes those businesses responsible for the different steps in this chain.

It is important to define that, for GEA purposes, energy services refer to illumination, information and communication, transport and mobility of people and goods, hot water, thermal comfort, cooking, refrigeration, and mechanical power. Electricity and kerosene are examples of energy carriers, not energy services. All goods and services are provided using energy and thus have energy embedded in them; however, they are not energy services *per se*.

The supply side of energy systems consists of energy resources and the technologies that convert them into energy carriers for final use. Increased demand for improved energy services, mostly in developing countries, and driven in part by population growth and socioeconomic development, is inevitable. Meeting the increased global demand will require a transformation of current energy supply systems (as well as of conversion and end-use systems, as previously described) globally. Such a transformation is not a new phenomenon. Figure TS-1 shows how the relative role of different sources has varied during the growth of global primary energy over the decades. The first transition was from biomass to coal, followed by the transition from coal to oil, which currently remains the largest source of primary energy, although natural gas is steadily increasing its share.

The energy supply situation in 2005 is illustrated by Figure TS-9. Fossil fuels dominate in all regions of the world, with oil having the largest share in the Organisation for Economic Co-operation and Development (OECD), Countries the Middle East and Africa (MAF), and Latin America and the Caribbean (LAC), while coal dominates in Asia and natural gas in Eastern Europe and the Former Soviet Union (REF).

The distribution of primary sources of energy in 2005 shows fossil fuels contributing over 78%, renewables (including large hydro) over 16%, and nuclear over 5% (Figures TS-9 and TS-10). In 2009, fossil fuels were used in 68% of electricity generation, hydropower contributed 16%, nuclear 13.5%, and other renewables contributed 2.6% (see Figure TS-17).

10 PM2.5 refers to particulate matter less than 2.5 micrometers in size.

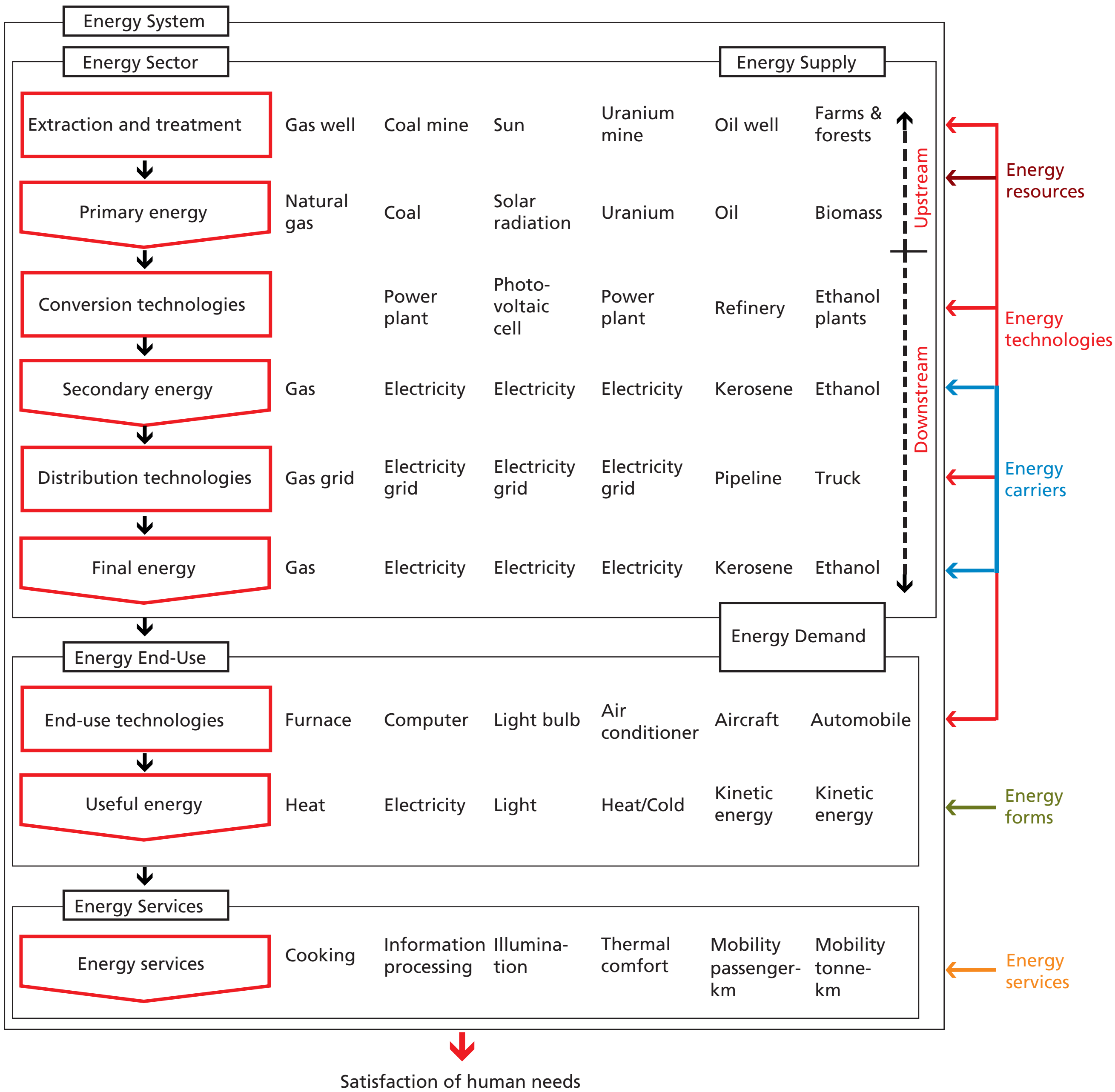


Figure TS-8 | Schematic diagram of the energy system with some illustrative examples of the energy sector, energy end-use, and energy services. The energy sector includes energy extraction, treatment, conversion, and distribution of final energy. The list is not exhaustive and the links shown between stages are not 'fixed'; for example, natural gas can also be used to generate electricity, and coal is not used exclusively for electricity generation. Source: adapted from Nakicenovic et al., 1996b; see Chapter 1.[11]

3.1 Energy Resources

An energy resource is the first step in the energy services supply chain. Provision of energy carriers is largely ignorant of the particular resource that supplies them, but the infrastructure, supply, and demand technologies, and fuels along the delivery chain, often depend highly on a

11 **Nakicenovic, N., A. Grubler, H. Ishitani, T. Johansson, G. Marland, J. R. Moreira and H.-H. Rogner, 1996b:** Energy primer. In *Climate Change 1995 – Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses, Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* R. T. Watson, M. C. Zinyowera and R. H. Moss (eds.), Cambridge University Press, Cambridge, UK, pp.75–92.

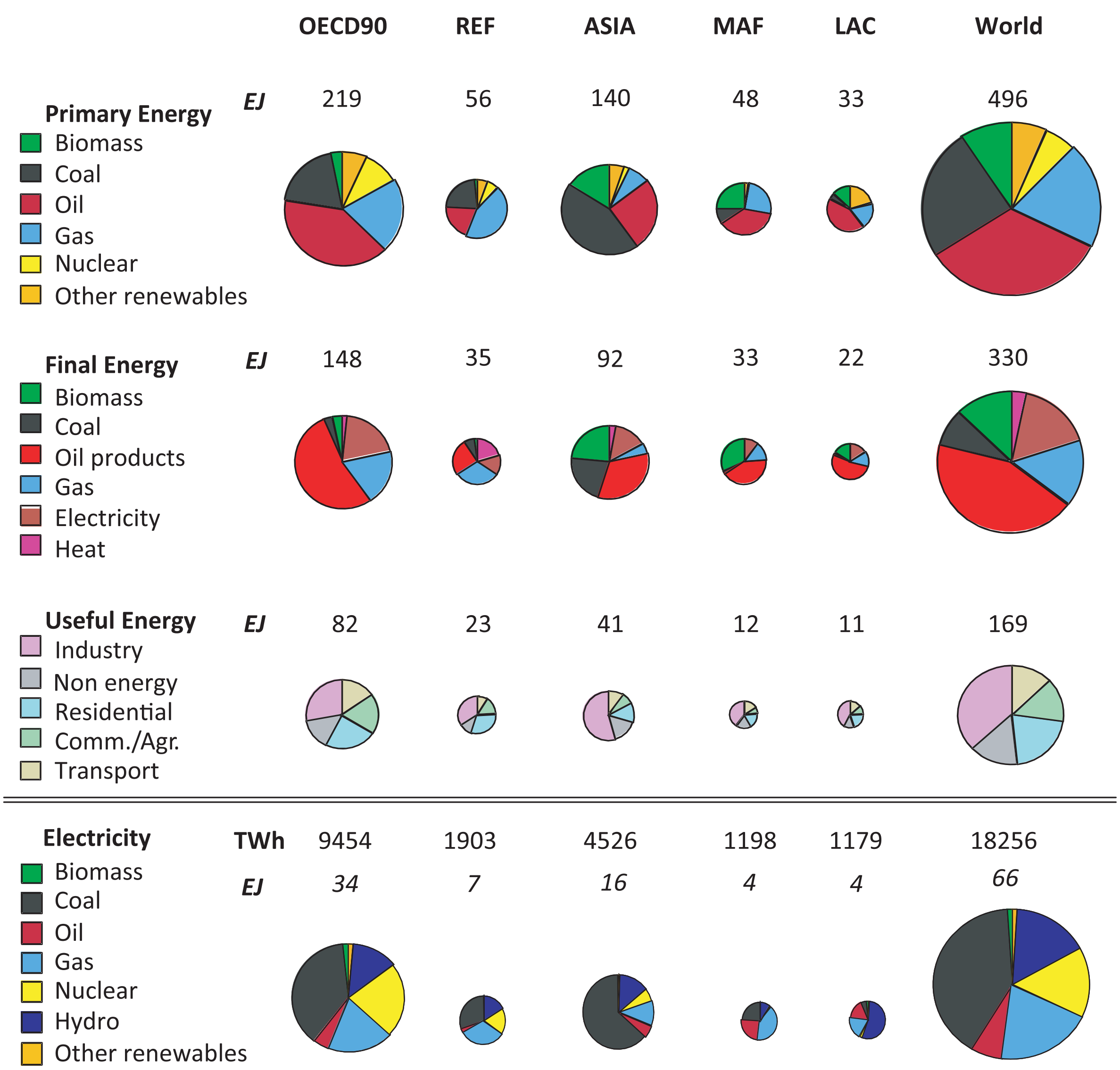


Figure TS-9 | World primary energy (by source), final energy (by energy carrier), useful energy (by sector/type of energy service), and electricity generated by different energy sources for 2005, World and five GEA regions.[12] Primary, final, and useful energy in EJ and electricity in TWh and EJ; feedstocks are included. Note: circle areas are proportional to electricity generated, but electricity graphs are not to the same scale as those for other energy forms; 1 TWh = 0.0036 EJ. Source: Chapter 1.

particular type of resource. The availability and costs of bringing energy resources to the point of end-use are key determinants of affordable and accessible energy carriers.

The availability of energy resources *per se* poses no inherent limitation to meeting the rapidly growing global energy demand as long as adequate upstream investments are forthcoming for exhaustible resources in exploration, production technology, and capacity and, by analogy, for renewables in conversion technologies. However, exploitation of sufficient energy resources will require major investments and is not without significant environmental and other consequences.

12 The five GEA regions consist of OECD90, which includes the UNFCCC Annex I countries; REF, which includes Eastern Europe and the Former Soviet Union; Asia, which excludes Asian OECD countries; MAF consisting of the Middle East and Africa; and LAC, which includes Latin America and the Caribbean.

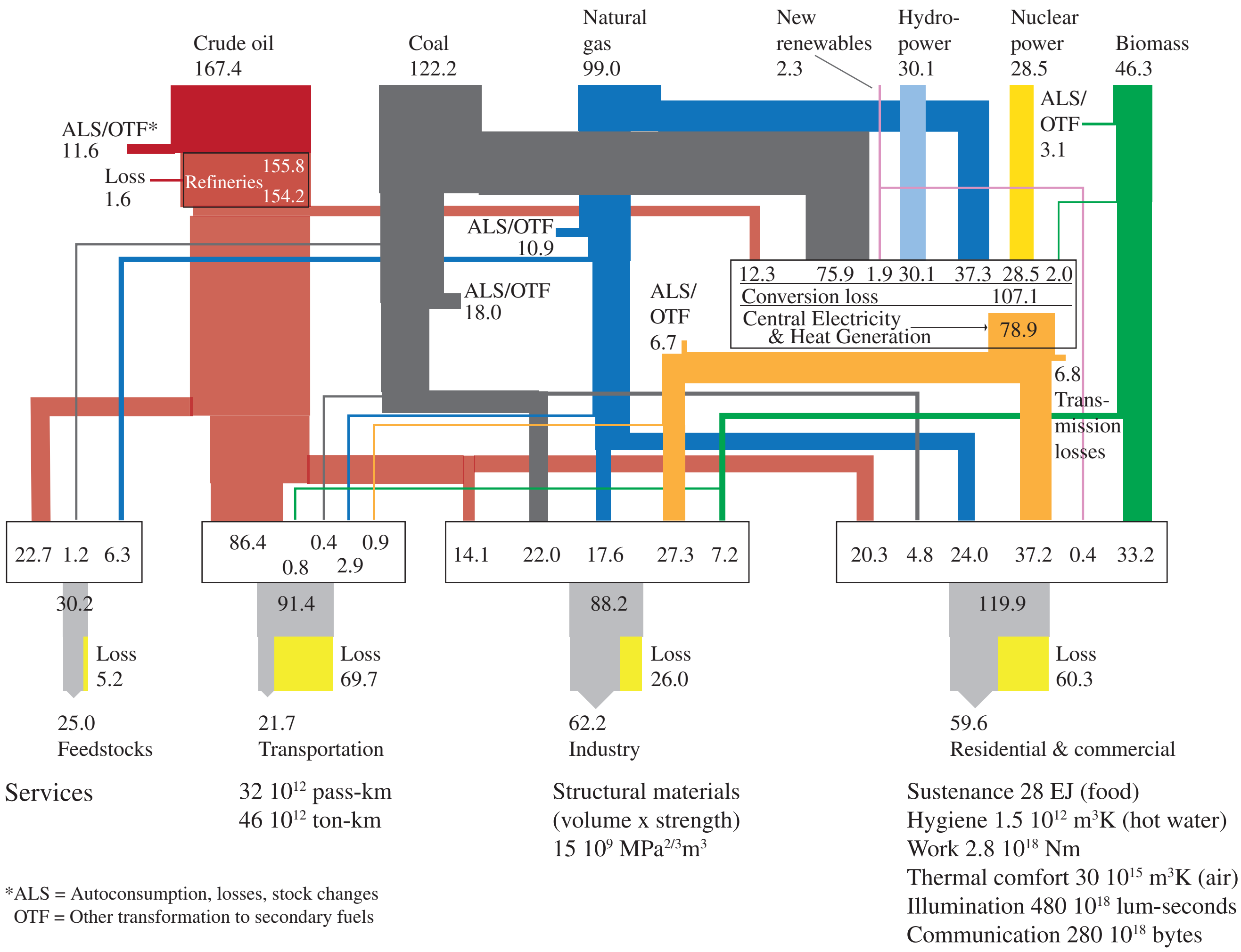


Figure TS-10 | Global energy flows (in EJ) from primary to useful energy by primary resource input, energy carrier (fuels), and end-use sector applications in 2005. Source: data from IEA, 2007a; 2007b (corrected for GEA primary energy accounting standard) and Cullen and Allwood, 2010, see Chapter 1.[13]

3.1.1 Hydrocarbons and Fissile Resources[14]

Hydrocarbons and fissile materials are plentiful in the Earth's crust, yet they are finite. The extent of ultimately recoverable oil, natural gas, coal, or uranium has been subject to numerous reviews, and there are wide ranges of estimates in the literature (see Table TS-2). For example, figures between 4900 and 13,700 exajoules (EJ) for conventional oil reserves and resources have caused continued debate and controversy. Such large ranges can be the result of varying boundaries of what is included in the analysis of a finite stock of an exhaustible resource (e.g., conventional oil only, or conventional oil plus unconventional occurrences such as oil shale, tar sands, and extra-heavy oils). Uranium resources are a function of the level of uranium ore concentrations in the source rocks considered technically and economically extractable over the long run as well as the prospects of tapping into the vast amounts in sea water.

Oil production from difficult-to-access areas or from unconventional resources is not only more energy-intensive, it is also technologically and environmentally more challenging. Production from tar sands, shale oil, and gas, or the deep-sea production of conventional oil and gas, raise further environmental risks – ranging from oil spillages, ground- and freshwater contamination, and GHG emissions, to the release of toxic materials and radioactivity. A significant fraction of the energy gained needs to be reinvested into the extraction of the next unit, adding to already higher exploration and production costs.

13 **IEA, 2007a:** *Energy Balances of OECD Countries*. International Energy Agency (IEA), IEA/OECD, Paris, France.
IEA, 2007b: *Energy Balances of Non-OECD Countries*. International Energy Agency (IEA), IEA/OECD, Paris, France.
Cullen, J. M. and J. M. Allwood, 2010: The efficient use of energy: Tracing the global flow of energy from fuel to service. *Energy Policy*, **38**: 75–81.

14 Section TS-3.1.1 is based on Chapter 7.

Table TS-2 | Fossil and uranium reserves, resources, and occurrences.[a]

	Historical production through 2005	Production 2005	Reserves	Resources	Additional occurrences
	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]
Conventional oil	6069	147.9	4900–7610	4170–6150	
Unconventional oil	513	20.2	3750–5600	11,280–14,800	>40,000
Conventional gas	3087	89.8	5000–7100	7200–8900	
Unconventional gas	113	9.6	20,100–67,100	40,200–121,900	>1,000,000
Coal	6712	123.8	17,300–21,000	291,000–435,000	
Conventional uranium[b]	1218	24.7	2400	7400	
Unconventional uranium	34	n.a.		7100	>2,600,000

[a] The data reflect the ranges found in the literature; the distinction between reserves and resources is based on current (exploration and production) technology and market conditions. Resource data are not cumulative and do not include reserves.

[b] Reserves, resources, and occurrences of uranium are based on a once-through fuel cycle operation. Closed fuel cycles and breeding technology would increase the uranium resource dimension 50–60 fold. Thorium-based fuel cycles would enlarge the fissile-resource base further.

Source: Chapter 7

Historically, technology change and knowledge accumulation have largely counterbalanced otherwise dwindling resource availabilities or steadily rising production costs (in real terms). They extended the exploration and production frontiers, which, to date, have allowed the exploitation of all finite energy resources to grow. The questions now are whether technology advances will be able to sustain growing levels of finite resource extraction, and what the necessary stimulating market conditions will be.

Resources first need to be identified and delineated before the technical and economic feasibility of their extraction can be determined. But having identified resources in the ground does not guarantee either that they can be technically recovered or their economic viability in the marketplace. The viability is determined by the demand for a resource (by the energy service-to-resource chain), the price it can obtain over time, and the technological capability to extract the resource efficiently.

Thus, timely aboveground investment in exploration and production capacities is essential in unlocking belowground resources. Private-sector investment is governed by expected future market and price developments, while public-sector investment competes with other development objectives. At least 10 years can elapse between investment in new production capacities and the actual start of deliveries, especially for the development of unconventional resources. Until new large-scale capacities come online, uncertainty and price volatility will prevail.

Nuclear fuel reserves are sufficient for approximately 100 years of consumption at today's production rates (see Table TS-2). The resources are much larger and, if uranium in seawater is included, practically sufficient for much longer, even with an expansion of global nuclear capacity.

There appears to be a consensus that there are sufficient fossil (for oil, see Figure TS-11) and fissile energy resources to fuel global energy

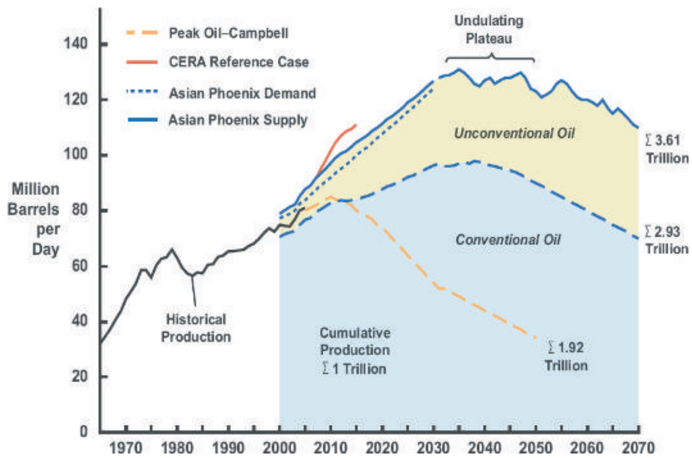


Figure TS-11 | The figure shows future oil production projections, comparing an undulating plateau with a peak oil projection. The Campbell peak oil projections is from Campbell (see Chapter 7) and is shown together with more optimistic projections of increased use of conventional oil resources as well as the use of unconventional oil resources. Source: Witze, 2007; see Chapter 7.[15]

needs for many decades. There is much less consensus as to their actual future availability in the marketplace. This availability is dependent on the balance between a variety of constraining and enabling factors. For example, the factors that can reduce the accessible stocks and flows from them include:

- smaller and smaller deposits in harsher and harsher environments, leading to rising exploration, production, and marketing costs;
- excessive environmental burdens;

15 **Witze, A., 2007:** Energy: That's oil folks…, *Nature*, **445**: 14–17.

Table TS-3 | Renewable energy flows, potential, and utilization in EJ of energy inputs provided by nature.[a]

	Primary Energy 2005[b] [EJ]	Utilization 2005 [EJ]	Technical potential [EJ/yr]	Annual flows [EJ/yr]
Biomass, MSW, etc.	46.3	46.3	160–270	2200
Geothermal	0.78	2.3	810–1545	1500
Hydro	30.1	11.7	50–60	200
Solar	0.39	0.5	62,000–280,000	3,900,000
Wind	1.1	1.3	1250–2250	110,000
Ocean	-	–	3240–10,500	1,000,000

[a] The data are energy-input data, not output. Considering technology-specific conversion factors greatly reduces the output potentials. For example, the technical 3150 EJ/yr of ocean energy in ocean thermal energy conversion (OTEC) would result in an electricity output of about 100 EJ/yr.

[b] Calculated using the GEA substitution method (see Chapter 1, Appendix 1.A.3).

Source: Chapter 7 (see also Chapter 11 for a discussion of renewable resource inventories and their differences). Note: MSW = municipal (and other) solid wastes.

- diminishing energy ratios;
- low rate of technological advances; and
- public intolerance of accident risks.

On the other hand, demand, high prices (plus associated investments), innovation, and technology change tend to increase stock sizes and flow rates. The question is: which combinations of these forces acting in opposite directions are going to govern fuels production in the mid to long term? It is likely that, due to the constraints, only a fraction of these resources may ever be produced.

In conclusion:

- Hydrocarbon resources are huge compared with conceivable future energy needs, but realizing any significant proportion of these available resources will require major investments and is not without significant consequences.
- Development of these resources and potentials is subject to many constraints, but not by a constraint on physical availability.
- The peak of oil and other fossil fuels is not caused by the lack of resources, but rather by other changes, such as the transformation toward sustainable futures and perhaps insufficient investments in the supply chains.

3.1.2 Renewable Energy Flows[16]

Renewable energy resources comprise the harvesting of naturally occurring energy flows. While these flows are abundant (see Table TS-3) and far exceed (by orders of magnitude) the highest future energy demand imagined for global energy needs, the challenge lies in developing adequate technologies to manage the often low or varying energy densities and supply intermittencies and to convert them into usable energy carriers or utilize them for meeting energy demands.

Solar radiation reaching the Earth's surface amounts to 3.9 million EJ/yr and, as such, is almost 8000 times larger than the annual global energy needs of some 500 EJ. Accounting for cloud coverage and empirical irradiance data, the local availability of solar energy is 633,000 EJ. The energy carried by wind flows is estimated at about 110,000 EJ/yr, and the energy in the water cycle amounts to more than 500,000 EJ/yr, of which 200 EJ/yr could theoretically be harnessed for hydroelectricity. Net primary biomass production is approximately 2400 EJ/yr, which after deducting the needs for food and animal feed, leaves, in theory, some 1330 EJ/yr for energy purposes. The global geothermal energy stored in the Earth's crust up to a depth of 5000 meters is estimated at 140,000 EJ/yr, with the annual rate of heat flow to the surface of about 1500 EJ/yr. Oceans are the largest solar energy collectors on Earth, absorbing on average some one million EJ/yr.

The amounts of these gigantic annual energy flows that can be technically and economically utilized are significantly lower, however. Renewables, except for biomass, convert resource flows directly into electricity or heat. Their technical potentials are limited by factors such as geographical orientation, terrain, or proximity of water, while their economic potentials are a direct function of the performance characteristics of their conversion technologies within a specific local market setting. The data shown in Table TS-3 are the energy input potentials provided by nature.

3.2 Energy End-Use

The sectoral and regional distributions of per capita final energy use are shown in Figure TS-2. Globally, of a total final energy use in 2005 of

16 Section TS-3.1.2 is based on Chapters 7 and 11.

330 EJ, three sectors dominate – buildings (residential and public/commercial) is the largest sector with 34% (112 EJ), followed by transport at 28% (91 EJ), and industry with 27% (88 EJ). The relative shares of these sectors vary somewhat by region, with high-income countries having greater shares of residential, commercial, public, and transportation energy use, while residential and industrial sectors dominate the energy use in low-income countries. Therefore, this section reviews the options for enhancing efficiency in the industry, transportation, and buildings sectors.

3.2.1 Industry[17]

As noted, the industrial sector accounted for about 27% (88 EJ) of global final energy use in 2005. The production of materials – chemicals, iron and steel, non-metallic minerals (including cement), non-ferrous metals, paper and pulp, and mining – accounts for about 70% of global industrial final energy use. The final energy use of 88 EJ in 2005 excludes the energy use in coke ovens and blast furnaces, and feedstock energy use for petrochemicals. The addition of the energy inputs for these subsectors results in a final energy use of 115 EJ in 2005.

There has been a geographic shift in primary materials production, with developing countries accounting for the majority of production capacity. China and India have high growth rates in the production of energy-intensive materials like cement, fertilizers, and steel (12–20% per year after 2000). In other economies, the demand for materials is seen to grow initially with income and then stabilizes. For example, in industrial countries per capita use seems to reach saturation at about 400–500 kilograms for cement and about 500 kilograms for steel.

The aggregate energy intensity in the industrial sector in different countries has shown steady declines due to improvements in energy efficiency and a change in the structure of the industrial output. In the EU-27, for example, the final energy use by industry has remained almost constant (13.4 EJ) at 1990 levels despite output growth; 30% of the reduction in energy intensity is due to structural changes, with the remainder due to energy efficiency improvements.

In different industrial sectors, adopting the best achievable technology can result in savings of 10–30% below the current average costs. An analysis of cost-cutting measures in 2005 indicated energy savings potentials of 2.2 EJ for motors and 3.3 EJ for steam systems. The economic payback period for these measures ranges from less than nine months to four years. A systematic analysis of materials and energy flows indicates significant potential savings for process integration, heat pumps, and cogeneration.

An exergy analysis (the second law of thermodynamics) reveals that the overall global industry efficiency is only 30%. Clearly, there are major energy efficiency improvements possible through research and development (R&D) in next-generation processes. The effective use of demand-side management can be facilitated by a combination of mandated measures and market strategies. To level the playing field for energy efficiency, a paradigm shift is required – with a focus on energy services, not energy supply *per se*. This requires a reorientation of energy supply, distribution companies, and energy equipment manufacturing companies.

Nevertheless, such a transformation has multiple benefits. Improved energy efficiency in industry results in significant energy productivity gains, for example, in improved motor systems; compressed air systems; ventilation, heat recovery, and air conditioning systems; and improvements in comfort and working environments through better lighting, thermal comfort, and reduced indoor air pollution from improved ventilation systems, and, in turn, improved productivity boosts corporate competitiveness.

Policies and capacity development to capture the opportunities are needed globally. New business models are also needed and are being deployed to deliver a transformation that shifts the focus to energy services. For example, energy service companies (ESCOs) are already a multibillion dollar market per year globally, and substantial new business opportunities await progressive enterprises and innovative technological and business initiatives.

A frozen efficiency scenario based on today's technologies (close to the GEA counterfactual pathway, see Section TS-4) has been constructed for industry between 2005 and 2030, which implies a demand for final energy of 225 EJ in 2030. This involves an increase of the industrial energy output in terms of manufacturing value added of 95% over the 2005 value. Owing to normal efficiency improvements from new technology designs over time, the BAU scenario results in a final energy demand being reduced from 225 EJ to 175 EJ in 2030.

An aggressive energy-efficient scenario (consistent with the GEA-Efficiency pathway, see Section TS-4) can result in a significant reduction in the energy intensity of the industrial sector. Such a scenario for 2030 has been constructed with the same increase in the manufacturing value added and only a 17% increase in final energy demand (to a total final energy demand for industry of 135 EJ) (see Figure TS-12.)

