October 2007

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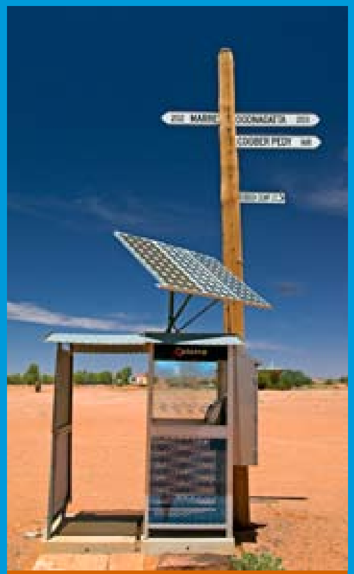
Lighting the way: Toward a sustainable energy future

InterAcademy Council

Lighting the way
Toward a sustainable energy future



InterAcademy Council

InterAcademy Council

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Lighting the way

ISBN 978-90-6984-531-9

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Design, typography and typesetting

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Foreword

As recognized in 1997 by the Kyoto Protocol, achieving a sustainable energy future presents an urgent challenge for the 21st century. Current patterns of energy resources and energy usage are proving detrimental to the long-term welfare of humanity. The integrity of essential natural systems is already at risk from climate change caused by the atmospheric emissions of greenhouse gases. At the same time, basic energy services are currently unavailable to a third of the world's people, and more energy will be essential for equitable, worldwide sustainable development. The national and global energy security risks are further exacerbated by an escalating energy cost and by the competition for unevenly distributed energy resources.

This global problem requires global solutions. Thus far, insufficient advantage has been taken of the world's leading scientists and their major institutions, even though these institutions are a powerful resource for communicating across national boundaries and for reaching agreement on rational approaches to long-term problems of this kind. The world's academies of science and of engineering—whose judgments are based on objective evidence and analysis—have the respect of their national governments but are not government-controlled. Thus, for example, scientists everywhere can generally agree even when their governments have different agendas. Many political leaders recognize the value of basing their decisions on the best scientific and technological advice, and they are increasingly calling upon their own academies of sciences and engineering to provide this advice for their nation. But the possibility and value of such advice at the international level—from an analogous source based on associations of academies—is a more recent development. In fact, only with the establishment of the InterAcademy Council (IAC) in 2000 did accessing such advice become a straightforward matter.[1] Thus far, three major reports have been released by the InterAcademy Council: on institutional capacity building in every nation for science and technology (S&T), on African agriculture, and on women for science.[2]

At the request of the Governments of China and Brazil, and with strong support from United Nations Secretary-General, Mr. Kofi Annan, the IAC Board has now harnessed the expertise of scientists and engineers throughout the world to produce *Lighting the Way: Toward a Sustainable Energy Future*. Here, we call special attention to three of the report's important messages.

First, science and engineering provide critical guiding principles for achieving a sustainable energy future. As the report states, 'science provides the basis for a rational discourse about trade-offs and risks, for selecting research and

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1 The eighteen-member InterAcademy Council Board is composed of presidents of fifteen academies of science and equivalent organizations representing Brazil, Chile, China, France, Germany, Hungary, India, Iran, Japan, Malaysia, Turkey, the United Kingdom, and the United States, plus the African Academy of Sciences and the Academy of Sciences for the Developing World (TWAS) and representatives of the InterAcademy Panel (IAP) of scientific academies, the International Council of Academies of Engineering and Technological Sciences (CAETS), and the InterAcademy Medical Panel (IAMP) of medical academies.

2 InterAcademy Council, *Inventing a Better Future: A Strategy for Building Worldwide Capacities in Science and Technology*, Amsterdam, 2004; InterAcademy Council, *Realizing the Promise and Potential of African Agriculture*, 2004; InterAcademy Council, *Women for Science: An Advisory Report*, Amsterdam, 2006. (Accessible at www.interacademycouncil.net)

development (R&D) priorities, and for identifying new opportunities—openness is one of its dominant values. Engineering, through the relentless optimization of the most promising technologies, can deliver solutions—learning by doing is among its dominant values. Better results will be achieved if many avenues are explored in parallel, if outcomes are evaluated with actual performance measures, if results are reported widely and fully, and if strategies are open to revision and adaptation.'