For existing industries, measures include developing capacity for systems assessment for motors, steam systems, and pinch analysis; sharing and documentation of best practices, benchmarks, and roadmaps for different industry segments; and enabling access to low-interest finance. A new energy management standard, ISO50001, for energy management in companies has been developed by the International Organization for Standardization. It will allow industries to systematically monitor and track energy efficiency improvements. To significantly improve energy efficiency, a paradigm shift is required – with a focus on energy services, not on energy supply *per se*. This requires a reorientation and new

17 Section TS-3.2.1 is based on Chapter 8.

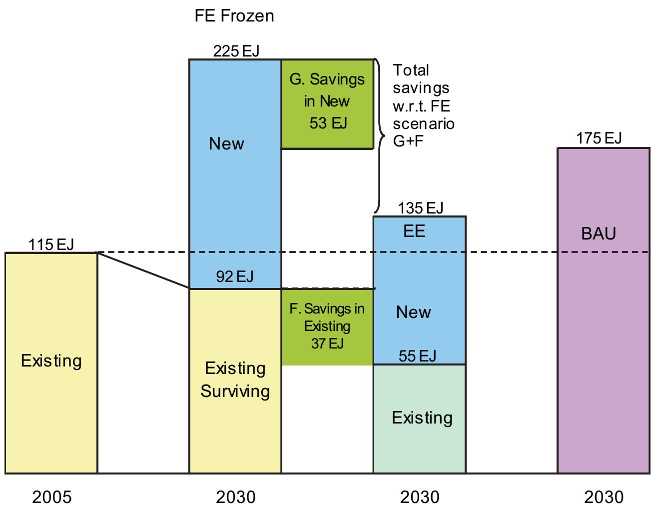


Figure TS-12 | Energy use in industry in 2005 and scenarios based on frozen efficiency and business-as-usual (BAU) scenarios for 2030 for an increase of manufacturing value added by 2030 of 95% over the 2005 level. The BAU and efficiency scenarios are consistent with GEA pathways. The surviving plants in 2030 from 2005 are subject to energy efficiency improvements (37 EJ) reducing their energy use from 92 EJ in 2005 to 55 EJ in 2030. Savings in the new capacity brings the frozen efficiency number from 225 – 92 = 133 EJ in 2005 to 80 EJ in 2030. Source: Chapter 8.

business models for energy supply, distribution companies, and energy equipment manufacturing companies.

Renewables currently account for 9% of the final energy use of industry (10 EJ in 2005). If an aggressive renewables strategy results in an increase in renewable energy supply to 23% in 2030 (23 EJ), it is possible to have a scenario of near-zero growth in GHG emissions in the industrial sector. Further reductions in overall energy use and emissions would be possible by dematerialization, redesign of products, and materials recycling.

Future industrial growth to 2030 is possible with net zero growth in GHG emissions provided there is a reorientation of the energy sector to focus on energy services, renewable energies (Chapter 11), and low-carbon fossil fuel use (Chapters 12 and 13).

3.2.2 Transport[18]

The transportation sector is responsible for approximately 28% (91 EJ) of global final energy demand. Road transport accounts for more than 70% of that total and 95% of transport energy comes from oil-based fuels. A major transformation of transportation is possible over the next 30–40 years and will require improving vehicle designs, infrastructure, fuels, and behavior. In the short term, improving overall sector energy efficiency, introducing alternative low-carbon fuels and electricity, and enhancing the diversification, quantity, and quality of public modes of transport is necessary. Medium-term goals require reducing travel distances within cities by implementing compact urban design that improves accessibility to jobs and services and facilitates use of non-motorized modes, and replacing and adopting vehicle and engine design (for trucks, airplanes, rail, and ships) following the best-available technological opportunities for increasing efficiency and societal acceptability.

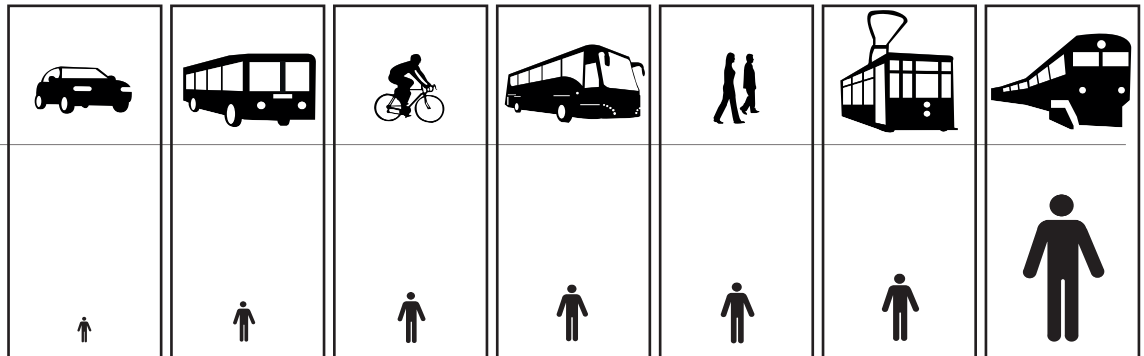
Transport policy goals for urbanization and equity include the adoption of measures for increasing accessibility and the affordable provision of urban mobility services and infrastructure that facilitates the widespread use of non-motorized options. Cities can be planned to be more compact with less urban sprawl and a greater mix of land uses and strategic siting of local markets to improve logistics and reduce the distances that passengers and goods need to travel. Urban form and street design and layout can facilitate walking, cycling, and their integration within a network of public transport modes. Employers in many sectors can enhance the job–housing balance of employees through their decisions on where to locate and can provide incentives for replacing some non-essential journeys for work purposes with the use of information technologies and communication.

Modal shares could move to modes that are less energy-intensive, both for passenger and freight transport. In cities, a combination of push-and-pull measures through traffic-demand management can induce shifts from cars to public transit and cycling and can realize multiple social and health benefits. In particular, non-motorized transportation could be promoted everywhere as there is wide agreement about its benefits to transportation and people's health. Parking policies and extensive car pooling and car sharing, combined with information technology options, can become key policies to reduce the use of cars. Efficient road-capacity utilization, energy use, and infrastructure costs for different modes could be considered when transport choices are made (see Figure TS-13).

Life cycle analyses (LCA), together with social and environmental impact assessments, are useful tools to compare different technologies. Significant uncertainties need to be addressed with respect to LCA system boundaries and modeling assumptions – especially in the case of biofuels and land use – and to future unknown technological advances. Hybrid electric vehicles (HEVs) can improve fuel economy by 7–50% over comparable conventional gasoline vehicles, depending on the precise technology used and on driving conditions (although comparable modern diesel engines can be equally fuel-efficient). Plug-in hybrid electric vehicles (PHEVs) allow for zero tailpipe emissions for low driving ranges, such as around 50 km in urban conditions. All-electric battery vehicles (BEVs) can achieve a very high efficiency (more than 90%, four times the efficiency of an internal combustion engine vehicle, but excluding the generation and transmission of the electricity), but they have a short driving range and battery life. Charging times are also, at present, significantly longer than fueling time for liquids. Consequently, BEVs have limited market penetration at present. If existing fuel saving

18 Section TS-3.2.2 is based on Chapters 9 and 17.

A)



	Car	Bus	Bicycle	BRT	Walking	Tram	Rail
A)	2 000	9 000	14 000	17 000	19 000	22 000	80 000
B) MJ/p-km	1.65-2.45	0.32-0.91*	0.1	0.24*	0.2	0.53-0.65	0.15-0.35
C) €/p-km infrastructure	2 500-5 000	200-500	50-150	600-500	50-150	2 500-7 000	15 000-60 000
D) Fuel	Fossil	Fossil	Food	Fossil	Food	Electricity	Electricity

*Lower values correspond to Austrian busses, upper values correspond to diesel busses in Mexico city before introduction of BRT system.

Key:

A) Values are indicative for European and Asian cities and can vary significantly across cities, world regions, and particular situations. For example, BRT capacity can more than double with a second lane. Suburban rails in India can transport up to 100,000 passengers per hour.

B) Energy intensity in MJ per passenger km. SUVs can exceed depicted values for cars. Energy values for bus in the US are generally higher due to low ridership. While BRT systems have similar energy efficiencies as normal busses, they provide signficant systemic energy savings via modal shift, small bus substitution, and reduction in parallel traffic. BRT systems can also be converted from oil based fuels to renewable based electricity and hydrogen.

C) Estimated infrastructure costs in euros per passenger kilometer are highest for subway systems and heavy rail. Costs for bus system can be significantly lower than for individual motorized transport. Infrastructure costs for non-motorized transport are very cost competitive and can realize significant social benefits.

D) Dominant fuels are given for each mode.

Figure TS-13 | Comparative corridor capacity (people per hour), energy intensity per passenger kilometer (MJ/p-km), infrastructure cost (€/p-km), and main source of energy. Source: modified from Breithaupt, 2010; see Chapter 9.[19]

and hybrid technologies are deployed on a broad scale, fleet-average specific fuel savings of a factor of two can be obtained in the next decade (Figure 9.41, Chapter 9).

Increasing the performance of high-energy density batteries for PHEVs could lead to higher market penetration of BEVs. Hydrogen fuel cell vehicles (FCVs) could alleviate the dependence on oil and reduce emissions significantly. For HEVs and FCVs, the emissions are determined by the mode of production of hydrogen and electricity. Further technological advances and/or cost reductions would be required in fuel cells, hydrogen storage, hydrogen or electricity production with low- or zero-carbon emissions, and batteries, including charging time. Substantial and sustained government support is required to reduce costs further and to build up the required infrastructure.

There are still many opportunities to improve conventional technologies. The combination of introducing incremental efficiency technologies, increasing the efficiency of converting the fuel energy to work by improving drivetrain efficiency, and recapturing energy losses and reducing loads (weight, rolling, air resistance, and accessory loads) on the vehicle has the potential to approximately double the fuel efficiency of 'new' light-duty vehicles from 7.5 liters per 100 km in 2010 to 3.0 liters per 100 km by 2050 (Figure 9.41, Chapter 9).

19 **Breithaupt, M., 2010:** *Low-carbon Land Transport Options towards Reducing Climate Impacts and Achieving Co-benefits*. Presented at the Fifth Regional Environmentally Sustainable Transport (EST) Forum in Asia, 23–25 August 2010, Bangkok, Thailand.

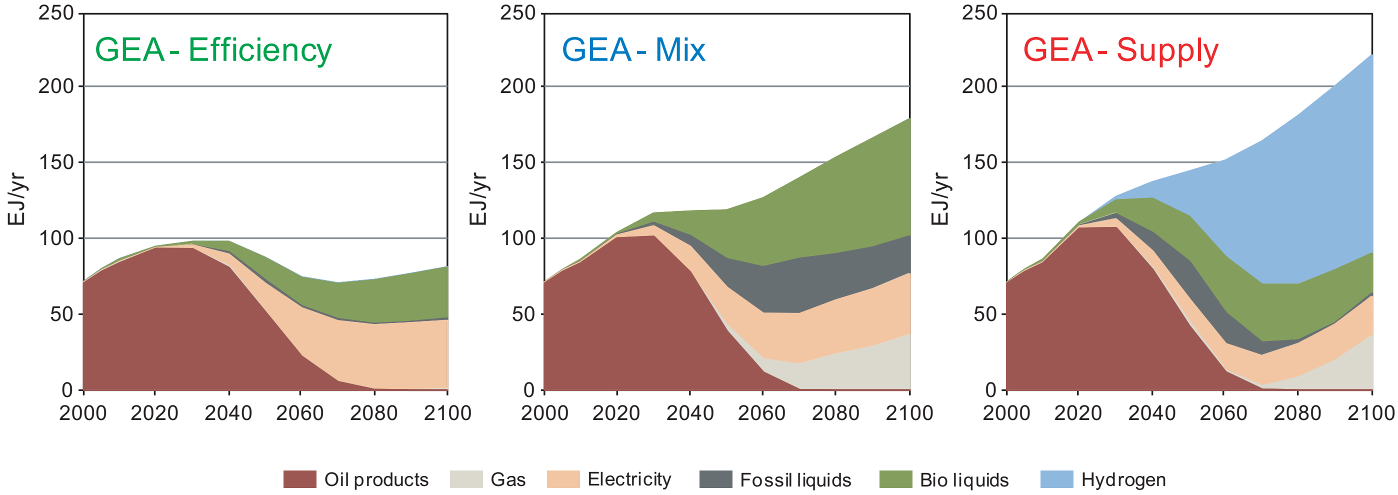


Figure TS-14 | Illustrative examples of fuel use in the transport sector for three GEA pathways. GEA-Supply features a strong technology push for new advanced technologies such as hydrogen, GEA-Efficiency features a strong reliance on regulation to reduce transport energy demand in combination with hybrid electric/biofuel technologies, and GEA-Mix features a co-evolution of both strategies, leading to regionally diverse transport systems. Source: Chapter 17 pathways and the GEA online database. For further details of the GEA pathways see the interactive web-based GEA scenario database hosted by IIASA: www.iiasa.ac.at/web-apps/ene/geadb.

Fuel economy standards have been effective in reducing fuel consumption and therefore could be adopted worldwide. The overall effectiveness of standards can be significantly enhanced if combined with fiscal incentives and consumer information. Taxes on vehicle purchase, registration, use, and motor fuels, as well as road and parking pricing policies, are important determinants of vehicle energy use and emissions.

Aviation transportation presents unique challenges owing to the requirement for very high density fuels. Studies indicate that fuel efficiency of aviation can be improved by 40–50% by 2050 through a variety of means, including technology, operation, and management of air traffic. As aviation's growth rate is projected to be the highest of the transport sub-sectors, such efficiency improvements will not be enough to keep overall energy use in the sector from increasing; thus, alternative low-carbon, high energy-density fuels will play a crucial role in decarbonizing emissions from aviation.

In the maritime sector, a combination of technical measures could reduce total energy use by 4–20% in older ships and 5–30% in new ships by applying state-of-the-art knowledge, such as hull and propeller design and maintenance. Reducing the speed at which a ship operates brings significant benefits in terms of lower energy use. For example, cutting a ship's speed from 26 to 23 knots can yield a 30% fuel saving.

GEA explored three distinctly different pathways for the transport sector (Figure TS-14), all of which satisfied the goals adopted for the GEA analysis (Section TS-4). In all pathways conventional oil is essentially phased out shortly after 2050. In the GEA-Efficiency pathway, electricity and biofuels dominate, while in GEA-Supply, hydrogen plays a large role. In GEA-Mix, natural gas and fossil/biofuel liquids are also being used. The conclusion is that there are many combinations of energy carriers that would be able to fuel the transport sector.

3.2.3 Buildings[20]

Buildings are integrated systems that encompass and deliver multiple energy services and that require holistic approaches to achieve substantial reductions in energy demand and associated benefits. The sector, and activities in buildings themselves, are responsible for approximately 34% (112 EJ) of global final energy demand, with three-quarters of this amount for thermal purposes. Several energy-related problems in buildings (such as poor indoor air quality or inadequate indoor temperatures) affect the health and productivity of residents significantly.

New and existing technologies, as well as non-technological opportunities, represent a major opportunity for transformative change of energy use in buildings. Passive houses that reduce energy use for heating and cooling by 90% or more, for example, are already found in many countries. Increased investments in a more energy-efficient building shell are in part offset by lower or fully eliminated investments in heating/cooling systems, with energy costs for operation almost avoided, making these new options very attractive. Passive-house performance is also possible for existing buildings, if it is included as a performance goal when major renovations are done. Energy Plus houses, delivering net energy to the

20 Section TS-3.2.3 is based on Chapter 10.

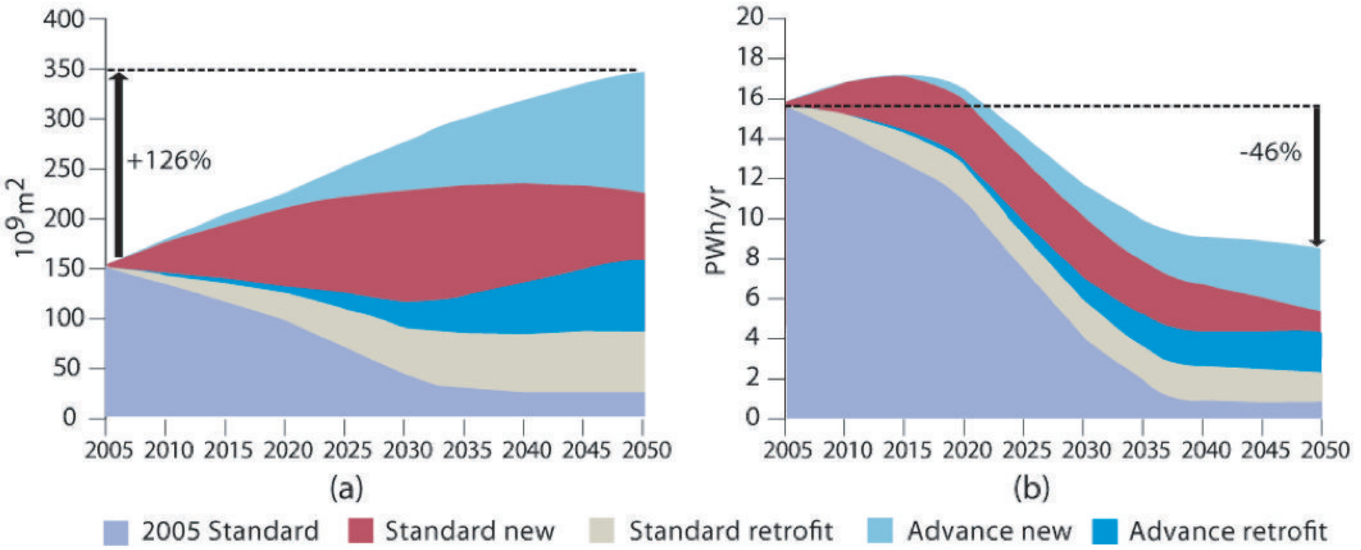


Figure TS-15 | Global final thermal energy use in buildings (a) and global floor area (b) in the state-of-the-art scenario (corresponding approximately to the 'GEA-Efficiency' group of pathways), 2005–2050. Source: Chapter 10.

Key: Explanations of efficiency categories: standard, today's stock; new, new buildings built to today's building code or anticipated new building codes (without additional policies); advance new, new buildings built to today's state-of-the-art performance levels; retrofit, assumes some efficiency gains, typically 35%; advanced retrofit, retrofit built to state-of-the-art levels.

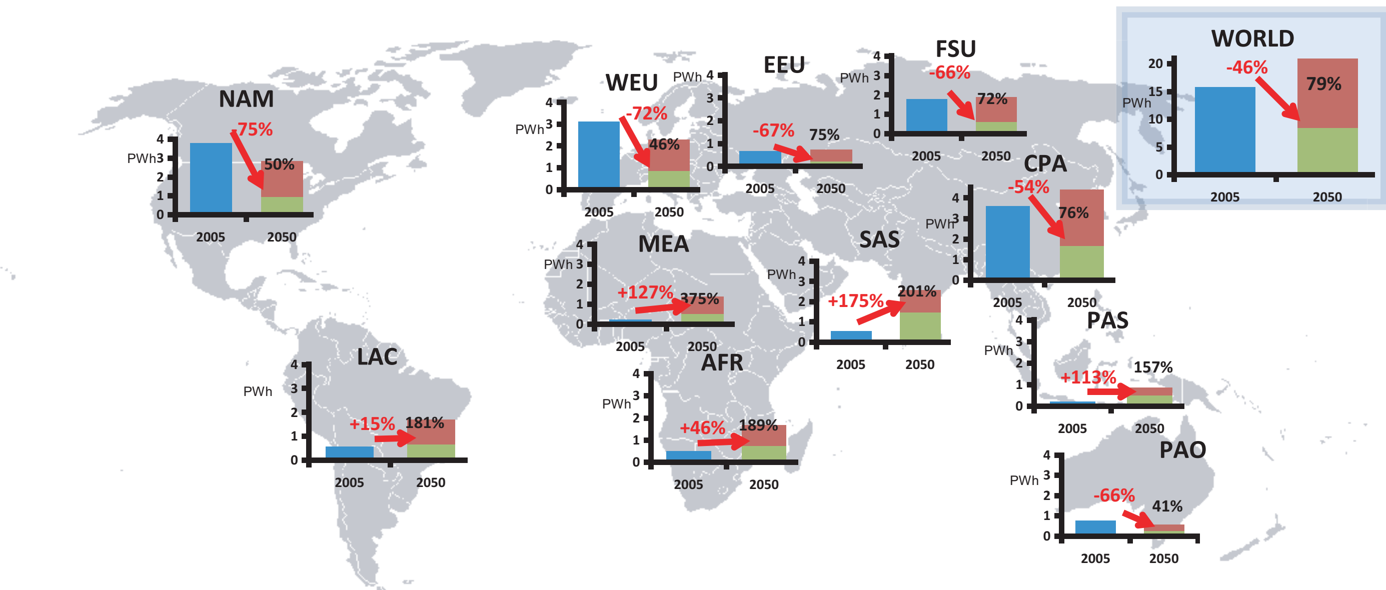


Figure TS-16 | Final building heating and cooling energy demand scenarios until 2050: state-of-the-art (~corresponding to the GEA-Efficiency set of pathways) and sub-optimal (~corresponding to the GEA-Supply set of pathways scenarios), with the lock-in risk (difference). Note: Green bars, indicated by red arrows and numbers, represent the opportunities through the state-of-the-art scenario, while the red bars with black numbers show the size of the lock-in risk (difference between the two scenarios). Percent figures are relative to 2005 values. Source: Chapter 10.

grid over a year, have been constructed even in high latitudes. Building-integrated solar photovoltaics (PVs) can contribute to meeting the electricity demand in buildings, especially in single-family homes, and solar water heaters can cover all or part of the heat required for hot water demand. However, requiring buildings to be zero-energy or net-energy suppliers may not be the lowest cost or most sustainable approach in addressing the multiple GEA goals, and sometimes may not be possible, depending on location.

Analysis carried out under the GEA pathway framework demonstrates that a reduction of global final energy use for heating and cooling of about 46% by 2050 compared with 2005 is possible through the full use

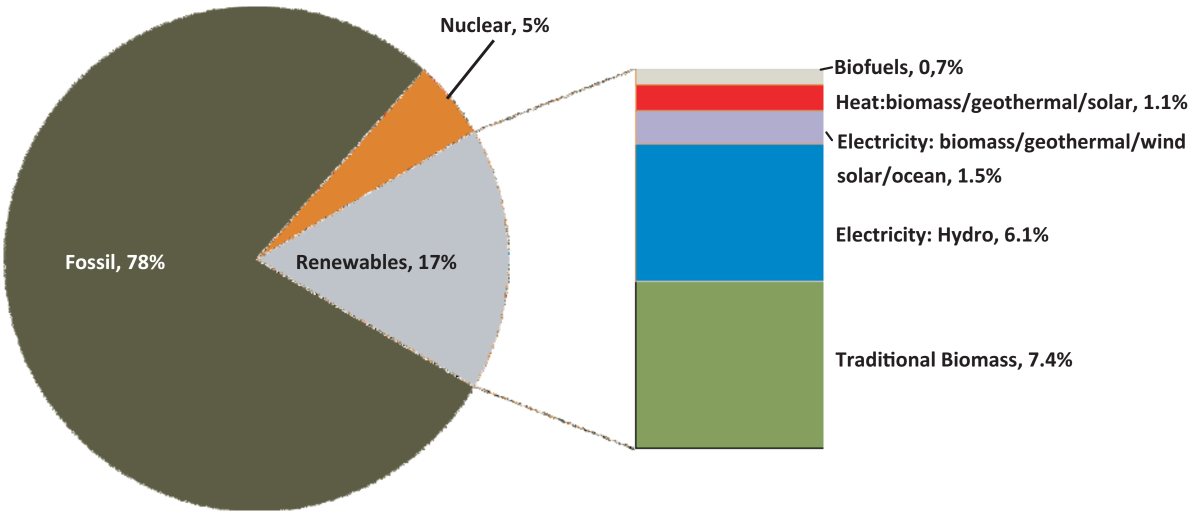


Figure TS-17 | Renewable share of primary energy use, 2009 (528 EJ). Source: Chapter 11.

of today's best practices in design, construction, and building operation technology and know-how. This can be obtained even while increasing amenities and comfort and simultaneously accommodating an increase in floor space of over 126% (see Figure TS-15.)

However, there is a significant risk of lock-in. If stringent building codes are not introduced universally and energy retrofits accelerate but are not subject to state-of-the-art efficiency levels, substantial energy use and corresponding GHG emissions can be 'locked in' for many decades. This could lead to a 33% increase in global energy use for buildings by 2050 instead of a decrease of 46% (see Figure TS-16).

Wide adoption of the state-of-the-art in the buildings sector would not only contribute significantly to meeting GEA's multiple goals, but such developments would also deliver a wide spectrum of other benefits. A review of quantified multiple benefits showed that productivity gains through reduced incidence of infections from exposure to indoor air pollution score particularly high. Other benefits included increases in productivity, energy security, indoor air quality and health, social welfare, real estate values, and employment. The approximately US$57 trillion cumulative energy-cost savings until 2050 in avoided heating and cooling energy costs alone substantially exceeds the estimated US$15 trillion investments that are needed to realize this pathway. The value of the additional benefits has also been shown to be substantial, often exceeding the energy cost savings. In several cases the multiple benefits are so significant and coincide with other important policy agendas (such as improved energy security, employment, poverty alleviation, competitiveness) that they provide easier and more attractive entry points for local policymaking than climate change or other environmental agendas.

A transition to a very low energy-use level for buildings requires a shift in the focus of energy-sector investment from the supply side to an integrated system solution and services perspective, as well as the innovation and cultivation of new business models.

A broad portfolio of approaches is available and has been increasingly applied worldwide to capture the cost-effective efficiency potentials. Owing to the large number and diversity of market barriers, single instruments such as a carbon pricing will not unlock the large efficiency potentials. Policy portfolios tailored to different target groups and a specific set of barriers are needed. Nevertheless, deep reductions in building-energy use will not be possible without ambitious and strictly enforced performance standards, including building codes for new construction and renovation as well as appliance standards.

3.3 Energy Supply

3.3.1 Renewable Energy[21]

The potential to provide electricity, heat, and transport fuels to deliver all energy services from renewable energies is huge. The resource base is more than sufficient to provide full coverage of human energy demand at several times the present level and potentially more than 10 times this level.

In 2009, renewable energy sources contributed about 17% of world primary energy use, mainly through traditional biomass (7.4%) and large hydropower (6.1%), while the share from solar, wind, modern biomass, geothermal, and ocean energy was 3.3% (see Figure TS-17).

Many examples exist of hydropower plants, geothermal power plants, and biomass combustion for heat and for combined heat and power

21 Section TS-3.3.1 is based on Chapter 11.

Table TS-4 | Current status of renewable energy technologies as of 2009 (all financial figures are in $US_{2005}$$).

Technology	Installed capacity increase in past five years (percent per year)	Operating capacity end 2009	Capacity factor (percent)	Secondary energy supply in 2009	Primary energy supply in 2009 (EJ/yr) based on the substitution calculation method	Turnkey investment costs ($/kW of output)	Current energy cost of new systems (¢/kWh, for biofuels $/GJ)	Potential future energy cost (¢/kWh, for biofuels $/GJ)
Biomass energy								
Electricity	6	54 GW_e	51[a]	~ 240 TWh_e	3.3	430–6200	2–22¢/kWh_e	2–22¢/kWh_e
Bioethanol	20	95 bln liter	80[a]	~ 76 bln liter	2.7	200–660	11–45 $/GJ	6–30 $/GJ
Biodiesel	50	24 bln liter	71[a]	~ 17 bln liter	0.9	170–325	10–27 $/GJ	12–25 $/GJ
Heat CHP	~ 3	~ 270 GW_{th}	25–80	~ 4.2 EJ	5.2	170–1000	6–12¢/kWh_{th}	6–12¢/kWh_{th}
Hydroelectricity								
Total capacity	3	~ 950 GW_e	30–80	~ 3100 TWh_e	32	1000–3000	1½-12¢/kWh_e	1½-10¢/kWh_e
Smaller scale plants (<10 MW)	~ 9	~ 60 GW_e	30–80	~ 210 TWh_e	2.2	1300–5000	1½-20¢/kWh_e	1½-20¢/kWh_e
Geothermal energy								
Electricity	4	~ 8 GW_e	70–90	~ 67 TWh_e	0.7	2000–4000	3–9¢/kWhe	3–9¢/kWh_e
Direct use of heat	12	~ 49 GW_{th}	20–50	~ 120 TWh_{th}	0.5	500–4200	2–19¢/kWh_{th}	2–19¢/kWh_{th}
Wind electricity								
Onshore	27	~ 160 GW_e	20–35	~ 350 TWh_e	3.6	1200–2100	4–15¢/kWh_e	3–15¢/kWh_e
Offshore	28	~ 2 GW_e	35–45	~ 7 TWh_e	0.07	3000–6000	7–25¢/kWh_e	5–15¢/kWh_e
Solar PV electricity	45	~ 24 GW_e	9–27	~ 32 TWh_e	0.33	3500–5000	15–70¢/kWh_e	3–13¢/kWh_e
Solar thermal electricity (CSP)								
Without heat storage	15	0.8 GW_e	30–40	~ 2 TWh_e	0.02	4500–7000	10–30¢/kWh_e	5–15¢/kWh_e
With 12h heat storage	–	–	50–65	–	–	8000–10,000	11–26¢/kWh_e	5–15¢/kWh_e
Low-temperature solar thermal energy	19	~ 180 GW_{th}	5–12	~ 120 TWh_{th}	0.55	150–2200	3–60¢/kWh_{th}	3–30¢/kWh_{th}
Ocean energy								
Tidal head energy	0	~ 0.3 GW_e	25–30	~ 0.5 TWh_e	0.005	4000–6000	10–31¢/kWh_e	9–30¢/kWh_e
Current energy	–	exp. phase	40–70	PM	–	5000–14,000	9–38¢/kWh_e	5–20¢/kWh_e
Wave energy	–	exp. phase	25	PM	–	6000–16,000	15–85¢/kWh_e	8–30¢/kWh_e
OTEC	–	exp. phase	70	PM	–	6000–12,000	8–23¢/kWh_e	6–20¢/kWh_e
Salinity gradient energy	–	R&D phase	80–90	–	–	–	–	–

[a] Industry-wide average figure; on plant level the CF may vary considerably.