Second, achieving a sustainable energy future will require an intensive effort at capacity building, as well as the participation of a broad array of institutions and constituencies. The report emphasizes that 'critical to the success of all the tasks ahead are the abilities of individuals and institutions to effect changes in energy resources and usage. Capacity building of individual expertise and institutional effectiveness must become an urgent priority of all principal actors—multinational organizations, governments, corporations, educational institutions, non-profit organizations, and the media. Above all, the general public must be provided with sound information about the choices ahead and the actions required for achieving a sustainable energy future.'

Third, although achieving a sustainable energy future requires long-range approaches, given the dire prospect of global climate change, the Study Panel urges that the following be done expeditiously and simultaneously:

- Concerted efforts should be mounted for improving energy efficiency and reducing the carbon intensity of the world economy, including the worldwide introduction of price signals for carbon emissions with consideration of different economic and energy systems in individual countries.
- Technologies should be developed and deployed for capturing and sequestering carbon from fossil fuels, particularly coal.
- Development and deployment of renewable energy technologies should be accelerated in an environmentally responsible way.

Also urgent as a moral, social, and economic imperative, the poorest people on this planet—who primarily reside in developing countries—should be supplied with modern, efficient, environmentally friendly and sustainable energy services. The scientific, engineering, and medical academies of the world, in partnership with the United Nations and many other concerned institutions and individuals, are poised to work together to help meet this urgent challenge.

We thank all of the Study Panel members, reviewers, and the two distinguished review monitors who contributed to the successful completion of this report. Special appreciation is due to the Study Panel Co-Chairs and staff who put so much time and devotion into ensuring that the final product would make a difference.

The InterAcademy Council gratefully acknowledges the leadership exhibited by the Government of China, the Government of Brazil, the William and Flora Hewlett Foundation, the Energy Foundation, the German Research Foundation (DFG), and the United Nations Foundation, which provided the financial support for the conduct of the study and the printing and distribution of this report. We are also grateful to the following organizations for their contributions in hosting regional IAC energy workshops: the Brazilian Academy of Sciences, the Chinese Academy of Sciences, the French Academy of Sciences, the Indian National Science Academy, and the Science Council of Japan.

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Preface

Human prosperity has been intimately tied to our ability to capture, collect, and harness energy. The control of fire and the domestication of plants and animals were two of the essential factors that allowed our ancestors to transition from a harsh, nomadic existence into stable, rooted societies that could generate the collective wealth needed to spawn civilizations. For millennia, energy in the form of biomass and fossilized biomass was used for cooking and heating, and for the creation of materials that ranged from bricks to bronze. Despite these developments, relative wealth in virtually all civilizations was fundamentally defined by access to and control over energy, as measured by the number of animal and humans that served at the beck and call of a particular individual.

The Industrial Revolution and all that followed have propelled an increasingly larger fraction of humanity into a dramatically different era. We go to the local market in automobiles that generate the pull of hundreds of horses, and we fly around the world with the power of a *hundred thousand* horses. Growing numbers of people around the world can take for granted that their homes will be warm in the winter, cool in the summer, and lit at night. The widespread use of energy is a fundamental reason why hundreds of millions of people enjoy a standard of living today that would have been unimaginable to most of humanity a mere century ago.

What has made all this possible is our ability to use energy with ever increasing dexterity. Science and technology have given us the means to obtain and exploit sources of energy, primarily fossil fuel, so that the power consumption of the world today is the equivalent of over *seventeen billion* horses working 24 hours per day, 7 days per week, 365 days a year. Put another way, the amount of energy needed to keep a human being alive varies between 2,000 and 3,000 kilocalories per day. By contrast, average per capita energy consumption in the United States is approximately 350 billion joules per year, or 230,000 kilocalories per day. Thus, the average American consumes enough energy to meet the biological needs of 100 people, while the average citizen in OECD countries uses the energy required to sustain approximately 50 people. By comparison, China and India currently consume approximately 9–30 times less energy per person than the United States. The worldwide consumption of energy has nearly doubled between 1971 and 2004, and is expected to grow another 50 percent by 2030, as developing countries move—in a business-as-usual scenario—toward an economic prosperity deeply rooted in increased energy use.

The path the world is currently taking is not sustainable: there are costs associated with the intensive use of energy. Heavy reliance on fossil fuels is causing environmental degradation at the local, regional, and global levels. Climate change, in particular, poses global risks and challenges that are perhaps unprecedented in their magnitude, complexity, and difficulty. At the same time, securing access to vital energy resources, particularly oil and natural gas, has become a powerful driver in geo-political alignments and strategies. Finally, if current trends continue, inequitable access to energy, particularly for people in rural areas of developing countries, and the eventual exhaustion of inexpensive oil supplies could have profound impacts on international security and economic prosperity.

While the current energy outlook is very sobering,

Preface updated 16 October 2007.

we believe that there are sustainable solutions to the energy problem. A combination of local, national, and international fiscal and regulatory polices can greatly accelerate efficiency improvements, which remain in many cases the most cost-effective and readily implemented part of the solution. Significant efficiency gains were achieved in recent years and more can be obtained with policy changes that encourage the development and deployment of better technologies. For developing countries with rapidly growing energy consumption, 'leapfrogging' past the wasteful energy trajectory historically followed by today's industrialized countries is in their best economic and societal interests. Providing assistance to these countries aimed at promoting the introduction of efficient and environmentally friendly energy technologies as early as possible should therefore be an urgent priority for the international community.

A timely transition to sustainable energy systems also requires policies that drive toward optimal societal choices, taking into account both the short- and long-term consequences of energy use. Discharging raw sewage into a river will always be less expensive at a micro-economic level than first treating the waste, especially for 'up-stream' polluters. At a macro scale, however, where the long-term costs to human health, quality of life, and the environment are folded into the calculation, sewage treatment clearly becomes the low-cost option for society as a whole. In the case of climate change, the predicted consequences of continued warming include a massive reduction of water supplies in some parts of the world, especially those that rely on the steady run-off of water from glaciers; the spread of malaria, cholera, and other diseases whose vectors or pathogens are temperature- and moisture-dependent; increased devastation from extreme weather events such as floods, droughts, wildfires, typhoons, and hurricanes; permanent displacement of tens to hundreds of millions of people due to rising sea levels; and significant loss of biodiversity.[3]

Meanwhile, other types of emissions associated with common forms of energy use today impose significant adverse health impacts on large numbers of people around the world—creating risks and costs that are often not captured in energy market choices or policy decisions. Thus, it becomes critical to consider the additional costs of mitigating these impacts when attempting to assess the true low-cost option in any long-term, macro-economic analysis of energy use and production. The cost of carbon emissions and other adverse impacts of current modes of energy use must be factored into market and policy decisions.

In addition to extensive energy efficiency enhancements and rapid deployment of low-carbon technologies, including advanced fossil-fuel systems with carbon capture and sequestration and nuclear energy, a sustainable energy future will be more readily attainable if renewable energy sources become a significant part of the energy supply portfolio. Science and technology are again essential to delivering this part of the solution. Significant improvements in our ability to convert solar energy into electricity are needed, as are economical, large-scale technologies for storing energy and transmitting it across long distances. Improved storage and transmission technologies would allow intermittent renewable sources to play a greater role in supplying

3 These and other impacts are predicted with a high level of confidence in Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of the Working Group II to the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY: Cambridge University Press, 2007. http://www.ipcc.ch/SPM13apr07.pdf

the world's electricity needs. At the same time, efficient methods of converting cellulosic biomass into high-quality liquid fuels could greatly reduce the carbon footprint of the world's rapidly growing transportation sector and relieve current supply pressures on increasingly precious petroleum fuels.