Source: Chapter 11

(CHP) that have been fully competitive with fossil fuels for decades. In select locations, and for specific markets (such as remote locations), wind and solar (or hybrid systems) have also provided least-cost, highly reliable energy supplies. In broader markets, starting from an initially very low level, very rapid growth of wind and solar technologies has occurred in the last decade, strongly stimulated by public policies. Wind energy has grown globally by more than 25% per year for more than 15 years and solar PV by more than 50% per year for around 10 years. Costs have dropped by 50–90% on a dollar per megawatt-hour basis over the past decades, and they continue to decline rapidly. Technologies such as solar water heaters and wind farms on good sites are nowadays competitive with conventional energy technologies on standard economic terms (without including any external costs and benefits). An overview of the present status and future potential of renewable energy options is presented in Table TS-4.

The rapid expansion in renewables, which largely has taken place in only a few countries, has usually been supported by different types of incentives or driven by quota requirements. The feed-in tariffs (FITs) used in the majority of EU countries, China, and elsewhere have been especially successful. Global investments in 2009 were slightly lower as a result of the financial crises (although with less reduction than for most other energy technologies) (see Figure TS-18); however, they rebounded in 2010. Both wind and solar PV electricity are already

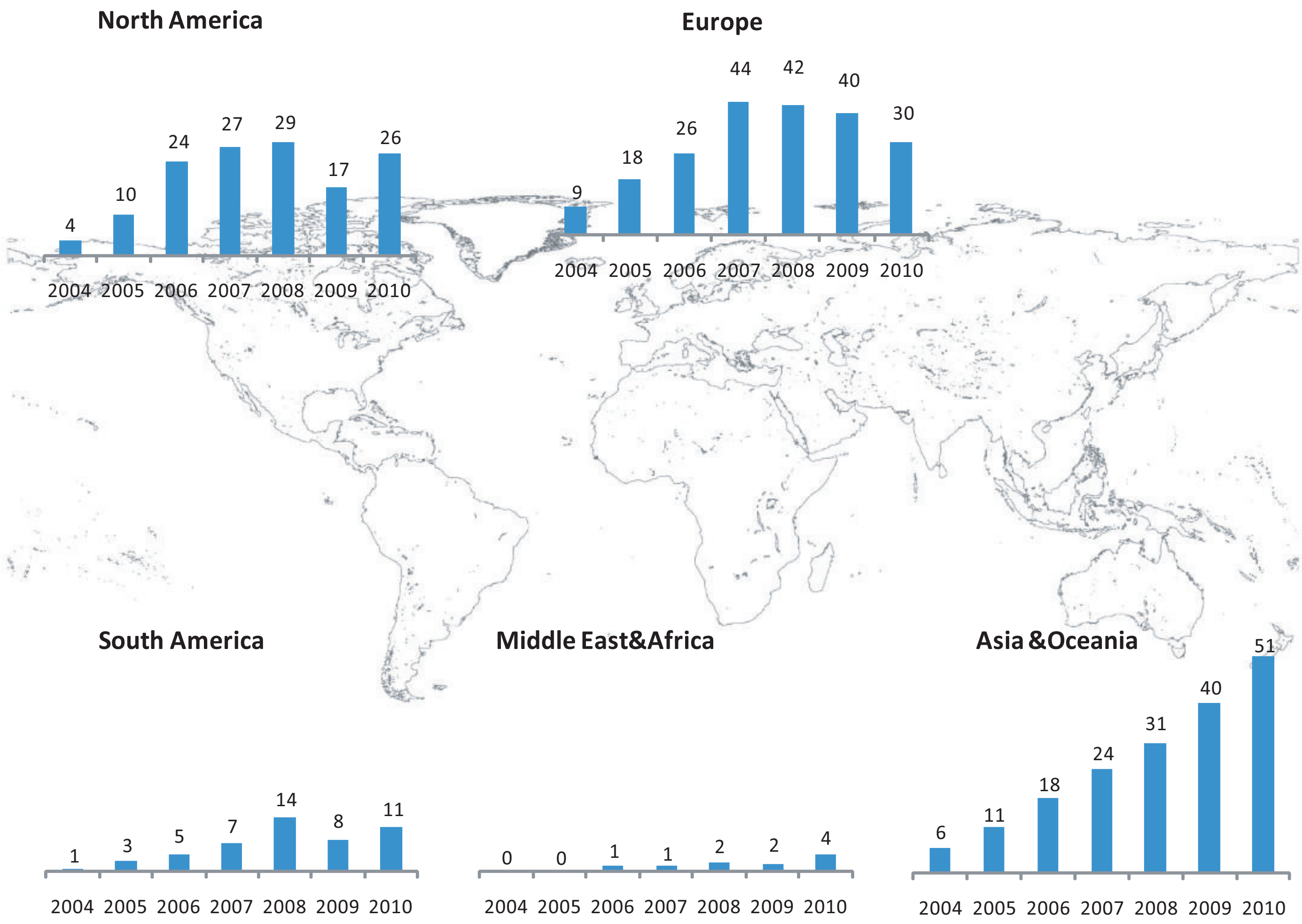


Figure TS-18 | New financial investments in renewable energy, by region, 2004–2010 (billion US_{2005}\$). New investment volume adjusted for reinvested equity; total values include estimates for undisclosed deals. This comparison does not include small-scale distributed energy projects or large-scale hydropower investments. Source: Chapter 11.

cost-competitive in some markets and are projected to become so in many more markets in the next 5–10 years without being favored by public policy. However, renewables face resistance due to lock-in to conventional energies and substantial market barriers in the majority of markets.

Renewable power capacity additions now represent more than one-third of all global power capacity additions (see Figure TS-19). While substantial on an annual basis, with a very large total installed capacity, renewables remain a relatively small contributor to global energy supply.

The intermittent and variable generation of wind, solar, and wave power must be handled within an electricity system that was not designed to accommodate it, and in which traditional base load-power from nuclear, geothermal, and fossil power stations with restricted flexibility limit the system's ability to follow load variations. Energy systems have historically been designed to handle loads that vary over seconds, days, weeks, and years with high reliability. These systems are becoming increasingly able to accommodate increased quantities of variable generation through use of so-called smart systems with advanced sensing and control capabilities. With support from accurate and timely load forecasting, capacity management, and overall intelligent load and demand-side management, experience has shown that at least 20%, and perhaps up to 50%, of variable renewable generation can be accommodated in most existing systems at low costs, and that it is feasible to accommodate additional intermittent generation with additional investment in grid flexibility, low capital cost fuel-based generation, storage, and demand-side management (smart grids).

Intelligent improvement and increase of interconnection between states and across geographic regions will help maintain and increase reliability of energy systems in an environment with rapidly increasing shares of variable renewable energies in the system. Wind and solar PV, and most hydrokinetic or ocean thermal technologies, offer the unique additional attribute of virtually complete elimination of additional water requirements for power generation. Other renewable options, including bio-based options, geothermal, concentrating solar, and hydropower on

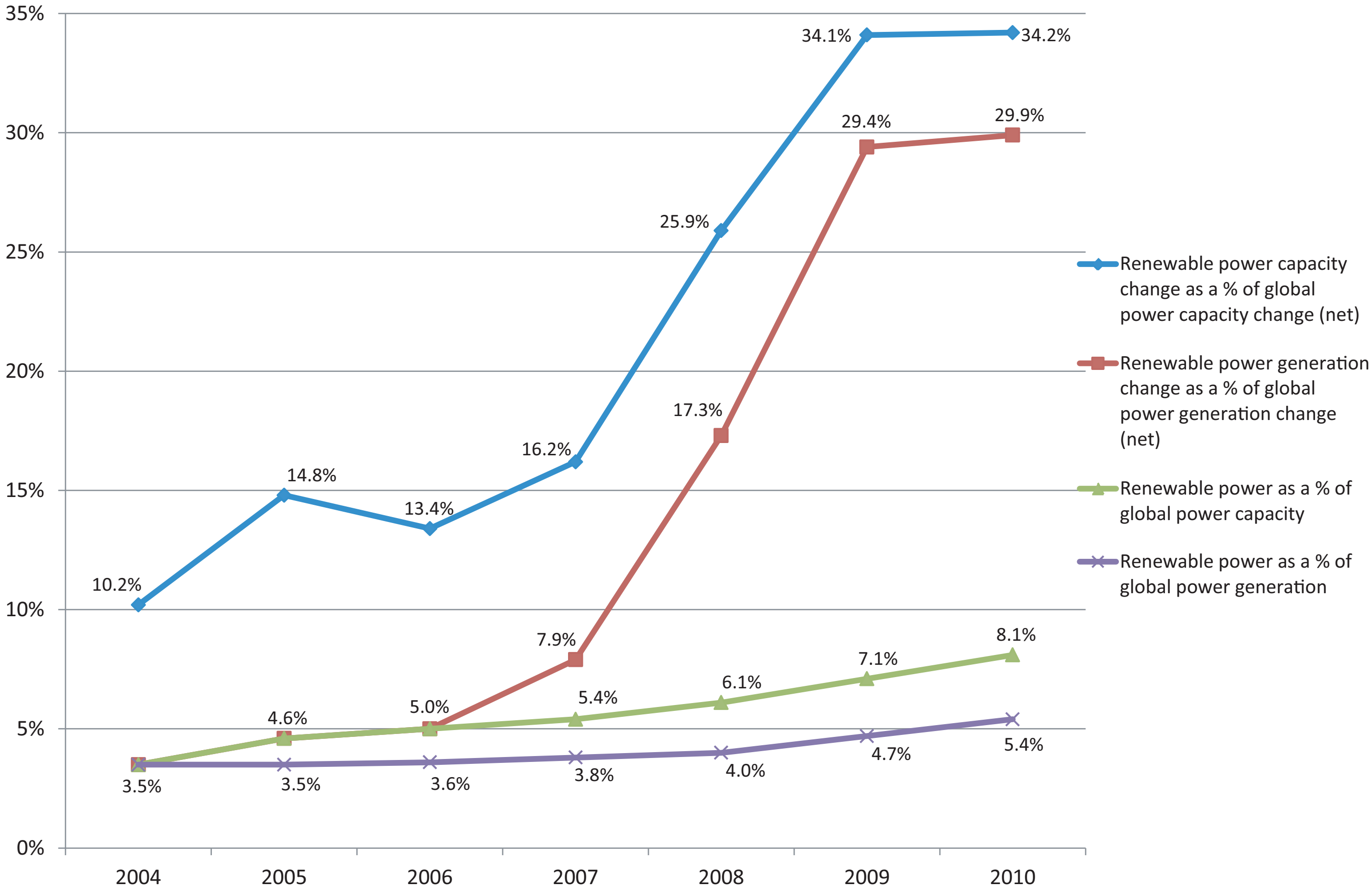


Figure TS-19 | Renewable power capacity (excluding large hydro) and generation as a percentage of global capacity and generation, respectively, and their rates of change also in percent; 2004–2010 Source: UNEP and BNEF, 2011; see Chapter 11.[22]

a life-cycle basis, still require water for cooling a steam turbine or are associated with large amounts of evaporation.

The development of high-voltage direct current transmission cables may allow the use of remote resources of wind and solar at costs projected to be affordable. Such cables have been installed for many years in submarine and on-shore locations, and demand is increasing (in the North Sea, for example). This is significant, as some of the best renewable energy resources are located far from load centers. In conjunction with energy storage at the generation location, such transmission cables can be used to provide base load electricity supply.

The GEA pathways show that renewable energies can meet up to 100% of projected energy demand for specific regions. The GEA pathways analysis indicates that a significant increase in renewable energy supplies from 17% of global primary energy use in 2009 up to 30–75% and would result in multiple benefits.

22 **UNEP and BNEF, 2011:** *Global Trends in Renewable Energy Investment 2011: Analysis of Trends and Issues in the Financing of Renewable Energy*. United Nations Environment Programme (UNEP), Nairobi, Kenya and Bloomberg New Energy Finance (BNEF), London, UK.

3.3.2 Fossil Energy Systems[23]

This section has two parts. The first part covers new opportunities in the conversion of fossil fuels to liquid energy carriers and electricity. Co-utilization of coal and biomass is highlighted in conjunction with CCS, which is the subject of the second part.

3.3.2.1 Fuels, Heat, and Electricity from Fossil Resources

A radical transformation of the fossil energy landscape is feasible for simultaneously meeting the multiple sustainability goals of wider access to modern energy carriers, reduced air pollution, enhanced energy security, and major GHG emissions reductions. The essential technology-related requirements for this transformation are continued enhancement of unit energy conversion efficiencies, the development of CO_2 capture and storage, use of both fossil and renewable energy in the same facilities, and efficient co-production of multiple energy carriers at the same facilities.

23 Section TS-3.3.2.1 is based on Chapter 12.

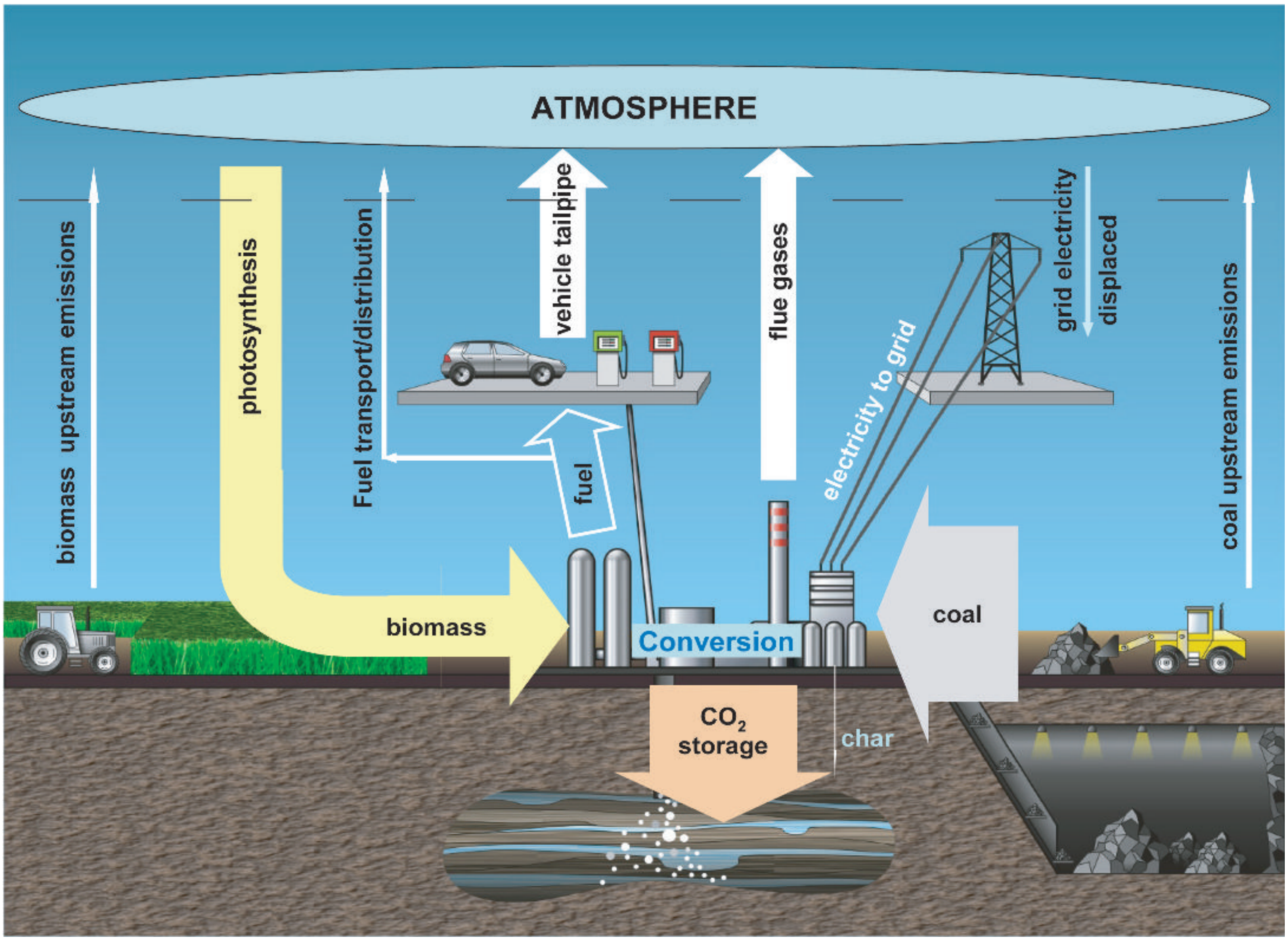


Figure TS-20 | Carbon flows for conversion of coal and biomass to liquid fuels and electricity. When biomass is approximately 30% of the feedstock input (on a higher heating value basis), the net fuel cycle GHG emissions associated with the produced liquid fuels and electricity would be less than 10% of the emissions for the displaced fossil energy. Source: Chapter 12.[24]

For developing and industrial countries alike, fossil fuels – which will dominate energy use for decades to come – must be used judiciously by designing energy systems for which the quality of energy supply is well matched to that required and also by exploiting other opportunities for realizing high efficiencies. Continued use of coal and other fossil fuels in a carbon-constrained world will increase the requirement for CO_2 capture and storage.

Since developing and industrial countries have different energy priorities, strategies for fossil energy development will vary in the short term, but they must converge in the long term. In developing countries, the emphasis could be on increasing access to energy services based on cleaner energy carriers, building new manufacturing and energy infrastructures that anticipate the evolution to low-carbon energy systems, and exploiting the rapid growth in these infrastructures to facilitate introduction of the advanced energy technologies needed to meet sustainability goals.

In industrial countries, where energy infrastructures are largely already in place, a high priority could be overhauling existing coal power plant sites to add additional capabilities (such as co-production of electricity and liquid transport fuels) and CCS. (Simply switching from coal to natural gas power generation without CCS will not achieve the needed carbon emission reductions.)

Among the technologies that use fossil fuels, only co-production and co-processing strategies using biomass with fossil fuel and with CCS have the ability to achieve deep reductions in CO_2 through 'net negative' emissions. These technologies could begin to be deployed in the 2015–2020 time frame as nearly all of their components are already in commercial use. In the long term, hydrogen made from fossil fuels with CCS is a decarbonization energy option, but infrastructure challenges are likely to limit this option in the near term.

24 **Larson, E. D., G. Fiorese, G. Liu, R. H. Williams, T. G. Kreutz and S. Consonni, 2010:** Co-production of Decarbonized Synfuels and Electricity from Coal + Biomass with CO_2 Capture and Storage: an Illinois Case Study. *Energy & Environmental Science*, **3**(1):28–42.

Co-production with CCS represents a low-cost approach for simultaneously greatly reducing carbon emissions for both electricity and transportation fuels (such as gasoline, diesel, and jet fuel), enhancing energy supply security, providing transportation fuels that are less polluting than petroleum-derived fuels in terms of conventional air pollutants, providing clean synthetic cooking fuels as alternatives to cooking with biomass and coal (critically important for developing countries), and greatly reducing the severe health-damage costs due to air pollution from conventional coal power plants.

Co-processing biomass with coal or natural gas in co-production systems requires, at most, half as much biomass to provide low-carbon transport fuels compared with advanced fuels made only from biomass such as cellulosic ethanol. Co-production also represents a promising approach for gaining early market experience with CCS (because CO_2 capture is less costly than for stand-alone power plants) and can serve as a bridge to enabling CCS as a routine activity for biomass energy (with corresponding negative GHG emissions) after 2030 (see Figure TS-20).

No technological breakthroughs are needed to get started with co-production strategies, but there are formidable institutional hurdles created by the need to manage two disparate feedstock supply chains (for a fossil fuel and biomass) and simultaneously provide three products (liquid fuels, electricity, and CO_2) serving three different commodity markets.

Creative public policies that promote the needed changes in the fossil fuel landscape would include the setting of a price on GHG emissions, more stringent regulations on air pollution, performance-based support for the early deployment of promising technology, and an emphasis on cost reduction through accelerated learning. These actions would need to be supported by international collaboration and intellectual and financial assistance from industrial to developing countries for technology adoption and technological and institutional capacity building.

3.3.2.2 Carbon Capture and Storage[25]

Over the past decade there has been a remarkable increase in interest and investment in CCS. In 2011, 280 projects were in various stages of development, and governments have committed billions of dollars for R&D, scale-up, and deployment. Considering full life-cycle emissions, CCS technology can reduce CO_2 emissions from fossil fuel combustion from stationary sources by about 65–85%. CCS is applicable to many of these sources, including the power generation and industrial sectors. Applying CCS with bioenergy would open up a route to achieving negative emissions.

Although the technology for CCS is available today, significant improvements are needed to support its widespread deployment. CCS involves the integration of four elements: CO_2 capture (separation and compression of CO_2), transportation to a storage location, and isolation from the atmosphere by pumping the CO_2 into appropriate saline aquifers, oil and gas reservoirs, and coal beds with effective seals that keep it safely and securely trapped underground.

Successful experiences with five ongoing projects (Weyburn-Midale, La Barge, In Salah, Sleipner, Snøhvit) demonstrate that, at least on a limited scale, CCS appears to be safe and effective for reducing emissions. Moreover, relevant experience from nearly 40 years of CO_2 utilization for enhanced oil recovery, currently at the aggregate rate of 40 Mt/yr, also shows that CO_2 can safely be pumped and retained underground.

Significant scale-up will be needed to achieve large reductions in CO_2 emissions through CCS. A five- to ten-fold scale-up in the size of individual projects is needed to capture and store emissions from a typical coal-fired power plant. A thousand-fold scale-up in CCS would be needed to reduce emissions by billions of tonnes per year.

Worldwide storage capacity estimations are improving, but more experience is needed. Estimates for oil and gas reservoirs are about 1000 billion tonnes (Gt) CO_2, saline aquifers are estimated to have a capacity ranging from about 4000 to 23,000 Gt, and coal beds have about 200 Gt. However, there is still considerable debate about how much sequestration capacity actually exists, particularly in saline aquifers. Research, geological assessments, and – most important – commercial-scale demonstration projects will be needed to improve confidence in capacity estimates.

Added costs and reduced energy efficiencies are associated with CCS. Costs for CCS are estimated to be from below US$30 to above US$200 per tonne of CO_2 avoided, depending on the type of fuel, the capture technology, and the assumptions about the baseline technology. And they would increase the cost of stand-alone power generation by 50–100%. Capital costs and parasitic energy requirements of 15–30% are the major cost drivers. Further R&D could help reduce costs and energy requirements. In addition, pursuing electricity generation via co-production with transportation fuels could also reduce costs for generating decarbonized electricity from coal (as described in Chapter 12).

Early CCS demonstration projects are likely to cost much more than projected long-term costs, but there are opportunities to keep costs down for demonstration by coupling to existing sources of low-cost CO_2 (e.g., coal-to-chemicals or fuels facilities in China) and/or to storage of anthropogenic CO_2 via enhanced oil recovery (as currently practiced in a large-scale CO_2 storage project in Canada).

Access to capital for large-scale deployment could be a major factor limiting the widespread use of CCS. Owing to the added costs, CCS will not take place without strong incentives to limit CO_2 emissions. Certainty about the policy and regulatory regimes will be crucial for obtaining access to capital to build these multibillion dollar projects.

25 Section TS-3.3.2.2 is based on Chapter 13.

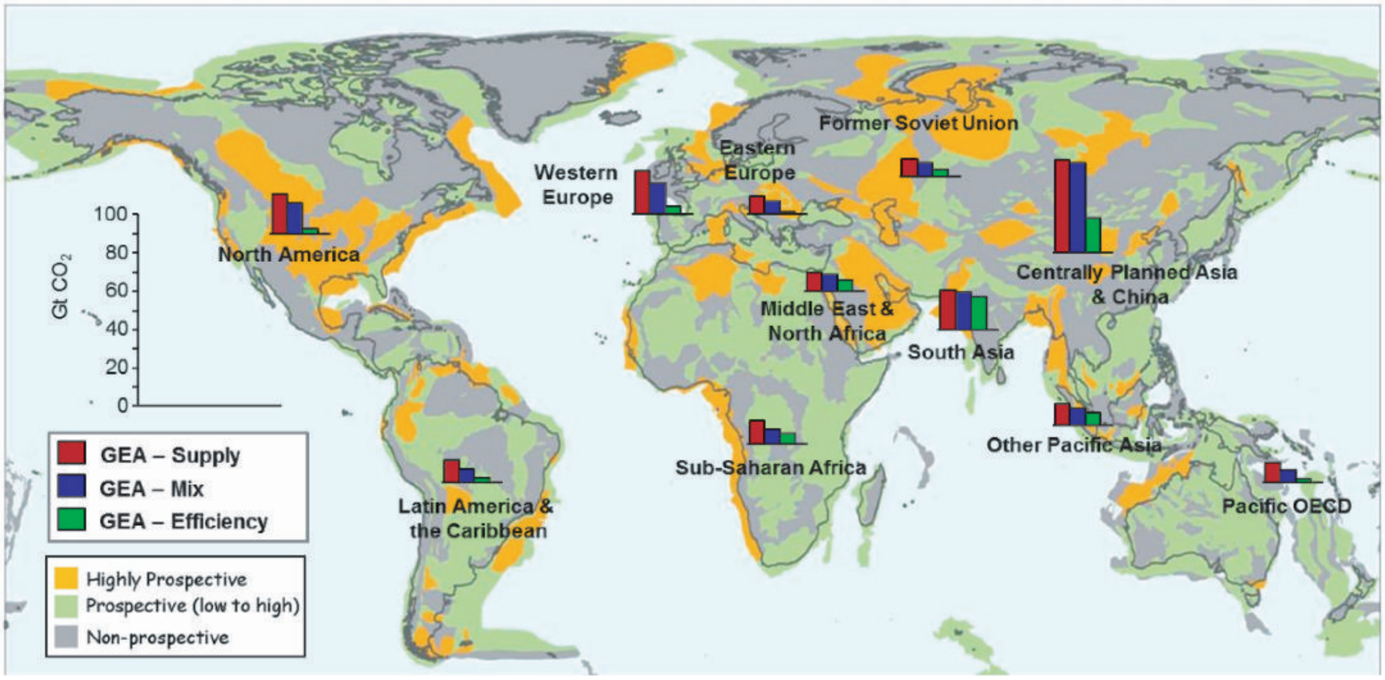


Figure TS-21 | Global map showing prospective geological carbon storage areas (Bradshaw and Dance, 2005)[26] superimposed on the estimated CO_2 storage requirements from CCS across the three illustrative GEA pathways (Chapter 17). Storage requirements in the illustrative GEA pathways are below 250 $GtCO_2$ by 2050, and below 1300 $GtCO_2$ by 2100. This is significantly less compared to the global geological CO_2 storage capacity, which includes saline aquifers ranging from about 4000 to 23,000 $GtCO_2$, and oil and gas reservoirs of about 1000 $GtCO_2$ (Chapter 13). For further details of the GEA pathways see the interactive web-based GEA scenario database hosted by IIASA: www.iiasa.ac.at/web-apps/ene/geadb.

To manage the environmental risks of CCS, clear and sufficient regulations are needed and enforced to ensure due diligence over the lifecycle of the project – particularly siting decisions, operating guidelines, monitoring, and closure of a storage facility.

Social, economic, policy, and political factors may limit deployment of CCS if not adequately addressed. Critical issues include ownership of underground pore space, long-term liability and stewardship, GHG accounting approaches, and verification and regulatory oversight regimes. Government support to lower barriers for early deployment is needed to encourage private-sector adoption. Developing countries will need support for getting access to technologies, lowering the cost of CCS, developing workforce capacity, and training regulators for permitting, monitoring, and oversight. CCS combined with biomass gasification has negative emissions, which are likely to be needed to achieve atmospheric stabilization of CO_2 and may provide an additional incentive for CCS adoption.

The assessment of future pathways suggests an overall requirement of CCS of up to 250 $GtCO_2$ of cumulative captured emissions by 2050. This is much less than the estimated storage capacity (see Figure TS-21).