At this point, much has been written about the sustainable energy problem and its potential solutions. The defining feature of this report by the InterAcademy Council (IAC) is that it was developed by a study panel that brought together experts nominated by over ninety national academies of science around the world. Members of the panel in turn drew upon the expertise of colleagues within and outside their own countries, so that the resulting report—which was further informed by a series of workshops held in different parts of the world and by numerous commissioned studies—represents a uniquely international and diverse perspective. It is our hope that the conclusions and actionable recommendations contained in Chapter 5, The Case for Immediate Action, will provide a useful roadmap for navigating the energy challenges we confront this century. Effecting a successful transition to sustainable energy systems will require the active and informed participation of all for whom this report is intended, from citizens and policymakers to scientists, business leaders, and entrepreneurs—in industrialized and developing countries alike.

It has also become evident to us, in surveying the current energy situation from multiple vantage points and through different country lenses, that it will be critical to expand and improve the capacity of international institutions and actors to respond effectively to global challenges and opportunities. Accordingly, we have personally recommended that the UN Secretary General appoint a small committee of experts who can advise him and member nations on implementing successful technologies and strategies for promoting sustainable energy outcomes. By identifying promising options and recommending modifications, where necessary, to suit different country contexts, this committee could accelerate the global dissemination of sustainable energy solutions. At the same time, it could promote a dialogue with industrial stakeholders and policymakers to identify the most effective incentives, policies, and regulations that would lead to the implementation of those solutions. Appropriately designed changes in government policy can, like the rudder of a ship, be used to steer a shift in direction that produce enormous course changes over time. We have seen examples where relatively modest government policies in our own countries have led to great successes—from California's success in holding constant the electricity consumption per capita over the last thirty years (at a time when electricity use in the rest of the United States had grown by sixty percent) to Brazil's success in nurturing a pioneering biofuels industry that has leapt ahead of far more economically developed countries.

In sum, we believe that aggressive support of energy science and technology, coupled with incentives that accelerate the concurrent development and deployment of innovative solutions, can transform the entire landscape of energy demand and supply. This transformation will make it possible, both technically and economically, to elevate the living conditions of most of humanity to the level now enjoyed by a large middle class in industrialized countries while substantially reducing the environmental and energy-security risks associated with current patterns of energy production and use. What the world does in the coming decade will have enormous consequences that will last for centuries; it is imperative that we begin without further delay.

On December 10, 1950, William Faulkner, the Nobel Laureate in Literature, spoke at the Nobel Banquet in Stockholm:

> ... I believe that man will not merely endure: he will prevail. He is immortal, not because he alone among creatures has an inexhaustible voice, but because he has a soul, a spirit capable of compassion and sacrifice and endurance.

With these virtues, the world can and will prevail over this great energy challenge.

Steven CHU
Study Panel Co-Chair

José GOLDEMBERG
Study Panel Co-Chair

Report review

This report was externally reviewed in draft form by 15 internationally renowned experts chosen for their diverse perspectives, technical knowledge, and geographical representation, in accordance with procedures approved by the IAC Board. The purpose of this independent review was to provide candid and critical comments that would help the IAC to produce a sound report that met the IAC standards for objectivity, evidence, and responsiveness to the study charge. The review procedure and draft manuscript remain confidential to protect the integrity of the deliberative process. The IAC wishes to thank the following individuals for their review of this report:

Eric ASH, former Rector, Imperial College, London, UK

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Jacques L. WILLEMS, Professor Emeritus, Faculty of Engineering, Ghent University, Ghent, Belgium

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions and recommendations, nor did they see the final draft of the report before its release.