26 **Bradshaw, J. and T. Dance, 2005:** Mapping geological storage prospectivity of CO2 for the world's sedimentary basins and regional source to sink matching. *Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies*.

3.3.3 Nuclear Energy[27]

The share of nuclear energy, currently 14% of world electricity, has declined in recent years. Nevertheless, there are 441 nuclear power reactors in the world with 374 GWe of generating capacity, and another 65 under construction, of which 45 have been launched in the past five years, 27 of them in China. New grid connections peaked at 30 GW/yr in the mid-1980s, and the last decade has witnessed a decline to an average of 3 GWe/yr in new nuclear capacity and 1 GWe/yr of retirements for a net increase of 2 GWe/yr. Increases in the capacity factors of existing units have, to a degree, compensated for a slower increase in installed capacity. Efforts are being made to extend the lives of existing plants and to encourage the construction of new ones with government loan guarantees, caps on liability for the consequences of accidents, and other subsidies, and thereby sustain, and even increase by a few percent, the share of nuclear energy in a growing global electric power sector. This is the most that the International Atomic Energy Agency believes is achievable by 2050, based on its review of national plans.

Although the momentum of global nuclear power expansion slowed considerably in recent decades, there are important differences between nations and regions. In OECD countries, home of 83% of global installed nuclear capacity, very little construction is under way. Costs per unit remain high, and may even be increasing in Western Europe and North

27 Section TS-3.3.3 is based on Chapter 14.

America, which together account for 63% of global capacity. Among the reasons for cost increases in the 1980s and 1990s were increased stringency in safety requirements and construction delays in the United States after the Three Mile Island accident (see Figure TS-23). These factors can be expected to play a role again for some time after the accident at Japan's Fukushima Daiichi nuclear power plant in 2011. Costs are lower in East Asia and Russia, where most of the new construction is underway. There has been concern in China, however, about the availability of qualified workers and the adequacy of regulatory oversight. After the Fukushima accident, Germany, Italy, Switzerland, and Japan have decided, or announced plans, to scale back nuclear energy, and the United States, European Union, Japan and China announced comprehensive safety reviews.

Many developing countries have aspirations to build their first nuclear power plant, but a large fraction do not have the funds and currently have grid capacities that are too small to manage the large unit sizes of the currently available nuclear power plants. There is currently interest in the nuclear energy establishments of the developed countries, but in smaller reactors whose costs may be reduced through mass production.

Although over the past decades many proposals have been made for improving reactor safety and strengthening the barriers blocking the misuse of nuclear energy technologies for weapons purposes, it is still not clear how these problems will be dealt with. Most importantly, it has been understood since the end of World War II that the non-proliferation regime would be greatly strengthened if enrichment and plutonium were placed under international or multinational control. Plutonium separation and recycle persists in some countries, however, despite the fact that it is unlikely to be economic for the foreseeable future. Also countries continue to build national enrichment plants that could be misused to produce highly enriched uranium for weapons. Consequently, unless problems associated with proliferation and safety are effectively addressed, nuclear energy may not be a preferred climate change mitigation option even though it has low carbon emissions – other low-carbon electric power supply options may be more attractive.

Uncertainty characterizes the long-term role of nuclear energy in the GEA pathways. As with other energy technologies, it is an option, not a necessity, to meet future energy needs in a climate-friendly way. As discussed later, the scenarios in GEA demonstrate it is possible to meet all the GEA goals, including the climate goals, without nuclear power, even in the case of high demand scenarios. At the same time, in some scenarios with higher energy demand, it plays a large role in the energy mix. The resulting nuclear installed capacity in the scenarios ranges between 75 and 1850 GWe by 2050 with the lower bound resulting in a complete phase-out in the second half of the century. This uncertainty in the future of nuclear energy results from uncertainties in its future cost and public concerns about reactor safety, the proliferation of weapons-grade fissile materials, and the absence of arrangements in most countries for final disposal of spent fuel and/or the radioactive waste from spent-fuel reprocessing and plutonium recycle. Note that the high end of the above range is higher than the high projection put forward by the IAEA, based on the high ends of national projections before the Fukushima accident in 2011. In the past, nuclear growth has been far below the IAEA's high projection – and, until 2000, even below its low projections.

We have not considered nuclear fusion separately in the scenarios, given that fusion power is not likely to become a commercial energy option before the middle of the century at the earliest and would compete most directly with fission. However, pure fusion would have significant advantages relative to fission with regard to safety, proliferation resistance, and radioactive waste. Fusion–fission hybrids would not have these advantages.

3.4 Energy Systems[28]

The mechanisms by which energy is supplied to the final consumer are critical to the success of global and local economies. For the complex and diverse energy supply system to operate smoothly, many sources of energy – and their conversion to forms that can be delivered for use by consumers, from households to industry and commercial businesses – must operate in harmony within stable markets. Without the smooth operation of this complex interwoven system, the global economy cannot function (Chapter 15.1).

Energy supply systems differ between regions, between major economies, and between developing and industrial countries. Approaches to the necessary transitions[29] to create energy systems for a sustainable future therefore vary, and policies that work successfully in one region may fail in another. Nevertheless, there are lessons to be learned from shared experiences. The evolution of energy systems will depend on how well technologies are implemented and how well policies are instituted to bring about these changes.

Sustainable conversion from energy sources to energy carriers and efficient transmission and distribution for end-uses is crucial. This places particular emphasis on energy carriers such as electricity, hydrogen, heat, natural gas, biogas, and liquid fuels. All are key to transporting energy from more-remote production locations to growing urban population centers. Marketplaces will determine how much of each is used in any geographic region and when and how rapidly that use occurs.

As noted earlier, industry accounts for 27% of global final energy use, residential and public/commercial buildings use 34%, transport uses 28%, and agriculture/feedstocks/other uses account for 11%. Electricity

28 Section TS-3.4 is based on Chapters 15.

29 Transitions are covered more generally in Section TS-3.4.1 and in Chapters 16, 24, and 25.

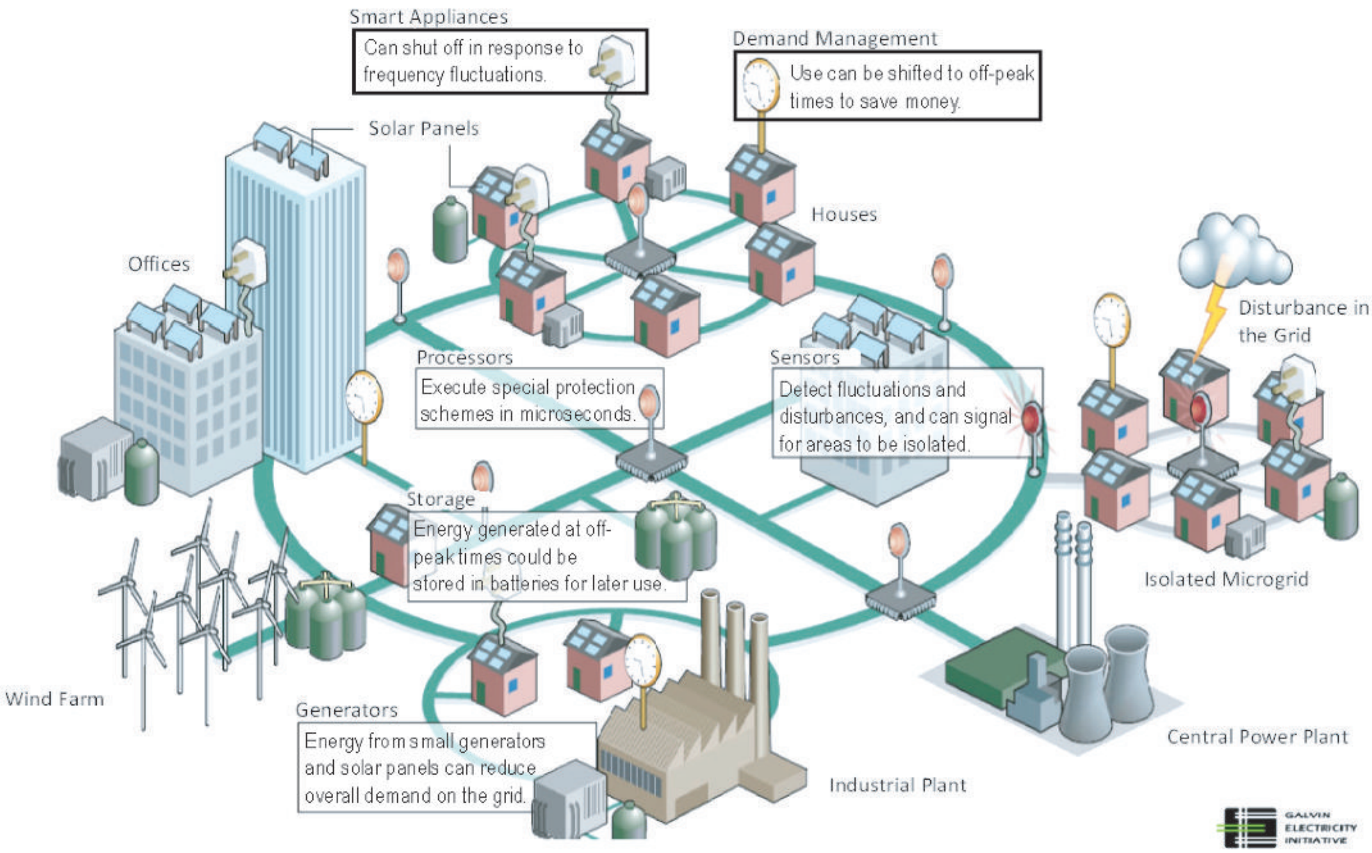


Figure TS-22 | Example of a smart grid, a network of integrated microgrids that can monitor and heal itself. Source: Amin, 2008; see Chapter 15.[30]

generation accounts for over one-third of the world's primary energy demand, with an average conversion efficiency of only around 36% (ranging from up to 90% for large hydro to less than 15% in some very old coal-fired power stations). Over half of all electricity generated is used in buildings, a category that includes households, services, and the public sector. More importantly, 40% of primary energy use results in heat, and much of this is wasted. Using more heat from thermal and geothermal power stations for industrial processes, district-heating schemes, and so on, would increase the overall efficiency of energy use (Chapter 15.2.1).

Providing integrated and affordable energy storage systems for modern energy carriers is essential. This is perhaps the largest and most perplexing part of the energy systems for a sustainable future that is needed for future economic security since costs are relatively high; pumped hydro storage being the lowest storage cost where feasible.

The entire energy grid for each energy source, from conversion to end-use, must be optimized into 'smart grids' using a digital system that continuously communicates between source and end-use and that integrates all energy carriers and their transmission and distribution systems (see Figure TS-22).

The potential of competitive electricity markets to most efficiently match energy supply and demand is a proven principle that is at the heart of the industrial world's economic system. Based on that success, it is rapidly becoming the standard for economic systems around the world.

In countries with well-developed energy markets, spot-market energy trading has been introduced and long-term contracts are becoming less frequent. The result for countries that supply energy is generally negative, and it is now more difficult to ensure long-term returns on large-scale investments. This is a threat to the financing of large capital-intensive energy supply projects.

Effective approaches to improving energy systems will be led by the private sector – but it is essential that there be a stable governance framework, facilitation of physical infrastructure, capital investments, and the social cohesion necessary for economic development and poverty reduction. Success will depend on the implementation of robust global public/private partnerships that can achieve unprecedented cooperation and integration between governments, between businesses, and between governments and businesses. This needs to happen rapidly to achieve energy systems for a sustainable future envisioned in the GEA goals.

30 **Amin, M., 2008:** Interview with Massoud, Amin, "Upgrading the Grid". *Nature*, **454**: 570–573.

Crucial to improved energy systems to meet rapidly changing needs is the urgent requirement to boost development and investment in advanced systems (Chapter 15, Sections 15.7.5, 15.8.5, and 15.9). The lag time between research and large-scale commercial deployment is long, yet funding for energy system R&D and demonstrations has been declining for 20 years. This trend must be reversed and involves enhanced cooperation among and between private and public sectors.

3.4.1 Transitions in Energy Systems[31]

The beginning of transformative change may be seen in a number of innovations and experiments in the energy sector. These experiments include technology-driven innovations in generation and end-use; system-level innovations that could reconfigure existing systems; and business-model innovations centered on energy service delivery. Experiments in generation include hybrid systems, where combining multiple primary energy sources help address issues such as intermittency. Experiments in end-use include technology options for the simultaneous delivery of multiple energy services, or even energy and non-energy services. System-level experiments include innovations in storage, distributed generation, and the facilitation of energy efficiency by effectively monetizing savings in energy use and the creation of new intermediaries such as ESCOs. In some of these experiments, technology can lead to changing relationships between players or changing roles for players; for example, the process of consumers becoming producers as seen in small-scale biogas projects.

To generate a base of innovations and effectively support those that show promise, understanding of the dynamics of technology transitions is essential. The transitions literature suggests that large-scale, transformative change in technology systems involves a hierarchy of changes from experiments to niches to technology regimes, with linkages across different scales.

3.4.2 Opportunities in System Integration

It is important to focus energy-related solutions on providing the energy services needed rather than on energy supply *per se*. Examples include telecommuting and electronic/IT services (such as e-banking) that replace the need for many routine car trips, or a relaxation of summer dress codes in offices (saving the energy used for air conditioning).

Measures to improve efficiency on the end-use side of the energy chain typically save more primary energy and associated pollution than measures on the supply side. This is because 1 kilowatt-hour (kWh) saved on the end-use side can often reduce 2–3 kWh worth of primary energy use and associated emissions. The GEA pathways assessment (Section TS-4) concludes that strategies focusing more on improved energy efficiency are by and large associated with lower costs for reaching the GEA goals than those focusing more on supply-side options.

GEA also finds that end-use-focused solutions reduce the risk that sustainability goals become unattainable. They increase the chances for multiple benefits, including improved local and indoor air pollution, and thus result in significant health gains, reduced congestion, reduced poverty, productivity gains, increased comfort and well-being, potential energy security improvements, new business opportunities, and sometimes enhanced employment opportunities.

The efficiency of end-use devices is also important when providing energy access. Lowest-cost devises, sometimes second-hand, can lock poor populations into using much more energy than needed; conversely, if efficient basic devices or appliances are also subsidized when providing access, consumers will be able to afford a higher level of energy services.

While individual system-, process-, and component-level efficiencies have improved significantly over the last few decades, the major opportunities for reducing energy intensity of economic activities lie in system optimization strategies rather than a focus on single components.

In industry, major advances have been achieved in process efficiency, with relatively fewer potentials remaining for such improvements. Still, most markets and policymakers tend to focus on individual system components (e.g., motors and drives, compressors, pumps, and boilers) with improvement potentials of 2–5%, while systems have much more impressive improvement potentials: 20% or more for motor systems and 10% or more for steam and process-heating systems.

Another way to reduce energy use in industry is to use fewer materials, as 70% of industrial energy use goes into the production of materials. A focus on increasing the rates of product reuse, renovation, remanufacture, and recycling has significant potential.

In buildings, novel approaches focusing on holistic methods that involve integrated design principles have been known to achieve as much as 90% energy reductions for heating and cooling purposes compared with standard practices (Section TS-3.2.3). Small-scale CHP has attracted interest for large buildings, and with the cost declines of PV, even if currently more expensive than grid electricity, the prospect of not being dependent on grid electricity has emerged. However, for feasibility, economic, and environmental reasons, requiring buildings to be zero-energy or net-energy suppliers is not likely to be the lowest cost or most sustainable approach in eliminating fossil fuel use, and is sometimes even impossible.

Energy use in densely built and populated areas, up to hundreds of watts per square meter (W/m^2) land area, typically significantly exceeds

31 Section TS-3.4.1 is based on Chapter 16.

annual average local renewable energy flows (typically below 1 W/m²). Therefore net zero-energy buildings are only feasible in low-density areas and in building types with low power or heat loads. High-rise or commercial buildings with high energy use, such as hospitals, cannot meet their entire energy demand through building-integrated renewable energy sources.

It is typically single-family or low-rise, lower-density multifamily residential neighborhoods that can become zero net-energy users for their residential energy needs (excluding transportation). Therefore, care needs to be exercised that zero-energy housing mandates do not incentivize further urban sprawl that leads to more automobile dependence and a growth in transport energy use, as efficient public transport systems are not economical in low-density urban areas.

Rather than aiming for buildings that use zero fossil fuel energy as quickly as possible, an economically sustainable energy strategy would implement a combination of the following: reduced demand for energy; use of available waste heat from industrial, commercial, or decentralized electricity production; on-site generation of heat and electricity; and off-site supply of electricity. Many forms of off-site renewable energy are less expensive than on-site PV generation of electricity and are thus able to achieve more mitigation and sustainable energy supply per unit of expenditure. At the same time, PV costs are expected to become competitive for grid-connected small consumers in major grid markets during this decade. Furthermore, PV must compete against the retail rather than the wholesale cost of electricity produced off-site. On-site production of electricity also improves overall system reliability by relieving transmission bottlenecks within urban demand centers. All of these steps point to the importance of policy integration.

3.5 Evaluating Options

The previous sub-sections describe various supply-side and end-use technologies, as well as the primary energy sources and their availability, and the changes taking place in the entire energy system. A number of

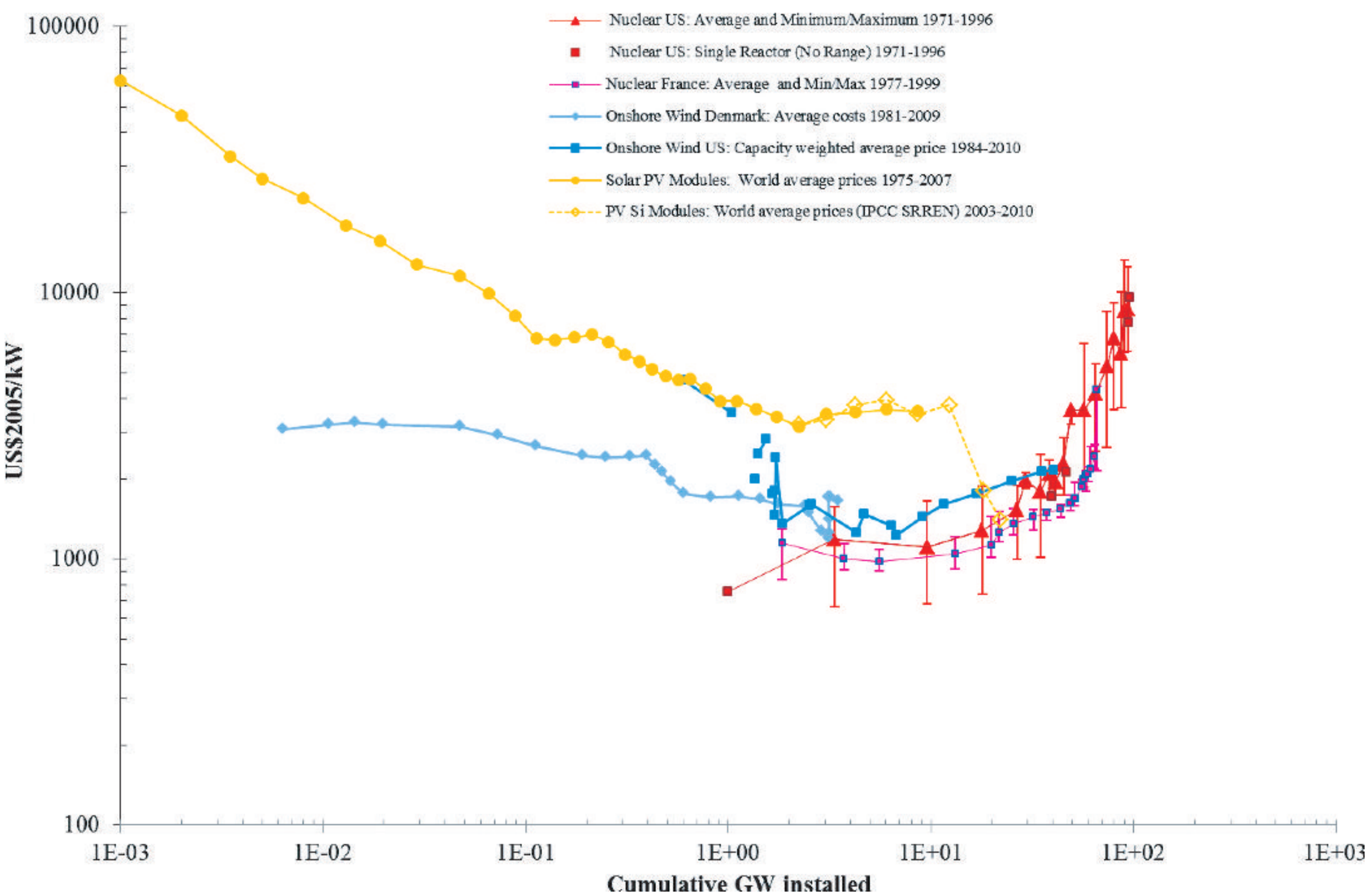


Figure TS-23 | Cost trends of selected non-fossil energy technologies (US2005$/kW installed capacity) versus cumulative deployment (cumulative GW installed) Chapter 24 data have been updated with the most recent cost trends (2010) available in the literature for PV Si Modules and US onshore wind turbines. Note that the summary illustrates comparative cost trends only and is not suitable for a direct economic comparison of different energy technologies due to important differences between the economics of technology components (e.g., PV modules versus total systems installed), cost versus price data, and also differences in load factors across technologies (e.g., nuclear's electricity output per kW installed is three to four times larger than that of PV or wind turbine systems). Source: Chapter 24.

attributes of these options need to be considered while evaluating their feasibility, appropriateness, and attractiveness. These include costs, benefits, environmental outcomes, and trade-offs across multiple objectives.

3.5.1 Costs and Environmental Performance of Options

Costs of Non-fossil Energy Supply Options

Figure TS-23 shows cost trends of selected non-fossil energy technologies. Despite a wide range in experiences of cost trend across technologies, two important observations stand out. First, there is a marked contrast between nuclear technologies, showing persistent cost escalations, versus the other non-fossil technologies, which generally show declining costs/prices with accumulated market deployment experience. Second, improvement trends are highly variable across technologies and also over time. For some technologies (e.g., wind in the United States and Europe) historical cost improvements were temporarily reversed after the year 2003–2004, suggesting possible effects of ambitious demand-pull policies in face of manufacturing capacity constraints and rising profit margins that (along with rising commodity and raw material prices) have led to cost escalations in renewable energy technologies as well.

Greenhouse Gas Emissions

One of the goals in the GEA analysis is to reduce emissions of GHGs. Tables TS-5 and TS-6 present the specific emissions per kWh for different technologies. Data are all life-cycle emissions of the major gases converted to CO_2 equivalent per GJ. The lowest emissions from renewables are from run-of-the-river hydropower, followed by hydro (reservoir), which displays a large variation depending on biological material in the reservoir, solar PV, wind, biomass, and geothermal. Nuclear energy has lower emissions than fossil-based generation, even if CCS is applied.

Combining fossil fuels with CCS reduces emissions significantly, although they are still significantly higher than renewables and nuclear. Combined use of fossil fuel and biomass with CCS can offer electricity and fuels with no net or negative emissions. As photosynthesis removes CO_2 from of the atmosphere, this results in negative emissions – that is, removal and storage of CO_2 when the biomass fuel is combined with CCS, which returns the CO_2 molecules to the ground (Table TS-7).

Quantifying emissions for electricity co-produced with liquid fuels (or for liquid fuels co-produced with electricity) is complicated by the issue of how to apportion emissions between the different products. The approach adopted here is to assign a percentage reduction (or increase) in emissions equal to the emission for the complete co-production system divided by emissions for a reference system consisting of separate conventional fossil fuel technologies (without CCS) that collectively produce the same amount of fuels and electricity.

Table TS-5 | Life-cycle emissions of GHGs for electricity generation. These numbers include direct emissions at the power plant and associated emissions upstream and downstream of the plant. The numbers here must be regarded as approximate as they depend on many assumptions, including the composition of the present energy systems.

Type	Conversion scheme	g CO_2-eq per kWh_e	
		w/o CCS	with CCS
Renewables	Solar photovoltaic[a]	16	
	Wind[b]	8	
	Hydro (reservoir)[c]	2–48	
	Hydro (run-of-river)	1–18	
	Geothermal[d]	~100	
	Biomass-IGCC[e]	25	–776
Fossil	Sub-critical coal[f]	896	187
	Super-critical coal[f]	831	171
	Coal-IGCC[g] Coal+biomass in coproduction with transportation fuels[h]	787–833 750	126–162 71
	NGCC[i] Natural gas + biomass in co-production with transportation fuels[h]	421 448	110 87
Nuclear	LWR, once-through fuel cycle[j]	38 ± 27	

CCS = carbon capture and storage; CO_2-eq = carbon dioxide equivalents; HT = high-temperature; IGCC = integrated gasification combined cycle; LWR = light water reactor; MWh = megawatt-hour; and NGCC = natural gas combined cycle.

a) For an in-plane irradiation of 1700 kWh/m^2 and a value of 10 g CO_2-eq per kWh_e or even less, see Chapter 11, Section 11.6.

b) Data from ExternE, vol 6, 1995.

c) Chapter 11, Section 11.3 gives estimates on emissions from hydropower.

d) High temperature brine, Chapter 11, Section 11.4. Note: emissions are very variable between existing geothermal power plants.

e) As-received biomass moisture content is 15% by weight (see Chapter 12, Table 12.1). This assumes zero emissions associated with indirect land-use change, as would be the case with utilization of most biomass residues or biomass grown on abandoned cropland.f) From Chapter 12, Table 12.6.

g) From Chapter 12, Table 12.7.

h) With co-production, how the life-cycle emissions for the system are allocated to each product is arbitrary. In Chapter 12 a Greenhouse Gas Emissions Index (GHGI) for co-production is defined as the system life-cycle emissions divided by life-cycle emissions for a reference system producing the same amount of electricity and transportation fuels. The reference system makes electricity in a supercritical coal-fired plant with CO_2 vented and transportation fuels from petroleum. The emissions rates given in this table are calculated as GHGI × (831 $kgCO_2eq$/kWh), where the GHGI values are from Table 12.27. The GHGI values will change with the fraction of fuel input to co-production that is biomass. For the systems in this table, biomass accounts for 29% of the higher heating value fuel input for the coal+biomass system and 34% for the natural gas+biomass system.

i) From Chapter 12, Table 12.8.

j) From Chapter 14.

Table TS-6 | Life-cycle emissions of GHGs for different liquid fuel supply technologies. Note: ILUC: Indirect Land Use Change; GHGI: Greenhouse Gas Index; CTL: Coal to Fischer-Tropsch liquid fuels; BTL: biomass to Fischer-Tropsch liquid fuels.

	Without ILUC	With ILUC	Source
	$kgCO_2$-eq/GJ LHV		
FOSSIL FUELS			
Gasoline from crude oil	91.6		Table 12.15, Note (c)
Diesel from crude oil	91.8		
Kerosene-type jet fuel from crude oil	87.8		
LPG	86		Table 12.15, Note (c)
FIRST GENERATION BIOFUELS			
US Midwest corn ethanol	69	90–210[a]	Chapter 9
US Midwest soy biodiesel	20	82[b]	
EU rape biodiesel	49		Chapter 11, average values in Figure. 11.20
EU sugarbeet ethanol	46		
Brazil sugarcane ethanol	19[c]	73	Chapter 20, ref. Macedo et al, 2008
SECOND GENERATION BIOFUELS (electricity is at most a minor byproduct)			
Cellulosic ethanol (farmed trees)	2	20	Chapter 20, ref. Macedo et al, 2008
Cellulosic ethanol (switchgrass)*	16		Chapter 12, Table 12.26
Cellulosic ethanol with CCS (switchgrass)*	–19		Chapter 12, Table 12.26
BTL (waste wood)	5.8		Chapter 11, Figure 11.20
BTL (switchgrass)*	6		Chapter 12, Table 12.15
BTL with CCS (switchgrass)	–87		
FOSSIL FUELS and FOSSIL/BIOMASS COMBINATIONS (electricity is a minor byproduct)			
CTL (coal to liquids)*	157		Chapter 12, Table 12.15
CTL with CCS*	81		
Coal+biomass with CCS to liquids, 43% biomass input*	2.7		
GTL (gas to liquids)	101		Chapter 12, Section 12.4.3.1
GTL with CCS	82		
CO-PRODUCTION OF LIQUID FUELS AND ELECTRICITY (electricity is a major co-product)			
CTL with CCS*	64		Chapter 12, Table 12.22
Coal+biomass to FTL with CCS*	8.5		
Natural gas+biomass to FTL with CCS*	9.6		Chapter 12, Table 12.27

* The emissions estimates for these systems are from Chapter 12, based on the GHG emissions index (GHGI), defined in Table 12.15, note (c). The emissions rates in this table are calculated as GHGI × Z, where the GHGI values are taken from Chapter 12 and Z is the lifecycle GHG emissions for petroleum-derived fuels that would be displaced by the fuels produced from coal, gas, and/or biomass.

a) Chapter 11 (Fig. 11.20) gives range from 73 to 210 for corn ethanol (without ILUC).

b) Chapter 11 (Fig. 11.20) gives 19 (without ILUC)

c) Chapter 11 (Fig. 11.20) gives 23 $kgCO^2$-eq/GJ w/o ILUC

3.5.2 Multiple Benefits

The GEA pathways that meet the sustainability goals also generate substantial economic and social benefits. For example, achieving society's near-term pollution and health objectives is greatly furthered by investing in the same energy technologies that would be used to limit climate change. Increased stringency of air pollution policies globally and increased access to cleaner cooking fuels would bring significant improvements in pollution-related health impacts as compared to currently planned air-quality legislations and access trends, with a saving of 20 million disability adjusted life years (DALYs) from outdoor air pollution and more than 24 million DALYs from household air pollution.

This synergy is advantageous and important, given that measures which lead to local and national benefits, for example, improved health and environment, may be more easily adopted than those measures that are put forward solely on the grounds of global goals. Many energy efficiency and renewable energy options enjoy such synergies and generate

Table TS-7 | Synthesis and taxonomy of multiple benefits related to sustainable energy options. The options are discussed in the different rows, while the policy goal where the multiple benefits occur is covered in the different columns. The first five columns summarize how the various options discussed contribute to (or occasionally compromise) reaching the multiple objectives of GEA. The remaining three columns identify further multiple benefits and impacts. The table focuses on the more sustainable sub-options within the rows, and acknowledges if there are major differences in the particular impact among the sub-options (such as with and without CCS). It is important to recognize, however, that this is a synthesis table and thus cannot be fully comprehensive.

Sustainable Energy Options	Access	Energy Security	Health	Environment	Climate Change (mitigation and adaptation)	Development and Economic benefits, poverty alleviation	Risks of large accidents	Employment (local)
Efficiency								
Industry	–	Energy import need reductions due to saved energy; a robust industry makes for stronger social and defense systems	Reduced health impacts from lower regional industrial and energy-related air pollution	Reduced energy-related emissions from saved energy; lower industrial pollution from material efficiency & recycling	Lower CO_2 emissions due to saved energy; lower non-CO_2 GHG emissions due to process/material efficiency	Productivity gains and increased competitiveness; For all end-use sectors: New business opportunities for efficiency implementation, e.g. ESCOs, Reduced investment needs in supply thus more funds for development	Lower risk of industrial accidents from more efficient, safer and fewer processes; Gains through displaced risky generation	New jobs in efficiency implementation, ESCOs, equipment production
Transport	Better and more equitable access to mobility services	Alternative fuels: Shift to non-oil dependent economy; lower oil consumption for efficiency, modal shift and non-motorized mobility	Health gains from lower urban air pollution; lower mortality and morbidity from reduced accidents	Significant improvement in urban air quality due to reduced specific emissions and transport volumes	Lower GHG emissions due to efficiency gains, alternative fuels, non-motorized and alternative mobility	Reduced economic damages from congestion; better access to economic activities; economic savings through lower transport costs due to efficiency and alternative mobility; more time for productive activity from improved mobility	Lower risk for oil spills due to lower oil consumption and trade	Local employment gains for public transport
Buildings (residential, public and services)	Access to higher energy service levels from same budget and production capacity through efficiency	Reduced needs for imports due to saved energy; more resilient energy systems from building-integrated distributed generation	Clean/efficient cooking; lower respiratory infectious morbidity in well-ventilated buildings; reduced noise exposure	Reduced energy-related emissions from saved energy; both local and regional	Reduced GHG emissions: CO_2 from saved energy, non-CO_2 from less cooling; more climate and heat resilience: adaptation gains	Increased social welfare: More disposable income through saved energy costs; potentially eliminated poverty; Reduced needs for tariff subsidies; productivity gains from reduced illnesses in well-ventilated buildings; increased value for real estate	Gains if energy savings are large enough to displace risky power generation	Large net local employment benefits, especially for retrofits; high employment intensity of energy savings' through efficiency
Systems and grids								
Advanced electricity and gas systems (possibly hydrogen in future)	Inexpensive and more linked systems provide easier access; Distributed generation provides access where needed	Smart systems provide redundancy through rapid deployment of energy, and enhanced use of alternatives. Microgrids offer autonomy, stability, flexibility	Smart systems are more efficient, reducing air pollution from sources	Smart systems reduce overall need for energy with less environmental impact; Can assimilate large amounts of variable renewable energy source (RES)	More efficient, use less energy and produce fewer GHGs	ICT, smart systems, microgrids, and distributed generation increase efficiency and productivity by providing stability and instant flexibility; Smart systems are less expensive and thus more ubiquitous.	Faster, more reliable and redundant systems reduce accident risks	Distributed generation and smart systems mean mostly local jobs
Supply								

Oil (with and without CCS)	Oil products such as kerosene and LPG provide clean solutions to the access to cleaner cooking goal, and would reduce GHG emissions from the cooking	Dependence from producers in politically unstable regions; control of oil sources as demonstrated cause of armed conflicts	Health benefits if cleaner fuels replace traditional biomass use	Lower indoor and local pollution if cleaner oil-based fuels replace traditional biomass	Lower black carbon emissions if cleaner oil-based fuels replace traditional biomass; with CCS: reduced CO_2 emissions for large point-sources	Major income source for many oil-rich countries; with CCS can provide low GHG energy source for many places and uses. Its price volatility can impact the economies; and affects mobility affordability	Risk of spills in the extraction and transport of oil and oil products	Mostly low labor intensity of extraction and use; mostly centralized
Coal (with and without CCS and biomass)	Can provide the fuels for access to cleaner cooking in many countries; provided technology routes such as analyzed in Chapter 12	Coal and biomass are geographically rather equally available; can be imported easily	Health impacts through mining and burning-related emissions need to be addressed along the lines in Chapter 12	Potential major landscape impacts from mining. Large particulate and other emissions, including radioactive; damages through mining, may be difficult to avoid	Highest specific emissions without CCS; with biomass co-gasification CCS enables CO_2-free power; and can even have negative emissions	With high oil prices low C electricity can be provided at costs that are much lower than for power-only plants with CCS via coal/biomass co-production with CCS systems that simultaneously offer low C fuels at lower costs than biofuels.	Risk of coal mine accidents, although not large mortalities; for CCS: risk of leakage	If the primary future role of coal is shifted from the present focus on generating electricity to co-production of liquid fuels and electricity with CCS from coal + biomass, there would be significant new industries associated with making these liquid fuels that would replace oil imports
Natural gas	Provides access to more energy services if available locally	Might reduce reliance on other imported energy if available locally; more equally distributed than oil	Little or no impact due to relatively perfect combustion	Lower emissions than other fossil fuels	High GHG emissions prices needed to induce CCS for power-only systems, a challenge that can be greatly mitigated if instead electricity and synfuels are co-produced with CCS; CH_4 emissions can be controlled	Can provide low-cost energy needs for economic development in regions where available; cleaner with CCS, the added cost of CCS can be mitigated in a world of high oil prices by making synthetic fuels + electricity instead of just electricity	Risks of gas leaks from storage and pipelines and exposures	Low labor intensity of extraction and use
Nuclear	Can provide the energy for access in countries with insufficient local energy sources	More ubiquitously available/importable than many other sources. Major security risks from facilitating nuclear-weapon proliferation	Large health benefits in comparison with fossil and traditional biomass energy	Occasional radioactive releases from whole fuel cycle; radioactive waste challenges	Much lower emissions of CO_2 than fossil-fueled power plants on a life-cycle basis	Can provide the energy for development in regions where insufficient local resources are available; though at what cost depends on many factors	Risk of large releases of radioactivity; risks from facilitating nuclear-weapon proliferation	Low employment intensity; centralized employment

Sustainable Energy Options	Access	Energy Security	Health	Environment	Climate Change (mitigation and adaptation)	Development and Economic benefits, poverty alleviation	Risks of large accidents	Employment (local)
Renewables								
Solar (CSP and PV)	PV: Provides interim power source until full access to grid is provided; Thermal: provides some hot water. Can be self-made	Security gains through reduced energy and fuel import needs	Improved health due to lower emissions and pollution	Reduced emissions from fossil fuels and resources depletion; lifecycle environmental impact for PV	Limited life-cycle GHG	Most distributed energy source: can provide the energy right where needed; High cost of solar electric technology, but no fuel expenditures once equipment is installed; low cost (potentially self-made) for solar thermal; new industrial opportunities	Risk reductions through avoided conventional risky generation	More employment intensive than large-scale power generation, but many related jobs can be 'exported'
Wind	Better access to electricity through local/regional power generation	Security gains through reduced energy import needs	Improved health due to lower emissions, pollution	Reduced emissions from fossil fuels, but noise and visual impacts; some ecological impacts	Limited life-cycle GHG emissions	Most competitive RES-E technology and thus can provide affordable power; new industrial opportunities; eliminated fuel costs: no fuel import costs eliminate price volatility	Risk reductions through avoided conventional risky generation	More employment intensive than large-scale power generation, but many related jobs can be 'exported'
Hydro	Better access to electricity through local power generation (e.g., small hydro)	Security gains through reduced energy import needs	Improved health due to lower emissions, pollution	Reduced emissions from fossil fuels, but large hydro has serious environment and social liabilities	Limited life-cycle GHG emissions	Large hydro is the most ubiquitous large RES, can provide significant energy for development in many countries. Can be very affordable; can help in flood regulation; new recreational space creation	Risk of dam break and catastrophic flooding for large hydro	Can be employment intensive, part of jobs created are local
Biomass (with and without CCS)	If biomass is used primarily to make synthetic transportation fuels via gasification, LPG which can be used as a clean cooking fuel will be an inevitable byproduct, and much lower cooking fuel use rate via LPG compared to burning biomass implies that the LPG could go a long way in meeting cooking fuel needs even if providing transportation fuel is the main objective. This is discussed in Chapter 12	Security gains through reduced energy import needs; biomass can be ubiquitously available and easily imported, land use competition issues can be avoided with adequate zoning as done in Brazil	Traditional biomass burning can have very high indoor pollution and related health toll	Like any agricultural crop, needs to be sustainably produced to avoid deforestation and other major environmental impacts; risk of ecological damages through monocultures, which can be avoided with adequate environmental legislation such as fauna corridors and maintenance of local native forest.	Variable life-cycle GHG emissions; needs to be consciously minimized. *With CCS it can provide one of the few opportunities for negative GHG emissions*	Presently provides the most ubiquitous source of energy for the poorest, but with large impacts when not produced in a sustainable way; If sustainably produced, can fuel development in many regions, but potential competition with food production and thus impact on food prices	Risk reductions through avoided conventional risky generation	Very employment intensive if sustainably produced, most jobs created are local

benefits across multiple objectives. Some of these benefits can be so substantial for certain investments/measures that they may offer more attractive entry points into policymaking than climate or social targets. This is particularly the case where benefits are local rather than global. Seeking local benefits and receiving global benefits as a bonus is very attractive, and this is often the case for investments in energy efficiency and renewable sources of energy.

Therefore, even if some of these multiple benefits cannot be easily monetized, identifying and considering them explicitly may be important for decision making. Cost-effectiveness (or cost–benefit) analyses evaluating sustainable energy options may fare differently when several benefits are combined into one investment evaluation.

The enhancement of end-use efficiency in buildings, transport, and industry offers many examples of benefits across multiple social and economic objectives. Among the most important ones are: improved social welfare, including alleviated or eliminated poverty as a result of very high efficiency and thus very low fuel-cost buildings; reduced need for public funds spent on energy price subsidies or social relief for poor people; and health benefits through significantly reduced indoor and outdoor air pollution, often translating into commendable productivity gains. Productivity gains and general improvements in operational efficiency in industry translate into improved competitiveness. Improving efficiency by increasing the rate of building retrofits can be a source of employment generation. Other benefits that are non-quantifiable or difficult to account for include improved comfort and well-being, reduced congestion, new business opportunities, and improved and more durable capital stock.

Other economic benefits of rapidly decarbonizing the energy system are the reduced need for subsidies into carbon-intensive petroleum products and coal. At present, subsidies for these fuels amount to approximately US$132–240 billion per year[32] (Chapter 17). Only 15% of this total is spent directly toward poor people who have limited access to clean energy. As noted in Section TS-5.2.1, subsidies to poor people must be increased in order to achieve universal access. GHG mitigation in the GEA pathways would, however, at the same time reduce consumption of carbon-intensive fossil fuels by the rest of the population, leading to a reduction in the need for subsidies for oil products and coal in the order of US$70–130 billion per year by 2050 compared to today.

A review of the co-benefits related to the discussions in this assessment, that is, selected key routes through which the various sustainable energy options described earlier in this section and in Chapters 7–15 of the report contribute to different policy goals, is presented in Table TS-7. The purpose is to summarize the main routes of impacts through which the various options affect the multiple objectives set out in GEA, as well as to identify further benefits. However, whether an impact is a benefit or a liability depends on the baseline and local situation: for example, while liquid petroleum gas (LPG) has major environmental and climate impacts in itself, it still has major advantages in many areas when it replaces traditional biomass burning. Thus, a key novelty of Table TS-7 is that it provides a new, additional framework for a well-founded assessment for individual choices among various energy alternatives that complements the financial appraisals. For example, in jurisdictions where access to modern forms of energy is a major energy policy goal, evaluations in the 'energy security' column may play a key role in ranking the different options available at comparable costs. In other areas, access or employment may be key secondary objectives of energy policy and these may play the chief role in additional prioritization of options with comparable local costs. The evaluations Table TS-7 are qualitative and, due to the challenges of comparing very different types of effects, are indicative only.

Table TS-7 demonstrates that there is a very broad array of different benefits in a large spectrum of policy target areas, representing many potential entry points into policymaking. However, some options can have a wider range of co-benefits than others, such as improved efficiency, system solutions, and some renewables, such as biomass with CCS and fossil fuel/biomass co-processing with CCS. The lowest levels of co-benefits arise from nuclear power and fossil-fuel related options, even with CCS. There are less-marked differences among the options with regard to policy goals, such as energy security: most of the sustainability options discussed in this report have positive impacts on security. In contrast, others, such as poverty and access, are harder to contribute to: it is mainly renewable forms of energy that can significantly contribute to these goals. Improved efficiency, at the same time, has positive impacts on almost all policy goal areas and often has the broadest range and largest co-benefits.

3.5.3 Trade-offs and Constraints[33]

Changes in food and energy use will not only have substantial environmental impacts, they will also influence each other in many ways. At the same time, the production of food and energy and their dependence on water resources will be affected by global environmental change, including climate change.

Population growth and economic growth are major factors contributing to increased demand for land and water. In addition, growth in incomes is strongly correlated with increased consumption of animal-derived food (meat, milk, eggs). This combination will increase pressure on land and water resources if not counteracted by environmentally sound land- or water-saving innovations.

Sustainability issues arising from competition and synergies between the future production of bioenergy and food are highly important in this context, but they can be avoided with adequate policies, as discussed in

32 'Tax-inclusive' subsidies are higher at a little below US$500 billion.

33 Section TS-3.5.3 is based on Chapter 20.

Chapter 20. The global bioenergy potential from dedicated energy crops, considering sustainability constraints (such as maintenance of forests, areas with high biodiversity value, or protected areas) as well as food demand and feed demand of livestock, was estimated to be 44–133 EJ/yr in 2050. Substantially higher or lower levels could also be possible, as there are large uncertainties with respect to many important factors: land and water availability; feedbacks between food, livestock, and energy systems (in particular, future crop yields and feeding efficiency of livestock); and climate change.

Food prices are a concern, particularly in poorer areas of the world. They are influenced by many factors, including temperature and precipitation, pest attacks, and oil and fertilizer prices. There is a concern that major bioenergy crop expansion would become a significant factor, but there are studies, as mentioned in Chapter 20, that show different points of view. The potential indicated above takes such concerns into consideration. However, land allocation for different purposes will have to be monitored and managed carefully, as free competition between food, bioenergy, and other markets (e.g., fiber) could lead to swings in agricultural prices and supply. Adequate policies for introducing bioenergy plantations could avoid adverse social, economic, and ecological effects, while best-practice examples suggest that bioenergy plantations could be highly beneficial in terms of sustainability if based on sound strategies. Monitoring, managing, and enforcing adequate policies are required to ensure sustainability of bioenergy production. Adequate land and water-use environmental zoning and planning should be implemented to consider specific environmental conditions of each region.

Policies that support biofuels expansion should carefully evaluate the price and related food-security implications of scenarios relevant to the situation in each country. They should ensure sustainable production for any agricultural product and give priority to the diversification of technologies and fuels, while identifying different options for the future, based on adequate environmental zoning, and sustainable policies, as well as considering the overall impacts of each fuel. This must occur through public policies that govern and regulate markets and stimulate efficient technologies. These policies include biofuels sustainability based, for example, on certification schemes adequate for each country

The impact of climate change on land use systems is, at present, rather imperfectly understood. In subtropical and tropical regions, changes in climate and the rainfall regime may change the agricultural suitability of a region significantly. Temperature change may require the migration of some crops and agricultural areas to regions with a more temperate climate or higher levels of soil moisture and rainfall. In general, crop productivity in the tropics may decline even with a 1–2°C increase in local temperature. This would also have significant impacts on renewable energy resources, for example cloud cover, rainfall, and wind speed.

Multiple uses of water – for human consumption, hydro and thermal power generation, manufacturing, agriculture, water security, bioenergy, and so on – are feasible and associated with environmental, social, and strategic aspects, as well as with potential trade-offs. Competition between food and energy crops may not always be over ‘the same water’. Depending on the type of feedstock, it is possible to cultivate adequate bioenergy crops in areas where conventional food production is not feasible due to, for example, water constraints – that is, the ‘water footprints’ are of a different character.

3.5.4 Rethinking Consumption[34]

The well-being of the ‘final consumer’ drives the production of goods and services and consequent energy service demand. Is a lifestyle that has high throughput of energy and materials globally sustainable in the long run? The literature on ecological footprints shows the unsustainability of ever-growing consumption in a growth path led by economic well-being. Studies offer the potential to get life-cycle approaches into a decision-making context and open up the possibility of a diversification of the policy portfolio.

The growing constraints on people’s time as they pursue economic well-being have led people to buy appliances that save labor but use more energy. Walking, cycling, jogging, and natural green spaces are being taken over by energy-guzzling health clubs and the like, and by highly irrigated green spaces, while small traditional retail stores are being replaced by high energy using air-conditioned shopping malls. A convergence in the high level of energy service demands across various cultures, geographies, and income classes is the dominant trend.

Technology, income levels, and lifestyles are causing important changes in both direct and indirect energy requirements of households. While energy efficiency through technological improvement is helping, energy use and GDP growth have not really been decoupled in many countries. Lifestyle changes are essential to realize the full benefits of the technical potential.

In the short term, for incremental changes it is advantageous to consider consumers as shoppers and purchasers in a marketplace. By controlling information, education, and so on, what people buy can be influenced to achieve the desired outcome. In the medium term, an approach that relies on human well-being in terms of sustainable development, on Millennium Development Goal indicators, and on the triple bottom line (with more emphasis toward environmentalism) can have a moderate dampening effect on energy use.

In the longer term, an ecological footprint index and the criterion of ‘sufficiency’ provide promising policy options in individualistic liberal

34 Section TS-5.4.4 is based on Chapter 21.

societies for increasing sustainability in the energy system and motivating the adoption of a new value system. A human well-being indicator needs to evolve beyond GDP and the Human Development Index to reflect responsible individual and community behavior, sufficiency, happiness, and social ecosystem balance. Transformational change in the social fabric that places individual and community actions in the proper context has a role to play in reaching a low-energy path.

Despite health alerts and religious taboos, meat consumption has increased due to the aggressive marketing strategies of producers and distributors, creating an association between wealthy people's diet and meat consumption. There is a lack of awareness that a reduction in per capita meat consumption, especially in industrial countries, could reduce numerous health risks as well as global energy use and GHG emissions.

Education systems in modern societies can promote the virtues of going beyond classical humanistic contents of individual freedom and dignity and instead emphasize more collective aspects. The role of the state is to ensure adoption of a rights-based policy line that can make the duty to 'do no harm' a global right that matches the right to not be harmed. Governance that evolves organically can shape the course of action that involves the state and various communities such as non-government organizations, corporations, communities, civil society, and religious institutions.

Formal, informal, ethical, public, and mass media systems of education could generate social values that redefine modernism through more cultural diversity and local specificities instead of homogenization. Responsible individual and community behavior that justifies sufficiency in liberal societies needs broader and faster dissemination through investments in various institutions.

4 GEA Transformational pathways[35]

GEA explored 60 alternative pathways of energy transformations toward a sustainable future that simultaneously satisfy all its normative social and environmental goals of continued economic development, universal access to modern energy carriers, climate and environment protection, improved human health, and higher energy security (see Section TS-2.6).

The pathways were divided into three different groups, called GEA-Supply, GEA-Mix, and GEA-Efficiency, representing three alternative evolutions of the energy system toward sustainable futures. The pathways within each group portray multiple sensitivity analyses about the 'robustness' of the three different approaches in mastering the transformational changes needed to reach more sustainable futures. Of the 60 pathways explored, 41 clearly simultaneously fulfilled all the normative goals – indicating that such futures are reachable from a resource, technology, and economic point of view.

For such a transformation to be achieved, the pathways presume that political commitment, the availability of necessary financing (coming forward in response to the right market signals), and technological learning and diffusion occur pervasively throughout the world. Achieving the goals assumed in GEA generates significant benefits. Realizing these benefits requires governments to provide market conditions that ensure appropriate investments are mobilized (see Section TS-5). Thus, planning for a future energy system requires going beyond pure economic costs and needs to factor in salient environmental and social externalities. Thus, the 41 pathways jointly indicate the plausibility of transformative changes if the externalities and benefits related to the GEA sustainability goals are appropriately accounted for.

Together, these 41 transformational pathways integrate the conclusions of individual GEA chapters on major challenges and options into a consistent framework of scenario analysis. The analysis included a narrative that constituted the initial platform for the three alternative sets of quantitative pathways, which were developed by two different integrated assessment modeling frameworks (MESSAGE and IMAGE).

The energy transformations captured by the pathways encompass 11 world regions, grouped into five GEA regions. They also include various energy sectors, including supply and demand, with a full range of associated social, economic, environmental, and technological developments. They result in radically changed ways in which humanity uses energy, ranging from much more energy-efficient houses, mobility, products, and industrial processes to a different mix of energy supply – with a much larger proportion of renewable energy and advanced fossil fuel technologies.

The pathways indicate that the energy transformations need to be initiated without delay, gain momentum rapidly, and be sustained for decades. They will not occur on their own. In fact, the pathways imply a significant departure from recent trends. Serious policy commitments are therefore required. Furthermore, it would require the rapid introduction of policies and fundamental governance changes toward integrating global concerns, such as climate change, into local and national policy priorities, with an emphasis on energy options that contribute to addressing all these concerns simultaneously.

Although energy transformations in the pathways are fundamental and rapid, they are not historically unprecedented. In the past, energy systems have experienced similar, or even more profound, transformations – for example, when coal replaced biomass in the 19th century, or when electricity was introduced in the first half of the 20th century. More recently, a number of countries have rapidly shifted from coal to natural gas. Transformational changes closer to the consumer,

35 Section TS-4 is based on Chapter 17.

such as the replacement of horse carriages by automobiles, occurred within three decades in many parts of the world. The need for sustained transformation is, however, new and unprecedented on the global scale.

The GEA pathways are based on the assumption that the advanced technologies known today, often commercially unviable under current market conditions, would be improved through vigorous R&D and deployment to achieve cost reductions and better technical performance through economies of scale and through learning by using and by doing. Various combinations of resources, technologies, and policies are incorporated across the different pathways. While there is some flexibility in the choice of specific policy mechanisms, achieving all the GEA normative goals simultaneously is an extremely ambitious task.

For each of the three groups of pathways, one 'illustrative' case has been chosen that captures the salient characteristics of the group. The illustrative pathways are not necessarily the average or median of the set, but rather pathways that capture the overall characteristics of the respective group. They depict salient branching points for change and policy implementation. The characteristics differ significantly and depend on choices about technologies, infrastructures, behaviors, and lifestyles, as well as on future priorities on supply and demand-side policies. These choices have, in turn, widespread implications for technology availability and scale-up, institutional and capacity requirements, and financing needs.

The main distinguishing dimensions of the three illustrative GEA pathways are as follows:

- *Demand versus supply focus.* While the assessment shows that a combination of supply-side and demand-side measures is needed to transform the energy system, emphasis on either side is an important point of divergence, as exemplified by GEA-Supply compared to GEA-Efficiency. A critical factor is thus how much the changes in demand for energy services together with demand-side efficiency measures can reduce the amount of energy required to provide mobility, housing, and industrial services. This dimension is one of the main distinguishing characteristics and motivates the naming of the three illustrative pathways.

- *Global dominance of certain energy options versus regional and technological diversity.* Once technological change is initiated in a particular direction, it becomes increasingly difficult to alter its course. Whether the transformation of the future energy system follows a globally more uniform or diverse path thus has important implications, given irreversibility, 'lock-in', and the path dependency of the system. GEA-Efficiency and GEA-Supply pathways depict worlds with global dominance of certain demand and supply options, while GEA-Mix pathways are characterized by higher levels of regional diversity.

- *Incremental versus radical new solutions.* Given that the GEA sustainability objectives are ambitious, the transformational changes to realize them need to be introduced rapidly across all GEA pathways. For instance, all pathways feature decreasing shares of carbon-intensive supply options. The pathways differ, however, with respect to the emergence of new solutions. Some rely more heavily on today's advanced options (such as efficiency and renewables in GEA-Efficiency) and infrastructures (such as biofuels in GEA-Mix), while others depict futures with more radical developments (such as hydrogen or CCS in GEA-Supply).

The transformation can be achieved from different levels of energy demand as well as through alternative combinations of primary energy resources (see Box TS-1 and Figure TS-24).

4.1 Requirements for Achieving the Transformation

Despite the flexibility and choices available across the pathways regarding the direction and dynamics of the energy system transformations, also a large number of robust characteristics are common to all pathways. These commonalities are summarized below. They illustrate the magnitude of energy system changes that would need to be introduced to reach the GEA sustainability objectives.

Improvements to at least the historical rate of change in energy intensity are necessary to reduce the risk that the sustainability objectives become unreachable. Further improvements in energy intensity, entailing aggressive efforts to improve end-use efficiency, increase the flexibility of supply and improve the overall cost-effectiveness of the energy system transformation (see Box TS-2). 'Negawatts' provide more choices at lower costs than 'Megawatts'.[36]

A broad portfolio of supply-side options, focusing on low-carbon energy from renewables, bioenergy, nuclear power, and CCS, was explored, achieving at least a 60–80% share of zero-carbon options in primary energy by 2050. These include:

- Strong renewable energy growth beginning immediately and reaching between 165–650 EJ of primary energy by 2050. This corresponds to a global share of 30–75% of primary energy with some regions experiencing, in the high case, almost a complete shift toward renewables by 2050.

- Rising requirement for storage technologies and 'virtual' systems (e.g., smart grids and demand-side management) to support system integration of intermittent wind and solar.

36 Amory Lovins is well known for highlighting the need for achieving high energy efficiencies through "Negawatts rather than Megawatts".
Lovins, A.B., 1990: The Negawatt Revolution, *Across the Board*, **27**(9) 23–29. http://www.thewindway.us/pdf/E90–20_NegawattRevolution.pdf.

Box TS-1 | The three groups of GEA pathways

All GEA pathways share common socioeconomic assumptions, including demographic and economic developments. They differ radically in the structure of the future energy systems.

GEA-Efficiency pathways emphasize efficiency. The global pace of energy intensity improvements thus double compared to the long-term historical average. For example, this implies that in the buildings sector, efficiency would be improved by a factor of four by 2050. This would require measures and policies to achieve the rapid adoption of best-available technology throughout the energy system, for example, to, retrofit existing plants, enhance recycling, improve life-cycle product design in the industry sector; reduce energy demand through aggressive efficiency standards, including electrification, a shift to public transport, and reduction of demand for private mobility. Emphasis in GEA-Efficiency is thus on demand-side R&D and solutions to limit energy demand for services. This results in a primary energy demand level in 2050 of 700 EJ, compared to the level of 490 EJ in 2005.

GEA-Efficiency also relies on increasing renewable energy, approaching 75% of primary energy by 2050, and further increasing its contribution to about 90% by the end of the century. Figure TS-24 shows the illustrative efficiency pathway with various sensitivity analyses, indicating the changes by 2050. In some of the efficiency pathways nuclear power is assumed to be phased out over the lifetime of existing capacities, whereas CCS provides an optional bridge for the medium-term transition toward renewables. In the illustrative pathway, coal use declines immediately while the oil peak is reached before 2030. Unconventional oil resources thus remain largely untapped, given the GEA environmental objectives to reduce GHG and air pollutant emissions. Natural gas contribution remains at about current levels as it is the least carbon-intensive of all fossil sources. In contrast, the role of renewables increases across all pathways.

GEA-Supply features a major focus on the rapid up-scaling of all supply-side options. A more modest emphasis on efficiency leads to energy intensity improvement rates roughly comparable to historical experience. Primary energy demand in the illustrative Supply pathway reaches about 1050 EJ in 2050. Massive up-scaling of energy supply R&D and deployment investments lead to new infrastructures and fuels (such as hydrogen and electric vehicles in the transportation sector). Renewables contribute about half of primary energy by the middle of the century. The GEA-Supply pathways show similar levels of expansion for renewables as those in the GEA-Efficiency pathways. As a result of relatively higher levels of energy demand, the share of renewables is, however, comparatively smaller in the GEA-Supply pathways. Further implications of the relatively higher energy demand is that fossil CCS is becoming an essential building block in the medium term to decarbonize the remaining fossil share of the supply system. In the long term, the contribution of fossil CCS declines as the transition toward zero-carbon options progresses. New nuclear power plants gain significant market share after 2030 in some of the supply pathways. This presupposes that issues related to weapons proliferation, nuclear waste, and other inherent risks of nuclear energy are satisfactorily resolved. However, supply pathways also include nuclear phase-out cases that imply vigorous increases of alternative energy sources given the relatively high energy demand. This is possible; however, it was not possible to formulate a GEA-Supply pathway without the CCS technology, indicating that CCS is a must with such high levels of demand for fossil fuels (Figure TS-24). In principle, fossil fuels can either be used with CCS at high demand levels or the energy demand level can be reduced to meet GHG emission reduction goals, as in GEA-Efficiency.

GEA-Mix pathways are intermediate with respect to many scenario characteristics, such as efficiency focus and the up-scaling of advanced and cleaner supply-side technologies discussed in Section TS-4. The primary energy demand level reaches 920 EJ in 2050. The main emphasis is on diversity of energy supply and technology portfolios, thus enhancing system resilience against innovation failures or technology shocks. Furthermore, large differences in regional implementation strategies reflect local choices and resource endowments. This results in the co-evolution of multiple fuels, particularly in the transport sector, where, for example, second-generation bio-liquids, fossil/bio-liquids with CCS, and electricity gain importance in different regions.

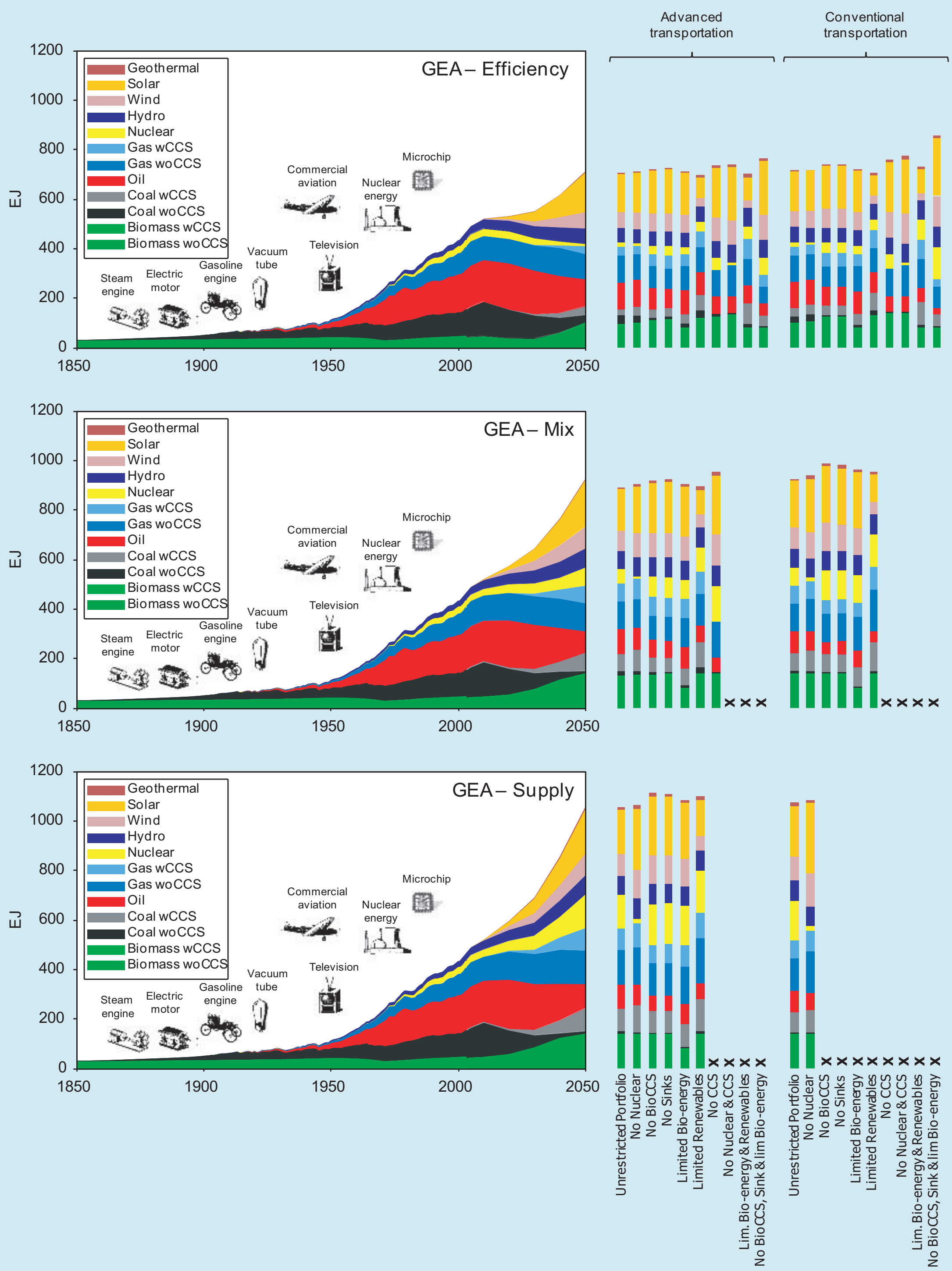


Figure TS-24 | Development of primary energy in the three sets of GEA pathways. Left-hand panels show the three illustrative GEA pathways, and right-hand bars give the 2050 primary energy mix of all 60 pathways explored. Conventional transportation refers to pathways that assume the continuation of a predominantly liquid-based transportation system, whereas advanced transportation refers to pathways that allow for fundamental changes in infrastructures – for example, high penetration of electric vehicles or other major breakthroughs in transportation technology such as hydrogen fuel cells. Pathways marked 'x' indicated the 19 cases where, under the specific combination of assumptions, the GEA normative goals could not be reached. For further details of the GEA pathways see the interactive web-based GEA scenario database hosted by IIASA: www.iiasa.ac.at/web-apps/ene/geadb.

- Strong bioenergy growth in the medium term from 45 EJ in 2005 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 power plays an important role in some of the pathways, while others assess the consequences of a nuclear phase-out. They illustrate that it is possible to meet the GEA normative goals even with a nuclear phase-out. The GEA-Efficiency pathways provide more flexibility in these cases. The range of nuclear in the GEA pathways is similar to the ranges found in other studies in the peer-reviewed scenario literature. In some GEA-Supply pathways, nuclear energy's contribution grows to 1850 GWe installed capacity, which is well above the IAEA's high projection of 1228 GWe. In the past, nuclear growth has been far below the IAEA's high projection – and, until 2000, even below the low projections. The nuclear contribution, however, is particularly uncertain across the pathways because of unresolved challenges surrounding its further deployment due to weapons proliferation risks and especially in the aftermath of Fukushima.

- Fossil CCS as an optional bridging or transitional technology in the medium term, unless there is high energy demand, in which case cumulative storage from CCS of up to 250 $GtCO_2$ by 2050 may be needed. In the pathways, it is a bridging technology that helps offset the gap between the need to vigorously decarbonize the energy system and the time needed to diffuse low-carbon options across the pathways. In the long term, CCS in conjunction with sustainable biomass is deployed in many pathways to achieve negative emissions and thus help achieve climate stabilization.

Vigorous decarbonization in the electricity sector leads to low-carbon shares in total generation of 75–100% by 2050, while coal power without CCS is phased out. Natural gas acts as a bridging or transitional technology in the short to medium term and provides 'virtual' storage for intermittent renewables.

The availability of energy resources by itself does not limit deployment on an aggregated global scale, but it may pose important constraints regionally, particularly in Asia, where energy demand is expected to grow rapidly.

Global energy systems investments need to increase to some US$1.7–2.2 trillion annually during the coming decades, with about US$300–550 billion of that being required for demand-side efficiency. This compares to about US$1 trillion supply-side investments and about $300 billion demand-side investments (energy components) per year currently. These investments correspond to about 2% of the world GDP in 2005, and would be about 2–3% by 2050, posing a major financing challenge. New policies would be needed to attract such capital flows to predominantly upfront investments with low long-term costs, but also low short-term rates of return.

4.2 Meeting Multiple Objectives

Universal access to electricity and cleaner cooking fuels requires the rapid shift from the use of traditional biomass to modern, cleaner, flexible energy carriers, and cleaner cooking appliances. This is achievable by 2030 provided that investments of US$36–41 billion per year are secured (half of which would be needed in Africa). About half of the investments would be required for a transition to modern fuels and stoves for cooking and the other half for electrifying rural populations.

Pollution control measures across all sectors need to be tightened beyond present and planned legislation so that the majority of the world population meets the WHO air-quality guideline (annual PM2.5 concentration $<10\ \mu g/m^3$ by 2030), while the remaining population stays well within the WHO Tier I-III levels (15–35 $\mu g/m^3$ by 2030). This would lead to total annual air pollution control costs of about US$200–350 billion by 2030. The ancillary benefits of climate mitigation policies enacted in the pathways reduce the overall pollution control costs by about 50–65%.

Limiting global temperature increase to less than 2°C over pre-industrial levels (with a probability of >50%) is achieved in the pathways through rapid reductions of global CO_2 emissions from the energy sector, peaking around 2020 and declining thereafter to 30–70% below 2000 emissions levels by 2050, ultimately reaching almost zero or even 'net' negative CO_2 emissions in the second half of the century.

Enhanced energy security across world regions is achieved in the pathways by limiting dependence on imported energy and by increasing the diversity and resilience of energy systems. A focus on energy efficiency improvement and renewable deployment across pathways increases the share of domestic (national or regional) supply by a factor of two and thus significantly decreases import dependency. At the same time, the share of oil in global energy trade is reduced from the present 75% to below 40% and no other fuel assumes a similarly dominant position in the future.

5 Policy Tools and Areas of Action[37]

The previous sections describe the need for transformative change in the energy system (Section TS-2.6) and the different combinations of supply side and end-use technologies that could enable this need to be met in a timely and adequate fashion (Section TS-4). As noted in Section TS-4, a number of such different combinations meet the normative goals of access, security, climate protection, and health. These combinations are very different in terms of the magnitude and

37 Section TS-5 is based on Chapter 22–25 and specific policy discussions in Chapters 8–10 and 11–15, and 17.

Box TS-2 | Flexibility of Supply

The pathways explore a wide range of future energy transformations that are consistent with the GEA sustainability goals. Some of them explore future developments in which selected supply-side options were either limited or excluded completely. These pathways focus on overall questions of the 'feasibility' of such limitations and their economic and resource implications. In sum, 60 pathways were explored and 41 were found to be compatible with the GEA sustainability goals. They constitute a wide portfolio of sensitivity analyses regarding the nature and direction of future energy transformations.

The main conclusion from the GEA pathways analysis is that energy efficiency improvements are the single most important option to increase the flexibility of supply and the structure of the regional and sectoral energy systems. With high rates of efficiency improvements in GEA-Efficiency, it was possible to achieve the GEA normative goals under any of the assumed portfolio restrictions. Only in the GEA-Efficiency pathways was it possible to do so in the absence of both nuclear energy and CCS.

GEA-Supply, with high energy demands, requires the rapid and simultaneous growth of many advanced technologies, resulting in reduced flexibility on the supply side. Some more critical options are needed in all GEA-Supply pathways, such as bioenergy, non-combustible renewables (i.e., hydropower, intermittent renewables, and geothermal), and CCS. Excluding, or limiting, these options renders the high demand pathways infeasible. Nevertheless, the high demand pathways explore feasible energy transformations with limitations of some options, such as nuclear energy, as shown in Figure TS-25.

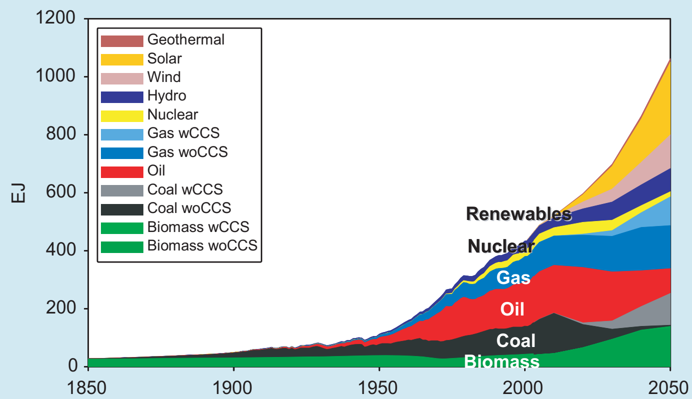


Figure TS-25 | Development of primary energy in the GEA-Supply pathway with a nuclear phase-out shortly after 2050. Source: Chapter 17 and the GEA online database.

The transportation sector configuration has profound implications for supply-side flexibility. In the case of rapid penetration of advanced transportation technologies (electricity or hydrogen), the GEA-Supply group of pathways was found to still be feasible if any one of BioCCS, carbon sink enhancement, nuclear energy, the full bioenergy supply, or large-scale renewable energy deployment are excluded as options in the future. In the case of restricted penetration of advanced transportation technologies, essentially the full set of supply-side options is needed to keep the GEA sustainability targets within reach (in GEA-Supply).

orientation of investments required. They would therefore require, at least in part, different policy packages and institutional arrangements for implementation.

The design and formulation of such policy packages needs to reflect the diversity and heterogeneity of national circumstances, the need to consider issues of sociopolitical feasibility and acceptability, and the need to adequately address implementation challenges, including institutional design.

This section describes the possible approaches, basic elements, and policy tools and instruments that may be utilized. Effective policy portfolios will require a combination of instruments, including regulatory and investment policies, as well as measures for strengthening capacity, stimulating innovation, and guiding behavior and lifestyle changes. Moreover, the energy goals cannot be pursued in isolation. Energy-focused policies must be coordinated and integrated with non-energy policies for socioeconomic development and environmental protection. These latter include, for example, policies that foster sustainable urban areas, preserve forested land and biodiversity, reduce poverty and inequality within and between countries, provide efficient and environmentally acceptable transportation, ensure vibrant rural areas, and improve human health.

The remainder of this section is organized as follows. Section TS-5.1 describes the main elements of, and areas for, policy intervention. We then consider two of the key challenges at the nexus of energy and development – those of universal access and of urbanization. Policies to address these challenges are discussed. Rapid improvement in energy efficiency, scaled up and accelerated development of renewables, and the modernization of fossil fuel systems (such as described in Section TS-3.3.2) form the key building blocks of all of the pathways meeting the sustainable goals. Policies to address these building blocks are discussed in Section TS-5.3. Section TS-5.4 examines the major areas of policy intervention – innovation, finance, and capacity building.

5.1 Framework for Policies and Policy Design[38]

If ***universal energy access*** is to be achieved by 2030, then energy policies must work in concert with economic development policies by harnessing the collective investment potential of markets, international organizations, central governments, regional governments, cooperatives, and local organizations. The global community must increase its support, including providing financial assistance for major clean-energy infrastructure, and leverage this where possible with private funds by creating a sound climate for sustainable energy-related investments. Bilateral cooperation and the role of Development Banks are key in supporting the necessary investments needed to achieve universal access.

Energy security can be enhanced by combined technically and strategically oriented policies, which various regions and countries will emphasize differently. The technical policies include steps that lead to timely energy network upgrades, greater interconnection and backup agreements between neighboring energy network operators, grid tariffs that induce short-term demand reductions in response to constrained market conditions, and long-term supply procurement strategies that foster local supplies and a diversity of external supplies. Strategically oriented policies would include international cooperation and agreements to reduce the risk of supply disruptions, such as coordination to protect international energy supply routes and to stockpile critical energy resources for release during acute market shortages.

Market power is a concern in much of the energy sector. Governments must recognize that policies to promote electricity competition must also prevent the short-term exercise of market power that results in unjustified excessive profits for some producers and speculators as well as price volatility for consumers. This will involve continued regulation and public involvement in energy system planning and long-term contracting to ensure operation of the system in a socially desirable manner.

The effective and transparent ***management of valuable resources*** is important in the energy sector. Oil and gas especially are valuable resource endowments that can provide great wealth if their exploitation is properly managed. Policies should maximize the collection of resource rents (via royalties, taxes, and, where applicable, national oil companies) for present and future generations, and should control the rate of exploitation to minimize inflationary harm to otherwise sustainable economic sectors. Depending on a country's current level of well-being, part of the resource rents should be streamed into sovereign wealth funds that are invested domestically to, among other goals, offset the negative impacts of resource exploitation at home, as well as abroad, in a balanced effort to maximize the benefits for future generations.

38 Section TS-5.1 is based on Chapter 22.

A multiplicity of policies is required to address the potential impacts of the energy system on ***human health and the environment***. A mix of regulations, information programs, and subsidies are needed, for example, to stimulate the rapid adoption of household energy-using devices that have virtually zero indoor emissions. Subsidies should be applied to equipment such as zero-emission stoves and efficient light bulbs to replace the indoor combustion of kerosene and other fuels for lighting and cooking.

Ambient air quality requires regulations on emissions from fuel combustion in buildings, industry, vehicles, power plants, and other sources. Some regulations may be highly prescriptive – specifying combustion technologies such as the use of catalytic converters, for instance, or restricting certain fuels – while others may focus on the absorptive capacity of a given air shed for a particular pollutant. The latter case could involve the establishment of air shed emission limits, perhaps using a cap-and-trade system. Similarly, regional air quality must be protected by technology and/or emissions regulations or by direct emissions pricing.

Extractive activities and the various uses of land and water – coal mines, oil and gas fields, hydropower dams, reservoirs, nuclear plants, storage sites for radioactive wastes and captured CO_2, wind farms, solar electricity farms – should all face a ***regulatory framework*** that assesses their benefits against a precautionary consideration of their impacts and risks, but that also ensures a streamlined regulatory process for more favorable projects.

Policies to foster ***energy from biomass*** should seek to minimize the trade-offs between biomass for food and biomass for fuel by encouraging the use of biomass residues and only the most sustainable and productive feedstocks and efficient conversion processes. Subsidies to corn-based ethanol could be replaced, for example, by emissions charges or by regulations requiring sustainability standards and minimum biofuel content in gasoline or diesel, motivating competitive markets to find the most efficient processes for producing biofuels. Many developing countries import all or most of their current liquid fuels at increasingly higher costs, and have, at the same time, large areas that are off-grid. One very successful example is that of *Jatropha* intercropped with food crops in an off-grid small town in Mali – which uses the jatropha oil to product electricity for a local grid.

GHG pricing policies will be key in shifting energy systems toward low-carbon emission technologies, fuels, and activities. While there is disagreement on which pricing method is best – carbon taxes or cap-and-trade – the two approaches can be designed so that their effects are quite similar. The price certainty of a carbon tax can be approximated with cap-and-trade by setting a price floor and a ceiling for permit prices. The revenues generated by a carbon tax can also be achieved by auctioning permits in cap-and-trade. Cap-and-trade will be difficult to apply at a global level, but the process could start with a subset of countries (as Europe and some countries and subregions of countries have done) and eventually link systems by various mechanisms. Or there could be parallel systems of cap-and-trade in some jurisdictions with carbon taxes in others. In the final analysis, environmental sustainability will need to be achieved at the lowest cost, and in an equitable manner.

In addition to GHG emissions pricing, other policies will be needed to develop, and then support, ***new technologies*** through the various stages from laboratory research to prototype demonstrations to wide-scale commercialization. These include R&D support, subsidies for large-scale technology demonstrations, and, for emerging favorites, market sales requirements or guarantees. Such policies will apply to initiatives such as CCS, new nuclear power technologies, renewable energy innovations, highly efficient energy-using devices, energy storage devices, grid management systems, and zero-emission vehicles and other transportation technologies.

It is important to complement GHG pricing with a portfolio of other regulatory and market mechanisms. This is because different instruments are most effective in different sectors, geographic/cultural regions, and for different options. For example, owing to the magnitude and diversity of market barriers prevailing in the building sector, different regulatory and market-based instruments and their packages are needed and tailored to overcome the specific barriers.

As a new technological pathway, CCS requires additional targeted policies to clarify pore space, property rights, storage site risk assessment, short- and long-term liabilities at storage sites, and measurement and crediting protocols to ensure that such projects are valued as emission reductions in GHG regulatory frameworks. Some CCS demonstrations should target low-cost CO_2 sources (existing or new coal-chemicals or coal-fuels plants) and enhanced oil recovery for CO_2 storage.

In cities, regulatory policies such as land use zoning, building codes, development permitting, and local emission standards must drive the shift toward low- and near-zero emission buildings, in some cases in concert with low- and near-zero emission decentralized energy supply. In addition to buildings, new urban developments should be required – with greater stringency in industrial countries initially – to be low- or near-zero emission (of local air pollutants and GHG emissions) through the local supply of renewable energy sources, where feasible, and through the import of energy from near-zero emission external sources. These requirements, which in part apply to rural areas as well, should also be gradually phased in to the retrofit of existing buildings and the redevelopment of existing urban areas.

Policy integration is especially important for unlocking energy-saving potentials due to the many barriers as well as multiple benefits. Strategic alliances and strong coordination among various policy fields will be able to capture a much larger share of technological potential by improving the economics of efficiency investments through the addition of further benefits to the cost-efficiency considerations, such as security, employment, social welfare, regional development, reduced congestion, and so on.

5.2 Policies for Meeting Energy-development Challenges

The importance of energy for achieving development goals is outlined above. Two challenges are of particular importance –providing universal access to modern forms of energy, and addressing urbanization and the provision of urban energy services.

5.2.1 Energy Access[39]

Access to affordable modern energy carriers and cleaner cooking improves well-being and enables people to alleviate poverty and expand their local economies. Even among people who have physical access to electricity and modern fuels, a lack of affordability and unreliable supplies limit their ability to use these resources. In addition to access to modern forms of energy, there must be access to end-use devices that provide the desired energy services. Those who can afford the improved energy carriers may still not be able to afford the upfront costs of connections or the conversion technology or equipment that makes that energy useful.

The lack of access to modern forms of energy is due to a number of factors. They include low income levels, unequal income distribution, inequitable distribution of modern forms of energy, a lack of financial resources to build the necessary infrastructure, weak institutional and legal frameworks, and a lack of political commitment to scaling-up access. Public policies should develop the strategies, and create the conditions, to overcome the mentioned barriers.

While the scale of the challenge is tremendous, access to energy for all, electricity for all, and modern fuels or stoves for all by 2030 is achievable. This will require global investments of US$36–41 billion annually – a small fraction of the total energy infrastructural investments required by 2030. It is expected that as households with public-sector support gain access to modern energy and end-use devices and start earning incomes, the standard of living and ability to pay for the energy services utilized would successively expand.

Access to Electricity

Between 1990 and 2008 almost two billion people gained access to electricity, more than the corresponding population increase of 1.4 billion people over that period (see also Figure TS-26). By 2030, the 1.4 billion people currently without access to electricity, plus the projected population increase to 2030 of 1.5 billion people, need to be connected to meet the GEA goal on universal electricity access. To achieve this, a multitrack approach is needed, combining grid extension with microgrids and household systems.

39 Section TS-5.2.1 is based on Chapters 2, 17, 19, and 23.

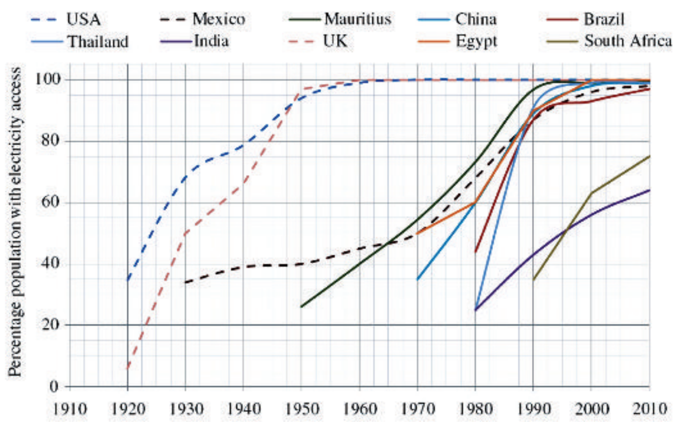


Figure TS-26 | Historical experience with household electrification in select countries. Source: Chapter 19.

Access to electricity can be arranged in several ways. In areas with high energy density, grid extension is currently the lowest cost per kWh delivered and also the preferred delivery form by most customers because of the capacity to deliver larger quantities of power for productive purposes. For many remote populations grid extension by 2030 will be highly unlikely and microgrids offer an alternative, based on local renewable energies or imported fossil fuels. An interesting approach to providing modern energy and development in remote villages is the multifunctional platform beginning to gain hold in West Africa (see Chapter 25). Household electrification is expanding rapidly in some countries, based on solar PVs that are financed by micro-credits and this has been done without increasing household expenses for energy (replacing candles and kerosene).

Experience shows that grid extension on commercial grounds is ineffective. Initial loads are small and provide insufficient income for the utilities. Privatizations of utilities have amplified this situation. The use of life-line rates or a free allocation of a small quantity of electricity per month per household has proven effective in starting a development process.

Grants should support equipment that uses energy more efficiently and more cleanly rather than subsidizing the energy used – except in the case of lifeline rates for the lowest-income customers, which can be achieved in part through cross-subsidies from other customers. Grants for high-voltage grid extensions and decentralized microgrids should involve competitive bidding to ensure the most cost-effective use of funds. Policies should support local participation in developing and managing energy systems, as this approach has been shown to have the best chance of providing a stable environment for new investment and reinvestment in increased energy access.

Cleaner cooking

About three billion people rely entirely, or to a large degree, on traditional biomass or coal for cooking and heating. This number has not changed appreciably over the last decades, particularly among households in rural areas. Indeed, more people rely on these fuels today than at any time in human history.

Access to cleaner cooking refers to liquid or gaseous fuels, especially biogas, LPG, ethanol, and others, or alternatively access to advanced biomass stoves with pollutants emissions similar to those of gas stoves. In many regions, current inefficient use of biomass fuels requires women and children to spend many hours per week collecting and carrying traditional biomass that is burnt in highly inefficient and polluting stoves. The resulting household air pollution leads to significant ill health (see Section TS-2.5).

Achieving universal access to modern energy is not likely to have negative implications for climate change. This is because transitioning to modern fuels (even in the case that these are fossil based) will displace large quantities of traditional biomass use. Current technologies that use traditional biomass are 4–5 times less efficient than cooking with modern fuels like LPG, and are associated with significant emissions of non-CO_2 Kyoto gases (e.g., CH_4, N_2O) and aerosols (e.g., black carbon, organic carbon) due to incomplete combustion.

Unlike the new biomass stoves, there is no feasible technology for burning coal cleanly at the household level. Attempts to provide 'clean coals' for household use attempted around the world over the last several decades had little success. Chimneys do not protect people sufficiently as they simply move the pollution from one place to another in the household environment. Country after country, therefore, has found that the only way to provide clean residential environments is to shift to other fuels. Only a few countries today, notably China, have significant household use of coal, which is a source of much ill-health, inefficient energy use, and high-climate impact per unit energy service delivered.

The observation that introducing cleaner cooking brings multiple benefits in terms of development (Section TS-2.2), situation of women, improved health from reduced exposure to household air pollution (Section TS-2.5), and reduced contributions to climate change (Section TS-2.4) should be very attractive for developing countries as well as for development cooperation organizations.

Policies for improving energy access in general

Providing universal and affordable access to electricity and cleaner cooking is possible if timely and adequate policies are put in place. Overall, and on the basis of successful experiences of increasing access to modern energy, no single approach can be recommended above others. What is clear, however, is that the current institutional arrangements and policies have met with mixed success, at best. Reforms are needed, on global and country levels, to strengthen the feasibility of energy projects for poor people, expand the range of players involved, open up the regulatory system, and allow for innovation.

Several examples demonstrate that the major features behind the success of programs include: political priority and government commitment; continued support and strengthening of programs through various administrations; effective mechanisms for targeting the available subsidies exclusively to poor families in need, thus ensuring highly efficient public expenditure; and integration of the energy-access program into governments' broader policies of social support for poverty alleviation.

Success depends on regional, national, and local circumstances. In some instances, a decentralized and participatory decision-making process and a holistic development approach is very important. This goes together with a strong community-mobilization process that focuses on organizational development, skills enhancement, capital formation, promotion of technology, environmental management, and empowerment of vulnerable communities.

Significant success has been achieved with small pilot projects to improve access in some rural areas and among poor communities in urban areas. But less thought has been focused on how to scale-up from these projects to market development and to meet the needs of the larger population.

A paradigm shift is needed in the approach to energy planning and policy implementation to facilitate access to modern forms of energy and cleaner cooking. Current supply-side approaches that simply take as their starting point the provision of electricity, petroleum, or gas, or of equipment of a particular type (solar technology, improved cookstoves, biogas, and other forms of bioenergy) are unable to reap the full potential of social and economic improvements that follow from improved energy access and cleaner cooking.

Several countries, including India, China, Argentina, Chile, Vietnam, Laos, and Brazil, have demonstrated that if effective political decisions are taken, the results are positive. This is not yet the situation in much of sub-Saharan Africa. Challenges and economic, sociocultural, and political barriers require more elaborate strategies and a higher global commitment to satisfy the GEA scenario objectives. Universal access in 20 years is not going to be available in Africa with micro actions and isolated measures unless they are integrated in long-term national programs with clear targets, dedicated and guaranteed funds, an adequate institutional framework, and robust strategies.

Policy recommendations in the form of general ideas or guidelines are provided below. Regional and national contexts should be considered in defining strategies, instruments, and measures.

- A better understanding and a clearer diagnosis of the structure and functioning of energy systems, along with the needs (energy services) to be supplied, are needed. These have often been absent in the discussion of proposals and the role of public policies. Good policies need good diagnoses. Support and funds for diagnosis and information should be part of the strategies.
- Subsidies are generally justified as a response to inequality and social expectations in energy provision. However, their net effect can be positive or negative depending on the intended goals of the subsidy, and the way a subsidy is implemented. An effective tariff and subsidy regime has to be transparent and minimize administrative costs to avoid gaming of the system and to maximize the benefits that accrue to the intended recipients. Subsidies to energy should be complemented with funds toward solving the first-cost capital financing problem, since upfront costs of equipment are, usually, the key barrier.
- Financing mechanisms are needed for every scale of energy intervention. Mobilizing affordable and genuine international, regional, national, and local funds is crucial.
- Energy-access policy is part of a wider development policy and should be aligned with other sector policies and objectives. If these policies are misaligned, they can reduce the effectiveness of any given policy. Policy misalignments can occur when different energy policies work at cross-purposes or when government priorities that could benefit from an effective energy policy are not aligned. In particular, there is a need to link rural and peri-urban energy supply more closely with rural development. This would shift the focus from minimal household supply to a more comprehensive approach to energy that includes productive activities and other welfare-enhancing uses of energy. Ideally, the linkages between energy and other policy priorities, such as health, education, and poverty alleviation, should be recognized explicitly and local solutions that address these needs should be encouraged and supported.
- Capacity development is needed, especially for the design and implementation of public policies oriented to poor people.

In the specific case of access to cleaner cooking, fuel subsidies alone will be neither sufficient nor cost-effective in terms of achieving ambitious energy-access objectives. Financial mechanisms, such as micro-credit, will need to complement subsidies to make critical end-use devices such as cleaner cookstoves affordable for poor people.

Leveraging funding and access to capital from public and private sources – for needed investments at the macro level and, at the micro level, for meeting costs for low-income households – is crucial in efforts to expand access to energy services for the poorest people. Figure TS-27 shows the estimated impacts of policy scenarios for cleaner cooking. It is only with the combined attention to fuel costs and equipment purchases that universal access is approached. Creative financing mechanisms and transparent cost and price structures will be critical to achieving the required scale-up and quick roll-out of solutions to improve access.

No single solution fits all in improving access to energy among rural and poor households. Programs need to be aware of local needs, resources, and existing institutional arrangements and capabilities. Diverse sources

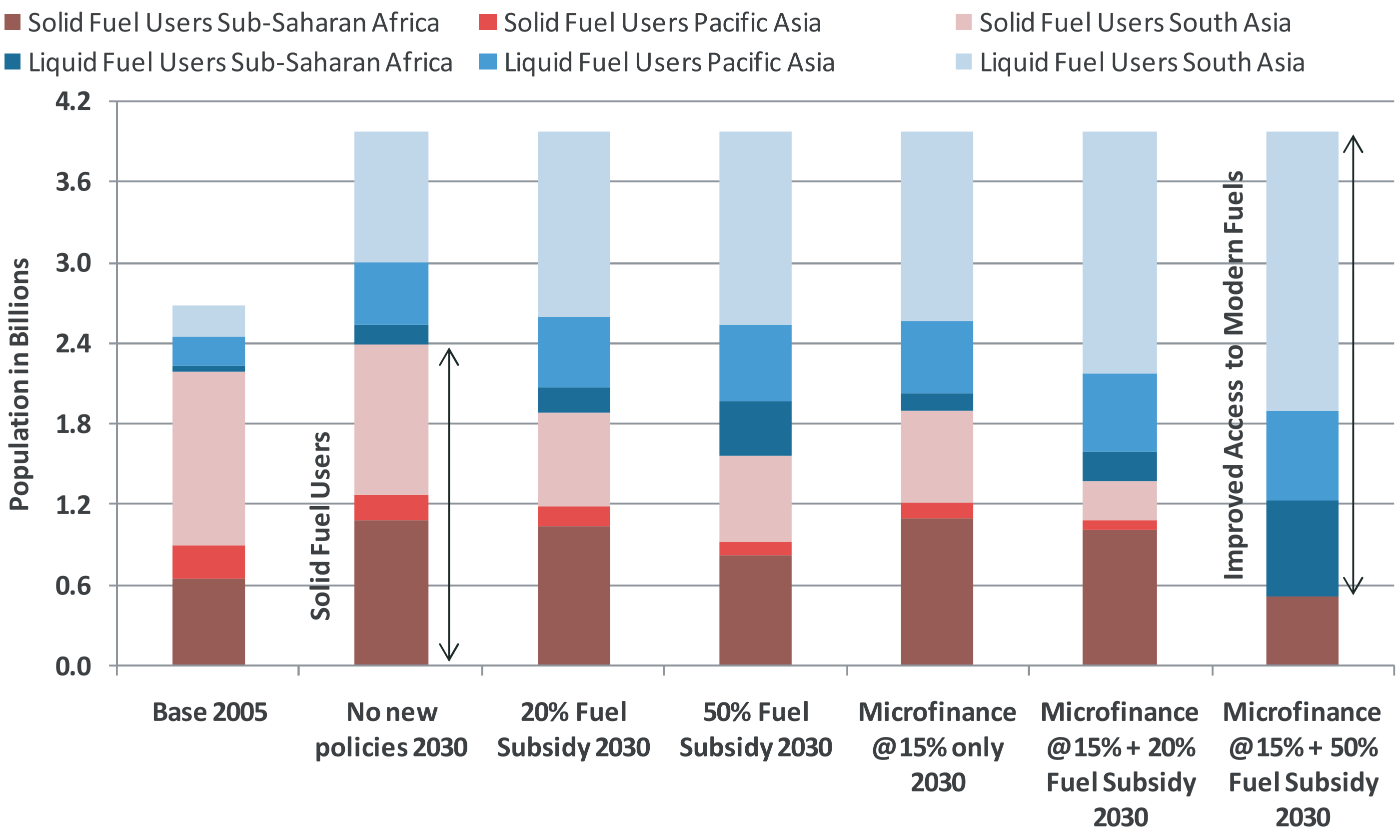


Figure TS-27 | Impact of alternative policy scenarios on access to cleaner cooking fuels in three developing regions. Subsidies are relative to consumer price levels and are additional to existing subsidies. Source: Chapter 17.

of energy supply (fossil and renewable), a wide portfolio of technologies, and a variety of institutional and innovative business models adapted to local circumstances are required to meet the challenge. An enabling environment shaped by sustained government commitment and enhanced capacity building at all levels is essential to ensure that access targets are met. Complementary development programs and enhancement of market infrastructure are needed to ensure sustained economic growth as well as steady employment and income generation for poor people to provide them with a means to pay for improved energy carriers.

As discussed in Chapter 12, establishing synthetic liquid transportation fuels in the market via gasification offers an innovative approach to expanding production of, and making more affordable access to, LPG, an inherent co-product of synthetic liquid transportation fuel manufacture. Such systems that co-produce electricity with CCS involving coal or the co-processing of coal and a modest amount of biomass (which could be deployed in this decade) would make available LPG with a significantly lower carbon footprint than LPG derived from petroleum sources, and with attractive system economics in a world with high oil prices.

Moreover, at GHG emissions prices that might be typical in the post-2030 period, small-scale systems making liquid transportation fuels from biomass with CCS would be able to provide substantial quantities of byproduct LPG for cooking at competitive costs in biomass-rich but regions lacking fossil fuels. Chapter 12 sketches out a plausible business model for making this domestically produced LPG affordable without subsidy, even for the very poorest households in such regions. Near-term actions to facilitate exploitation of this future opportunity include assessments of CO_2 storage capacity in such regions, building the human and physical infrastructure capacities needed to support these new industrial activities, establishing carbon trading systems that would facilitate realization of the attractive economics for these bioenergy with CCS systems, and testing alternative business models for providing the LPG to poor households without subsidy.

5.2.2 Urbanization[40]

Currently, about half the world population lives in urban areas, which also account for an overly large share of global economic output and energy use (an estimated 60–80% of the global total). Projections invariably suggest that almost all future population growth of some three billion people by 2050 would be absorbed by urban areas, which would also account for a majority of economic and energy demand growth. By 2050 the global urban population is expected to approach 6.4 billion people – about the size of the entire global population in 2005. In contrast, the global rural population would plateau around 2020 at 3.5 billion people and decline thereafter.

40 Section TS-5.2.2 is based on Chapter 18.

Most urban growth would continue to occur in small- to medium-size urban centers (between 100,000 and one million inhabitants) in the developing world, which poses serious policy challenges. In these smaller-scale cities, data and information to guide policy are largely absent, local resources to tackle development challenges are limited, and governance and institutional capacities are weak. Housing, infrastructure, energy and transport services, and a better urban environment (especially urban air quality) are the key sustainability challenges for urban poverty alleviation.

Several hundred million urban dwellers in low- and middle-income nations lack access to electricity and are unable to afford cleaner, safer fuels, such as gas or LPG. In addition to poverty and poor urban energy infrastructures, poor people face political or institutional obstacles to obtaining cleaner energy carriers.

Given capital constraints, daring new architectural and engineering designs of 'eco' or 'zero-carbon' cities can serve as inspirational goals and as field experiments, but they are unlikely to play any significant role in integrating some three billion additional urban dwellers by 2050 into the physical, economic, and social fabric of cities. (Building 'zero-carbon' cities for three billion new urban citizens along the Masdar model in Abu Dhabi would require some US$1000 trillion, or some 20 years of current world GDP.)

Cities in OECD countries generally have lower per capita final energy use than their respective national averages. Conversely, cities in developing and emerging economies generally have substantially higher per capita energy use than the national average, primarily due to substantially higher income levels than those in rural areas.

Urban systems are, however, by definition inherently open systems: they are characterized by vast imports of resources and commodities and by vast exports of goods and services to their respective hinterlands and the rest of the world. 'Embodied' energy (and GHG emissions) is, as a rule, several fold larger than the direct energy uses in urban settings, at least for the handful of megacities for which data are available.

The overall design of cities and their components affect the energy use to a large degree. For buildings, energy use for thermal purposes can cost-effectively be reduced by 90% or more, as compared with current standard practice (see Figure TS-15, Section TS-3.2.3). Not incentivizing the adoption of available building-efficiency technologies and practices will lock cities into a much higher energy-use level than necessary. Figure TS-16 illustrates this for energy use in buildings. Next to buildings, urban density, form, and usage mix are also important determinants of urban energy use and efficiency, especially in transportation (see Figure TS-13). Avoiding spatial lock-in into urban sprawl and ensuing automobile dependence should, therefore, be another important urban policy objective.

Significant potential co-benefits between urban energy and environmental policies do exist. However, they require more holistic policy approaches that integrate urban land use, transport, building, and energy policies with the more-traditional air pollution policy frameworks.

Urban energy and sustainability policies could focus on where local decision making and funding also provides the largest leverage effects:

- urban form and density (which are important macro-determinants of urban structures, activity patterns, and hence energy use, particularly for urban transport);
- the quality of the built environment (energy-efficient buildings in particular);
- urban transport policy (in particular the promotion of energy-efficient and 'eco-friendly' public transport and non-motorized mobility options); and
- improvements in urban energy systems through cogeneration or waste-heat recycling schemes, where feasible.

Illustrative model simulations for a 'synthetic' city suggest improvement potentials of at least a factor of two each by buildings that are more energy-efficient and by a more compact urban form (at least medium density and mixed-use layouts), with energy system optimization through distributed generation and resulting cogeneration of electricity, heat, and air conditioning adding another 10–15% improvement in urban energy use (see Figure TS-28).

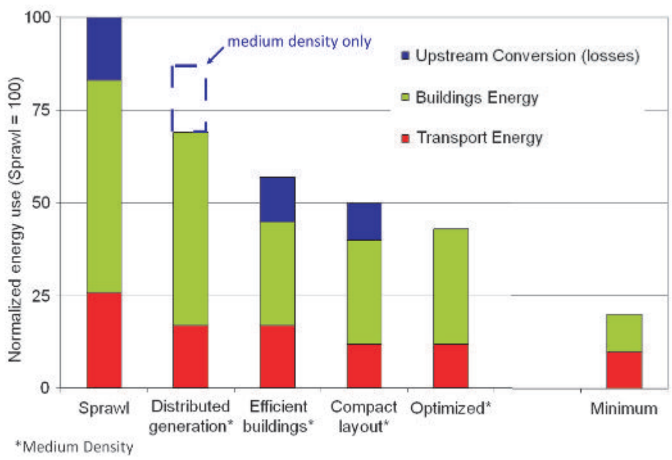


Figure TS-28 | Policy integration at the urban scale. Simulated energy use for an urban settlement of 20,000 inhabitants using the SimCity Model combining spatially explicit models of urban form, density, and energy infrastructures, with energy systems optimization. Individual policy options are first simulated individually and then combined in a total systems optimization. Baseline (index = 100) sprawl city corresponds to a secondary energy use of 144 GJ/capita; energy use is shown by major category: transport, buildings, and upstream energy conversion losses (which can be eliminated by local cogeneration of electricity and heat or by on-site energy systems). The potential for efficiency improvement of narrow energy sector-only policies (local renewables, cogeneration) at the urban scale is smaller than policies aiming at minimizing buildings energy use or at higher urban density and mixed uses, which minimize transport energy use. The largest improvement potentials can be realized by a combination of energy, building efficiency, and urban form and density policies. Source: Chapter 18.

There are important urban size and density thresholds that are useful guides for urban planning and policymaking. The literature review identified a robust density threshold of 50–150 inhabitants per gross hectare (5000–15,000 people per square kilometer) below which urban energy use, particularly for transport, increases substantially. Note that there is little empirical evidence to suggest substantial further energy efficiency gains at much higher densities. Energy-wise, there are pronounced diseconomies of scale of low urban densities (leading to lower efficiency and higher energy use), but no significant economy-of-scale effects beyond intermediary density levels.

5.3 Policies for Key Energy System Building Blocks

The GEA pathways describe the various combinations of transformations in energy systems required to meet the GEA's various goals and objectives simultaneously (see Section TS-4.) While they differ in terms of their relative proportions and the magnitudes of the various changes they involve, all of them include a dramatic increase in energy end-use efficiency, larger and more rapid deployment of renewables, decarbonization and modernization of fossil fuel systems, and the judicious use of nuclear energy. Policies to address the changes required in each of the building blocks are described below.

5.3.1 Energy Efficiency

Progress in accelerating the rate of energy efficiency improvement worldwide is critical to an energy system for sustainability. Quickly improving energy efficiency requires more focused and aggressive policies that: support rapid innovation; significantly tighten efficiency regulations in energy supply and demand; increase energy prices; create a culture of conservation among consumers and firms; change land use zoning to increase urban density; and integrate mixed land uses so that transportation needs decline and low-energy transportation modes flourish. In some cases, these policies will involve subsidies for new technologies, but these will not be effective unless they are combined with pricing of GHG emissions via taxes and/or cap-and-trade plus well-designed efficiency regulations.

Regulations, especially standards, are essential elements of energy policy portfolios of the transition. Building codes, appliance standards, fuel economy standards, and industrial energy management standards have proven to be very environmentally sound in improving efficiency and should be adopted globally. The combination of regulations, incentives (e.g., fiscal incentives), and measures to attract attention, (e.g., information, awareness, or public leadership programs) has the highest potential to increase energy efficiency. Policies encouraging the use of multi-generation and renewable energy in each end-use sector are important further components of energy policy portfolios.

The GEA analysis provides considerable evidence for the ability of such policy packages to deliver major change. However, the results from three decades of experience with energy efficiency policies in industrial countries also show other effects. For example, the adoption of energy efficiency devices has both a direct rebound effect (more-efficient fridges, with lower operating costs, encourage the adoption of larger fridges) and an indirect rebound effect (sometimes called a productivity rebound) that relates to the apparent causal link between energy efficiency breakthroughs and the development of new devices and new energy services (fridge efficiency improvements foster the development of new refrigeration devices, such as beer and wine coolers, water coolers, desk-top fridges and freezers, portable fridges, etc.). Evidence also shows that when estimating costs it is important to take into account all transaction costs and differences in technology risks and technology quality. Ideally, beyond transaction costs, all other indirect costs and benefits, including monetizable co-benefits, need to be integrated into cost-effectiveness assessments related to policy choices, as these can both be substantial and fundamentally alter final cost-effectiveness outcomes and thus instrument choices.

These cost factors and rebound effects mean that subsidies to encourage acquisition of energy-efficient devices are unlikely, on their own, to cause the dramatic energy efficiency gains called for in the GEA analysis. For these gains to be realized, a portfolio of stronger, carefully targeted policies is needed. Examples include: strong efficiency regulations that are updated regularly (say, every five years); incentives to reward manufacturers to push the technology design envelope toward advanced efficiency; increases in energy prices (because of direct or indirect emissions pricing); electricity tariffs that give high rewards to efficiency investments and behavior; land use planning and zoning that fosters efficient urban development and renewal; and public (and private) investments in efficient infrastructure such as mass transit, cycling paths, and CHP systems.

In the buildings sector, to be able to reduce final thermal energy use by over 40%, the goal in the GEA efficiency pathway, all jurisdictions need to introduce and strictly enforce building codes that mandate very low specific energy-use levels, equal or similar to passive-house levels. They also need to extend these requirements to renovations, and building retrofits will need to significantly accelerate the present rates. The remaining building energy needs can be met from locally generated renewable energy sources, where feasible, and economically and environmentally optimal – typically, low-density residential neighborhoods. Achieving the needed transformation in the buildings sector entails massive capacity-building efforts to retrain all the trades involved in the design and construction process, as well as the building owners, operators, and users.

Influencing energy use in the transport sector involves affecting transport needs, infrastructure, and modes, as well as vehicle energy efficiency.

Table TS-8 | Regulatory policies potential contribution to transport and GEA multiple goals.

GEA Overall Systemic Goals	Sustainable Transportation Systems Multiple Goals and Benefits	Aim: Establishing Clear Regulatory Framework								
		Vehicle Standards	Fuel Standards and Mandates	Reduce Travel Speed Limit in Urban Areas	Reduce Travel Speed/Volume of Freight Transport in Urban Areas	Reduce Speed of Airplanes	Reduce Speed of Commercial Maritime Transport	Improved Management Intelligent Transport System	Mandatory Vehicle Inspections	Traffic Safety Regulation
Economic Growth, Equity & Urbanization	Functionality, Efficiency	essential	essential	essential	uncertain	uncertain	uncertain	essential	essential	essential
	Accessibility	uncertain	uncertain	complementary	complementary	uncertain	uncertain	essential	essential	essential
	Affordability	uncertain	uncertain	complementary	complementary	uncertain	uncertain	uncertain	complementary	essential
	Acceptability	complementary	complementary	uncertain	essential	uncertain	uncertain	uncertain	uncertain	essential
Health & Environmental Protection	Traffic Safety	essential	uncertain	essential	essential	uncertain	uncertain	essential	essential	essential
	Acces of less fit	complementary	uncertain	essential	uncertain	uncertain	uncertain	uncertain	complementary	essential
	Human Motion	uncertain	uncertain	complementary	uncertain	uncertain	uncertain	uncertain	complementary	essential
	Reduce Air Pollution	essential	essential	essential	uncertain	essential	essential	essential	essential	essential
	Reduce Noise	essential	uncertain	essential	uncertain	essential	complementary	essential	essential	essential
	Reduce Congestion	uncertain	complementary	uncertain	uncertain	uncertain	uncertain	essential	essential	essential
Climate	Reduce GHG	essential	essential	uncertain	uncertain	essential	essential	essential	complementary	complementary
Energy Security	Diversification Energy sources	complementary	essential	complementary	complementary	uncertain	complementary	complementary	uncertain	complementary
	Independence from Fossil fuels	complementary	essential	uncertain	uncertain	uncertain	uncertain	uncertain	complementary	uncertain

Legend: Role of Policies or potential contribution to attainement of goal according to literature
- essential
- uncertain
- complementary

Source: Chapter 9.

Policies for urbanization will have a large impact on transport needs, infrastructure, and the viability of different transport modes on the local scale. Both the decision to travel and the choice of how to travel affect fuel consumption. With a focus on urban transport, a transition to sustainable transport can follow the framework known as 'avoid–shift–improve'. This considers three major principles under which diverse policy instruments are grouped, with interventions assuming different emphasis in industrial and developing countries. They need to focus on improving technological options, not only with respect to climate mitigation, but also with respect to local environmental conditions and social concerns. The other two components – modal shift and avoiding travel – influence the level of activity and structural components that link transport to carbon emissions.

This approach to urban transport would include policies and measures for developing alternatives to car use, reducing the need for travel, improving existing infrastructure use, and setting a clear regulatory framework (alternative fuels and efficient vehicles). In addition, policies targeting freight and long-distance travel (shipping, trucks, rail, and air) are needed. To illustrate the complexity of transportation policy, Table TS-8 shows some regulatory options and their potential impact.

For energy efficiency in industry it is useful to separate what can be achieved when a new plant is being built and what can be done in existing industry. Most of the new industrial growth will occur in developing countries. Under the business-as-usual scenario, a mix of technologies would be installed with varying levels of specific energy use. In addition to regulations and economic incentives, regional centers for industrial energy efficiency could be set up that help disseminate information related to specific energy use and best-available technologies for different processes. There could also be web-based facilities established where any industry that is being proposed can compare its design energy performance with the best available benchmark technologies. An incentive scheme should provide funding for energy performance analysis at the design stage. Governments could help provide financing of the incremental costs of energy-efficient technologies as low-interest loans through commercial banks.

In existing industries, realizing the potential for energy efficiency can be achieved through a combination of measures, including incentives for demand-side management. Regulatory commissions can provide regulations and standards for energy-using equipment and process improvements. Information gaps need to be reduced, especially the sharing and documentation of best practices. Capacity needs to be developed for systems assessment rather than individual components assessment.

In developing countries or jurisdictions with suppressed energy service levels, improved efficiency may lead to an increase in energy service levels rather than a decrease in energy demand. However, this should normally be the goal of efficiency policies in such jurisdictions. In industrial countries, such rebound effects need to be minimized through appropriate energy pricing and taxes that complement efficiency policies.

The transition into a very low energy future requires a shift in the focus of energy-sector investment from the supply-side to end-use capital stocks, as well as the cultivation of new innovative business models (such as performance contracting and ESCOs).

5.3.2 Renewable Energies

Increased use of renewable energy technologies can address a broad range of aims, including energy security, equity issues, and emission reductions, thereby linking beneficially with other policies related to poverty eradication, water provision, transport, agriculture, infrastructure development, industrial development, job creation, and development cooperation. For this to occur, policy measures must overcome the barriers within the current energy system that prevent wider uptake of renewables (see Table TS-9 for an overview). A key issue is how to accelerate the deployment of renewable energies so that their deep penetration into the energy system can be achieved quickly.

Given the enormous size and momentum of the existing global energy system, new technologies such as renewables face significant market barriers. To address these, policy measures should support a level playing field where renewables can compete fairly with other forms of energy; they should also support the development of renewables so that they can overcome additional hurdles to their deployment.

While competitive markets operate effectively for many goods and services, a number of failures need to be addressed in relation to energy. A central concern is the way that markets currently favor conventional forms of energy by not fully incorporating the externalities they are responsible for and by continuing to subsidize them – making it harder to incorporate new technologies, new entrants, and new services in the energy system. This both distorts the market and creates barriers for renewables.

Similarly, the potential benefits of renewables are also often not accounted for when evaluating the return on investment, such as increased energy security, access to energy, reduced economic impact volatility, climate change mitigation, and new manufacturing and employment opportunities. These issues are exacerbated by ongoing subsidies for fossil fuels that globally amount to hundreds of billions of US dollars per year, much more than the support renewables are receiving. It is through public policies that the values to society can be reflected in market conditions such that it will be advantageous for investors to seek out energy options that support and contribute to a sustainable future for all.

Using a portfolio of policies helps to increase successful innovation and commercialization, providing they complement each other. To expand renewable technologies, it is important to note that:

- market growth results from the use of combinations of policies;
- long-term, predictable policies are important;
- multi-level involvement and support from national to local players is important; and
- each policy mechanism evolves as experience of its use increases.

Policy approaches for renewable energy intend to address the innovation chain both technologically and socially, to pull technologies to the marketplace and commercialize them, and to improve the financial attractiveness and investment opportunities of renewables.

Of the market-pull policies, two are most common: a policy that sets a price to be paid for renewable energy and ensures connection to the grid and off-take (often known as a feed-in tariff or FIT), and a policy that sets an obligation to buy, but not necessarily an obligation on price (often known as a quota or obligation mechanism or a renewable portfolio standard). So far, FITs have been used for electricity only, although some countries, for example the United Kingdom, are now considering how to provide them for heat. Quotas have so far been used for electricity, heat, and transport. Biofuel quotas are now common globally.

A FIT that provides a strong, stable price for renewable electricity has proven successful in some countries for accelerating investment in renewables. Some jurisdictions prefer renewable portfolio standards that set a minimum, but growing, quota for renewable or low-emission electricity generation technologies. Although there is considerable debate between advocates of these two approaches, the detailed way in which they are implemented is the key to success. In addition, the GEA analysis for meeting climate stabilization goals shows that, currently, in industrial countries virtually no new investments in electricity generation should result in the new emission of GHGs. Unfortunately, such investments are still possible in countries with FITs, green certificate markets, or other renewable energy support schemes, and indeed this has been the case in most jurisdictions with such policies, although at a lower rate.

Table TS-9 | Summary of renewable energy policies.

Policy	Definition	End-use Sector		
		Electricity	Heat/ Cooling	Transport
Regulatory Policies				
Targets	A voluntary or mandated amount of renewable energy (RE), usually a percentage of total energy supply	X	X	X
Access-related Policies				
Net metering	Allows a two-way flow of electricity between generator and distribution company and also payment for the electricity supplied to the grid	X		
Priority access to network	Allows RE supplies unhindered access to network for remuneration	X	X	
Priority dispatch	Ensures RE is integrated into the energy system before supplies from other sources	X	X	
Quota-driven Policies				
Obligation, mandates, Renewable Portfolio Standards	Set a minimum percentage of energy to be provided by RE sources	X	X	X
Tendering/bidding	Public authorities organize tenders for a given quota of RE supplies and ensure payment	X		
Tradable certificates	A tool for trading and meeting RE obligations	X	X	
Price-driven Policies				
Feed-in tariff (FIT)	Guarantees RE supplies with priority access, dispatch, and a fixed price per unit payment (sometimes declining) delivered for a fixed number of years	X	X	X
Premium payment	Guarantees RE supplies an additional payment on top of their energy market price or end-use value	X	X	
Quality-driven Policies				
Green energy purchasing		X	X	
Green labeling	Usually government-sponsored labeling that guarantees that energy products meet certain criteria to facilitate voluntary green energy purchasing	X	X	X
Fiscal Policies				
Accelerated depreciation	Allows for reduction in tax burden	X	X	X
Investment grants, subsidies, and rebates	One-time direct payments usually from government but also from other actors, such as utilities	X	X	X
Renewable energy conversion payments	Direct payment by government per unit of energy extracted from RE sources	X	X	
Investment tax credit	Provides investor/owner with an annual tax credit related to investment amount	X	X	X
Other Public Policies				
Research and development	Funds for early innovation	X	X	X
Public procurement	Public entities preferentially purchasing RE or RE equipment	X	X	X
Information dissemination and capacity building	Communications campaigns, training, and certification	X	X	X

Source: Chapter 11

The obvious next step is to require that all new investments for electricity generation are in near-zero emissions technologies, and some jurisdictions have done this. Since 2006, for example, British Columbia in Canada has a 100% clean electricity standard for all new investments.

5.3.3 Modernized Fossil Fuels

Low-, zero-, or negative-emission fossil fuel use will require a transition to systems that co-utilize fossil fuels with renewable energy and with CCS. Co-processing of biomass with coal or natural gas for the co-production of power, fuels, and chemicals with CCS, is especially promising. New policies are needed that encourage environmentally acceptable deployment of such systems. Some of the following leading policies have already been enacted on an experimental basis, but these efforts would need to be intensified significantly over the next decades to realize a dramatic shift. Governments or regulators could, among others:

- implement GHG emissions pricing via carbon taxes and/or cap-and-trade systems;

- reduce all subsidies to fossil fuels without CCS. This includes fuel price subsidies that promote increased energy use; subsidies to private vehicle use (e.g., untolled roads), and a host of subsidies to industrial, commercial, institutional, and other combustion uses of fossil fuels;

- provide demonstration and commercialization subsidies;
- offer to pay above-market rates for electricity, heat, or low-net GHG-emitting fuels provided via projects that co-process sustainable biomass and fossil fuel feedstocks in systems with CCS. This would be similar to the FIT for renewables;
- ban construction of new coal-fired electricity plants that lack CCS or are not CCS ready;
- require land use planning that facilitates socially and environmentally acceptable siting of underground carbon storage and CO_2 pipelines. There is also a need for land use planning to safeguard against potential impacts of carbon storage on other uses of the subterranean, such as geothermal energy, or at least consider a balance between the possible uses;
- legally clarify geological rights to underground pore spaces for CO_2 storage; and
- establish short- and long-term liabilities and risk management and monitoring responsibilities at CO_2 storage sites and on CO_2 pipeline right-of-ways.

5.3.4 Nuclear Energy

People's views on the value and risks of nuclear power differ greatly and are often polarized. Some people see nuclear power as a risky technology. These perceived threats from nuclear power include catastrophic accidents at nuclear plants (either through operational failures or terrorist attacks), the inability to safely transport and permanently store radioactive wastes, and the exploitation of civilian nuclear expertise for the proliferation of nuclear weapons.

Depending on the severity of these concerns about nuclear power, its regulatory burden (for design, permitting, operation, and decommissioning) can be such that nuclear power is a high-cost option for electricity generation. However, where public policy (local, national, international) is able to allay these concerns, then nuclear power can be a competitive energy option. However, everything hinges on risk preferences among the public and decision makers, particularly with respect to trading off the extreme event risks of nuclear power with the ongoing impacts and risks of its alternatives. The following policies therefore focus on how to ensure a safe use of nuclear power that is both real and perceived:

- At the international level, governments and the nuclear industry need to continue to improve their mechanisms for monitoring and controlling the use of nuclear power and the reprocessing of nuclear fuel to prevent acquisition of expertise and materials for nuclear weapons production.
- Governments need to collaborate in the establishment of permanent storage sites for radioactive materials.
- By facilitating collaborative investments, governments can help the nuclear industry settle on two or three dominant designs that have the best chance of achieving regulatory approval and thus reducing regulatory costs, which have been very high in jurisdictions like the United States.

5.4 Elements of Policy Packages

The preceding sections describe a variety of policy instruments, tools, and approaches for different objectives, whether energy access or decarbonization through the use of renewables. Across the various domains of intervention, there are some common requirements for transformative change. For example, whether in the context of CCS or renewable energy technologies, accelerating the process of research, development, demonstration, and deployment is a common requirement. Similarly, it is necessary to enhance and reorient investment. Capacity building is essential to ensure that countries, regions, and policymakers are able to design and implement policies. It is possible that fundamental rethinking of lifestyles and consumption patterns may be required for sustainability. This may require new knowledge (such as green accounting practices) as well as a range of tools to influence public thinking, opinion, and behavior.

5.4.1 Innovation[41]

Innovation and technological change are integral to the energy system transformations described in the GEA pathways. Energy technology innovations range from incremental improvements to radical breakthroughs and from technologies and infrastructure to social institutions and individual behaviors. The innovation process involves many stages – from research through incubation, demonstration, (niche) market creation, and ultimate widespread diffusion. Feedback between these stages influences progress and likely success, yet innovation outcomes are unavoidably uncertain. Innovations do not happen in isolation; inter-dependence and complexity are the rule under an increasingly globalized innovation system.

A first, even if incomplete, assessment of the entire global investments into energy technologies – both supply- and demand-side technologies – across different innovation stages suggests RD&D investments of some US$50 billion, market formation investments (which rely on directed public policy support) of some US$150 billion, and an estimated range

41 **Grubler, A. and K. Riahi, 2010:** Do governments have the right mix in their energy R&D portfolios? *Carbon Management*, **1**(1):79–87.

of US$1–5 trillion investments in mature energy supply and end-use technologies (technology diffusion) are required. Demand-side investments are of critical importance, particularly as the lifetimes of end-use technologies can often be considerably shorter than those on the supply side. Demand-side investments might thus play an important role in achieving pervasive and rapid improvements in the energy system.

Major developing economies have become significant players in global energy technology RD&D, with public- and private-sector investments approaching some US$20 billion – in other words, almost half of global innovation investments – and are significantly above OECD public-sector energy RD&D investments (US$13 billion).

Policies now need to move toward a more integrated approach, simultaneously stimulating the development and adoption of efficient and cleaner energy technologies and measures. R&D initiatives without simultaneous incentives for consumers to adopt the outcomes of innovation efforts risk not only being ineffective, but also precluding the market feedbacks and learning that are critical for continued improvements in technologies.

Few systematic data are available for private-sector innovation inputs (including investments). Although some of the data constraints reflect legitimate concerns to protect intellectual property, most do not. Standardized mechanisms to collect, compile, and make data on energy technology innovation publicly available are urgently needed. The benefits of coupling these information needs to public policy support have been clearly demonstrated.

The energy technology innovation system is founded on knowledge generation and flows. Increasingly these are global, but need to be adapted, modified, and applied to local conditions. Long-term, consistent, and credible institutions underpin investments in knowledge generation, particularly from the private sector. Yet consistency does not preclude learning. Knowledge institutions have to be responsive to experience and adaptive to changing conditions; see, for example the discussion on open and distributed innovation, university-industry linkages, and knowledge networks (in the North, the South, and North–South) discussed in Chapter 25.7. Although knowledge flows through international cooperation and experience, sharing at present cannot be analyzed in detail; the scale of the innovation challenge emphasizes their importance alongside efforts to develop capacity to absorb and adapt knowledge to local needs and conditions.

Clear, stable, and consistent expectations about the direction and shape of the innovation system are necessary for innovators to commit time, money, and effort with only the uncertain promise of distant returns. To date, policy support for the innovation system has been characterized by volatility, changes in emphasis, and a lack of clarity. An example is the development of solar thermal electric (STE) technology in the United States (see Figure TS-29). After successful development during one decade, sudden policy changes in 1992 terminated interest in STE in the country. Now US interest has revived, with some projects underway in California (although none completed yet) with all the knowledge and technology imported from Europe (Spain), as associated knowledge entirely depreciated in the United States after the 1992 sudden policy changes.

Policies have to support a wide range of technologies. However seductive they may seem, silver bullets do not exist without the benefit of hindsight. Innovation policies should use a portfolio approach under a risk hedging and 'insurance policy' decision-making paradigm. The portfolio approach is also emphasized in Chapter 25 as part of a capacity development approach, especially in developing countries. The whole energy system should be represented, not just particular groups or types of technology. The entire suite of innovation processes should be included, not just particular stages or individual mechanisms. Less capital-intensive, smaller-scale (that is, granular) technologies or projects are a lower drain on scarce resources, and failures have less-serious consequences.

Public technology policy should not be beholden to incumbent interests that favor support for particular technologies that either perpetuate the lock-in of currently dominant technologies or transfer all high innovation risks of novel concepts to the public sector.

Portfolios need to recognize that innovation is inherently risky. Failures vastly outnumber successes. Experimentation, often for prolonged periods (decades rather than years), is critical to generate the applied knowledge necessary to support the scaling-up of innovations into the mass market.

Public sector energy R&D as a function of total public sector financed R&D has declined since the early 1980s, with a small reversal in the trend over the last few years (see Figure TS-30). Spending on technology groups has been relatively constant over time. Nuclear energy has received the largest part of the funding.

Technology needs from the pathway analysis shows a very different picture (see Figure TS-31). Energy efficiency dominates this analysis which also shows a doubling or more for renewable energies, and a significant lower emphasis on nuclear energy. This historical energy R&D portfolio bias needs to be addressed urgently to stimulate the innovations needed for realization of the GEA transition pathways.

5.4.2 Finance[42]

Some of the policies for energy sustainability described above simply involve an improvement of existing policies, such as better management of the electricity sector or more responsible use of fossil fuel resource rents. But the dominant message of the GEA is that the global energy system must be rapidly modified and expanded to provide energy access to those who have none, and must quickly transform to an energy system more supportive of sustainable development. This transition will require considerable investments over the coming decades. Table TS-10 indicates the

42 Section TS-5.4.1 is based on Chapter 24.

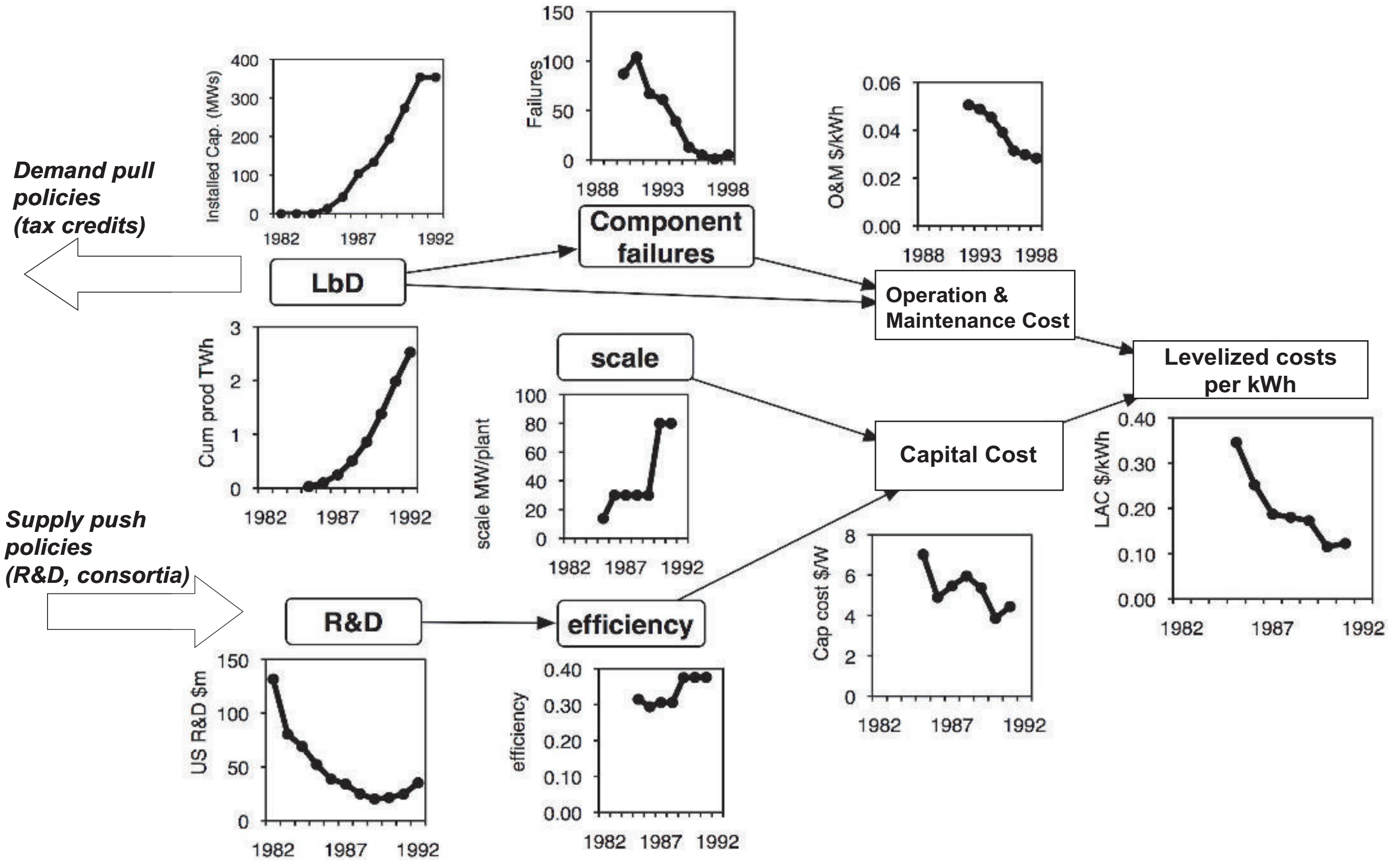


Figure TS-29 | History of the US solar thermal electricity program, 1982–1992. This shows a 'virtuous' technology development cycle as a result of well-coordinated policies. Demand pull policies enabled expanding market applications, which in turn enabled a scaling-up of the technology – reducing capital costs through economies of scale effects, learning by doing (LbD), and reductions in component failures (lowering operating costs). Supply push policies, such as R&D (even at declining budgets), led to technology improvements (efficiency) that further lowered capital costs. In the aggregate, levelized total costs per kWh declined by a factor of three over 10 years. This positive innovation development cycle came to an abrupt halt after 1992 with the sudden discontinuation of public policy support. Source: Chapter 24.

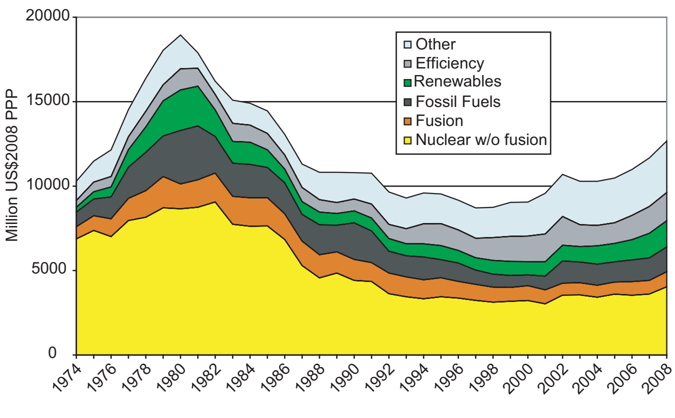


Figure TS-30 | Public sector energy RD&D in IEA Member countries by major technology group. Source: Chapter 24.[43]

necessary investments to achieve this, as estimated by the GEA, and links these to the types of policies needed. It also assesses these policies in terms of their necessity and their ability to complement or substitute for each other. Although considerable, these investment levels can be compared to estimates of global fossil fuel subsidy levels on the order of US$500 billion a year, of which an estimated US$100 billion goes to producers.

Table TS-10 compares the costs and policies for different technology options to those of promoting energy access. Different types of technologies and objectives will require different combinations of policy mechanisms to attract the necessary investments. Thus, Table TS-10 identifies 'essential' policy mechanisms that must be included for a specific option to achieve the rapid energy system transformation, 'desired' policy mechanisms that would help but are not a necessary condition, 'uncertain' policy mechanisms in which the outcome will depend on the policy emphasis and thus might favor or disfavor a specific option, and policies that are inadequate on their own but could 'complement' other essential policies.

The GEA findings indicate that global investments in combined energy efficiency and supplies have to increase to about US$1.7–2.2 trillion per

43 **IEA, 2009a:** *World Energy Outlook*. International Energy Agency, Organization for Economic Cooperation & Development, Paris.

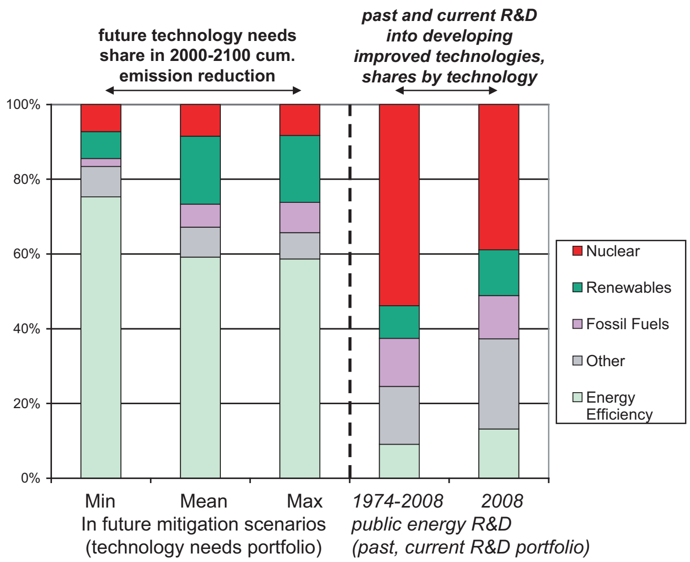


Figure TS-31 | Distribution of past (1974–2008) and current (2008) public sector energy technology R&D portfolios in member countries of the IEA (right) versus portfolios of future GHG mitigation needs (min/mean/max, left) derived from an extensive scenario uncertainty analysis. Source: Adapted from Grubler and Riahi, 2010, see Chapter 24.[44]

year compared with the present level of some US$1.3 trillion (2% of current world GDP). Given projected economic growth, this would be an approximately constant fraction of GDP in 2050.

For some objectives, such as energy access, future investment needs are comparatively modest. However, a variety of different policy mechanisms – including subsidies and regulation as well as capacity building programs – need to be in place. Regulations and standards are also essential for almost all other options listed in Table TS-10, while externality pricing might be necessary for capital-intensive technologies to achieve rapid deployment (such as a carbon tax to promote diffusion of renewables, CCS, or efficiency). Capital requirements for energy infrastructure are among the highest priorities of the options listed.

Increasing investments in the energy system as depicted by the GEA pathways requires the careful consideration of a wide portfolio of policies to create the necessary financial incentives and adequate institutions to promote and support them, and innovative financial instruments to facilitate them The portfolio needs to include regulations and technology standards in sectors with, for example, relatively low price elasticity in combination with externality pricing to avoid rebound effects, as well as targeted subsidies to promote specific 'no-regret' options while addressing affordability. In addition, focus needs to be given to capacity development to create an enabling technical, institutional, legal, and financial environment to complement traditional deployment policies (particularly in the developing world).

44 Section TS-5.4.2 is based on Chapter 6 and 17.

5.4.3 Capacity Development[45]

Wealthier countries need to improve mechanisms for supporting ***capacity development*** in developing countries, including financial support, technical training, and sharing of industry, trade, and institutional experiences. Any energy capacity strategy must, however, be tailored to the specific characteristics of a given country or region if it is to succeed in stimulating a rapid transition of the energy system to a more sustainable path. While this strategy must address basic needs for education and training, it must also be adapted to the local cultural norms and practices.

The transitions put forward in GEA require a transformation of energy systems that demand significant changes in the way energy is supplied and used today. These transitions are, by definition, long-term, socially embedded processes in the course of which capacities at the individual, organizational, and systems levels and the policies for capacity development themselves will inevitably change. From this perspective, capacity development can no longer be seen as a simple aggregation of individual skills and competences or the introduction of new 'technology'. Rather, it is a broad process of change in production and consumption patterns, knowledge, skills, organizational form, and – most important – established practices and norms of the players involved: in other words, a host of new and enhanced capacities. Energy transitions are thus innovative processes (Chapter 25.1).

The complexity, magnitude, and speed of the changes envisaged in these transitions will necessitate a major shift in the way that societies analyze and define the concept of 'capacities' and in the way in which they go about the important task of developing these capacities to meet the challenges of energy transitions. Different from some of the linear approaches to capacity development and to technology transfer and deployment used today, which often fail to appreciate the complexity of change processes, the concept of capacity development advanced by GEA is intimately linked to the energy transitions perspective based on multilayered processes of system change.

In these processes, special attention is paid to the informal institutions that arise out of historically shaped habits, practices, and vested interests of players in the system already in place and to the tendency for path dependence, where past choices constrain present options. They are given special attention because they constitute potential impediments to needed change. In the transitions perspective, both learning and unlearning such habits, practices, and norms in the course of change are important (Chapter 25.4).

Traditional habits, practices, and norms also shape the styles of communication in societies. Evidence shows that the more successful change processes take place in environments that tend to move away from top-down communication and consultation to more active and continuous

45 Section TS-5.4.3 is based on Chapter 25.

Table TS-10 | Energy investments needed between 2010 and 2050 to achieve GEA sustainability objectives and illustrative policy mechanisms for mobilizing financial resources.

Times	Investment (billions of US$/year)		Policy mechanisms			
		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* (feed-in tariff and renewable portfolio standards can complement GHG pricing)	*Essential* (GHG pricing is key to rapid development of renewables)	*Complement* (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 to electricity and cleaner cooking[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, micro-financing for appliances, subsidies for clean cookstoves)	*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 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 a).

[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 almost universal access by 2030 (including electricity grid connections and fuel subsidies for cleaner cooking fuels).

dialogue practices. Capacity development has an important role to play in building mechanisms of support and capacities for interactive feedback, flexibility, and adaptive management and change. And because these traditional habits, practices, and norms are embedded in a broader social context, building capacities for dialogue at the local level is essential.

Market development and the role of feedback and flexibility at the local and project level are also essential in support of the diffusion of new energy technologies, but they are usually ignored in the design of capacity building initiatives. Also important is the need to build and strengthen capacities for local manufacture, repair, and distribution of new energy-related technologies, whether related to improved cookstoves, solar home systems or other forms of early energy-access initiatives, or to the introduction of more modern and decentralized forms of energy. Successful examples of energy technology development and diffusion also point to the need to develop and strengthen local research capacities, participating in collaborative R&D efforts and coordinating across sectors and disciplines.

Brazil's sustained research effort that led to its development of the biofuels industry and to multiple development goals ranging from energy-access improvements to lowering GHG emissions is a good example of this interaction and the success that it brings (see Chapter 25.6.1). Research and advisory services have also played an important role in the development of smallholder jatropha farms to produce oil for off-grid electricity production in Mali (Chapter 25.6.1). Other examples where bottom-up approaches have been critical to the successful introduction of new energy technologies include experiences in the introduction of small hydropower schemes in China and village power schemes in Bhutan (Chapter 25.6.2).

Because the need to transform energy systems applies to all economies – whether industrial, emerging, developing, or poorest – the new concept of capacity development for energy transitions in some of the examples just mentioned must also apply to all programs, whether they relate to small energy-access projects or major transitions and innovations across society and at the national level. The differences reside in the types of objectives and outcomes sought – ranging from countries where the main objective may be to attain the highest levels of cleaner, sustainable, and secure forms of energy to those where the goal is to provide access to cleaner and affordable modern forms of energy to the largest possible number of residents.

Making choices about transition pathways requires access to a wide range of knowledge and information as well as the capacities to use this knowledge in the policy process. Two new approaches have emerged recently from contemporary business practices that may have great relevance in future capacity development approaches. These have developed over the past several decades as production has become more knowledge-intensive, competition more globalized, and information technology more accessible to the population at large. These 'open innovation' and 'distributed innovation' systems require very different and complex approaches to capacity development, involving special skills for managing risks and for creating innovative partnerships that speed the development and diffusion of new energy technologies (Chapter 25.7).

Open innovation involves a network culture in which the world outside is used to generate knowledge inside, and knowledge flows in and out of the institution purposefully rather than at random. The main objective is to leverage existing knowledge rather than depend solely on intellectual property. Distributed innovation, in contrast, is more closely associated with the development of open source software such as Linux, but the innovation has spread and is being practiced in other fields, including the biosciences. In this case, existing practices are not just modified but disrupted. The innovation power comes from a collected set of individuals whose individual actions 'snap together' to create something new.

These approaches point to the importance of building very special capacities for networking and knowledge networks and for appreciating the increasing relevance of open and distributed systems. Brazil's systematic collaborative research since the early 1980s that led to the biofuels success and the Dutch use of 'transition platforms' to advance efforts toward a low-carbon economy, relying on bottom-up processes and open networks involving business, the non-governmental sector, and government, illustrate the applicability of this approach for industrial as well as developing countries (Chapter 25.8.3). In these and other examples, the lesson is that access to information and the capacity to use such inputs are critical in making choices for energy transitions – for individual players, the community, or a national government.

But these new and emerging forms of knowledge networking, coupled with new and innovative forms of finance and technology research collaboration and development, require new and enhanced capacities for effective participation at the international level that many countries, particularly developing ones, do not have, or are not well-developed today. The increasingly complex and fast-paced world of energy and climate change finance is a good example of an area where present capacities fall far short of the needs. The recent climate change negotiations alone have generated pledges of fast-start finance up to 2012 of some US$30 billion and promises to work collaboratively so that this funding can grow to some US$100 billion by 2020.

This is only a small part of the overall investment projections needed to meet the growth in energy demand – some US$1.7–2.2 trillion per year are needed up to 2050. The world of energy finance has always been a large and complex market. The difference today is that it is becoming even more complex, with new and innovative instruments of finance, including the carbon market, and with countries demanding more attention to the need to develop, introduce, and diffuse new technologies. Under these conditions, a multi-goal approach can both speed the diffusion of new energy technologies as well as stimulate the development and energy transition processes in developing countries.

6 Conclusions

The world is undergoing severe and rapid change involving significant challenges. Although this situation poses a threat, it also offers a unique opportunity – a window of time in which to create a new, more sustainable, more equitable world, provided that the challenges can be addressed promptly and adequately. Energy is a pivotal area for actions to help address the challenges.

The interrelated world brought about by growth and globalization has increased the linkages among the major challenges of the 21st century. We do not have the luxury of being able to rank them in order of priority. As they are closely linked and interdependent, the task of addressing them simultaneously is imperative.

Energy offers a useful entry point into many of the challenges because of its immediate and direct connections with major social, economic, security, and development goals of the day. Among many other challenges, energy systems are tightly linked to global economic activities, to freshwater and land resources for energy generation and food production, to biodiversity and air quality through emissions of particulate matter and precursors of tropospheric ozone, and to climate change. Most of all, access to affordable and cleaner energy carriers is a fundamental prerequisite for development, which is why GEA places great emphasis on the need to integrate energy policy with social, economic, security, development, and environment policies.

The good news is that humanity has the resources, the ingenuity, and the technologies to create a better world. The bad news is that the lack of appropriate institutions, their interaction and integration, capacities, and governance structures makes the task difficult. Raising the level of political will to address some of these challenges could go a long way toward making significant progress in achieving multiple goals. This is a major task, however, given the tendency of current decision-making processes to aim for short-term, quick results. GEA endeavors to make a compelling case for the adoption of a new set of pathways – pathways that are essential, required urgently, and – most important – achievable.

GEA highlights essential technology-related requirements for radical energy transformation:

- significantly larger investment in energy efficiency improvements, especially end-use, across all sectors, with a focus on new investments as well as major retrofits;

- rapid escalation of investments in renewable energies: hydropower, wind, solar energy, modern bioenergy, and geothermal, as well as the smart and super grids that enable renewable energies to become the dominant sources of energy;

- reaching universal access to modern forms of energy and cleaner cooking through micro-financing and subsidies;

- use of fossil fuels and bioenergy at the same facilities for the efficient co-production of multiple energy carriers and chemicals;

- full-scale deployment of CCS; and

- on one extreme nuclear energy could make a significant contribution to the global electricity, but in the other, it could be phased out.

To meet humanity's need for energy services, comprehensive diffusion of advanced energy technologies and an increased contribution of energy efficiencies are required throughout the energy system – from energy collection and conversion to end-use. Rapid diffusion of renewable energies is the second, but equally most effective, option for reaching multiple objectives. Sustainable conversion to carriers such as electricity, hydrogen, and heat, along with smart transmission and distribution systems for the most important end-uses are crucial.

A major policy challenge is to resolve the current issue of split incentives, in the sense that those who would be paying for efficiency improvements and other energy investments are more oriented toward short-term rates of return than to the long-term profitability of the investments and, likewise, that they are rarely the beneficiaries of reduced energy bills and other public benefits.

GEA makes the case that energy system transformation is possible only if there is also an interactive and iterative transformation of the policy and regulatory landscape, thereby fostering a buildup of skills and institutions that encourage innovation to thrive, create conditions for business to invest, and generate new jobs and livelihood opportunities.

It is projected that, by mid-century, more than six billion people will live in urban environments. This underscores the importance for policymakers to consider the window of opportunity available in designing the urban landscape, specifically in terms of urban layout, transport structure, and individual buildings/structures and their energy use.

A major finding of GEA is that some energy options provide multiple benefits. This is particularly true of energy efficiency, renewables, and the co-production of synthetic transportation fuels, cooking fuels, and electricity with CCS, which offer advantages in terms of supporting all of the goals related to economic growth, jobs, energy security, local and regional environmental benefits, health, and climate change mitigation. All these advantages imply the creation of value. This value should be incorporated into the evaluation of these measures (and others) and in creating incentives for their use.

One implication of this is that nations and corporations can invest in efficiency and renewable energy for the reasons that are important to them, not just because of a global concern about, for example, climate change mitigation or energy security. But incentives for individual players to invest in options with large societal values must be strong and effective.

Finally, the GEA pathways describe the transformative changes needed to achieve development pathways toward a more sustainable future – a 'sustainable future' that simultaneously achieves normative goals related to the economic growth, energy security, health, and environmental impacts of energy conversion and use, including the mitigation of climate change.

In sum, GEA finds that attainment of a sustainable future for all is predicated on resolving energy challenges. This requires the creation of market conditions, via government interventions, that invite and stimulate investments in energy options that provide incentives for rapid investments in energy end-use and supply technologies and systems.