The review of this report was overseen by two review monitors:

Ralph J. CICERONE, President, United States National Academy of Sciences, Washington, DC, USA

R. A. MASHELKAR, President, Indian National Science Academy; and Bhatnagar Fellow, National Chemical Laboratory, Pune, India

Appointed by the IAC Co-Chairs, the review monitors were responsible for ascertaining that the independent examination of this report was carried out in accordance with IAC procedures and that all review comments were carefully considered. However, responsibility for the final content of this report rests entirely with the authoring Study Panel and the InterAcademy Council.

Acknowledgements

The Study Panel is grateful to the participants in the seven consultative workshops held during the course of this project. These workshop participants provided valuable insights that enabled the identification of the major strategic challenges and opportunities, which effectively helped the Study Panel in guiding its deliberations and in drafting this report.

The workshop participants include:

- *Durban Workshop*. Robert Baeta, Douglas Banks, Abdelfattah Barhdadi, Osman Benchikh, Mosad Elmissiry, Joseph Essandoh-Yeddu, Moses Haimbodi, Manfred Hellberg, I.P. Jain, Dirk Knoesen, Isaias C. Macedo, Cédric Philibert, Youba Sokona,Samir Succar, Annick Suzor-Weiner, and Brian Williams;
- *Beijing Workshop*. Paul Alivisatos, Bojie Fu, E. Michael Campbell, Chongyu Sun, Charles Christopher, Dadi Zhou, Fuqiang Yang, Hao Wen, Hin Mu, Hu Min, Kazunari Domen, Kebin He, Luguang Yan, Shuanshi Fan, Jack Siegel, Peng Chen, Qingshan Zhu, Xiu Yang, Xudong Yang, Wei Qin, Wenzhi Zhao, Yi Jiang, Yu Joe Huang, Zheng Li, Zhenyu Liu, and Zhihong Xu;
- *Berkeley Workshop*. Paul Alivisatos, E. Michael Campbell, Mildred Dresselhaus, Kazunari Domen, Jeffrey Greenblatt, Adam Heller, Robert Hill, Martin Hoffert, Marcelo Janssen, Jay Keasling, Richard Klausner, Banwari Larl, Nathan S. Lewis, Jane Long, Stephen Long, Amory Lovins, Thomas A. Moore, Daniel Nocera, Melvin Simon, Christopher Somerville, John Turner, Craig Venter, and Zhongxian Zhao
- *Rio de Janeiro Workshop*. Alfesio L. Braga, Kamala Ernest, André Faaij, Patrícia Guardabassi, Afonso Henriques, Gilberto Jannuzzi, Henry Josephy, Jr., Eric D. Larson, Lee Lynd, José R. Moreira, Marcelo Poppe, Fernando Reinach, Paulo Saldiva, Alfred Szwarc, Suani Coelho Teixeira, Boris Utria, Arnaldo Walter, and Brian Williams;
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- *Paris Workshop*. Edouard Brézin, Bernard Bigot, Leonid A. Bolshov, Alain Bucaille, Ayse Erzan, Harold A. Feiveson, Sergei Filippov, Karsten Neuhoff, Lars Nilsson, Martin Patel, Peter Pearson, Jim Platts, Mark Radka, Hans-Holger Rogner, Oliver Schaefer, and Bent Sorensen; and the
- *Tokyo Workshop*. Akira Fujishima, Hiromichi Fukui, Hideomi Koinuma, Kiyoshi Kurokawa, Takehiko Mikami, Chikashi Nishimura, Zempachi Ogumi, Ken-ichiro Ota, G. R. Narasimha Rao, and Ayao Tsuge, and Harumi Yokokawa.

The Study Panel is also grateful to the Brazilian Academy of Sciences, the Chinese Academy of Sciences, the French Academy of Sciences, the Indian National Science Academy, and the Science Council of Japan for their contributions in hosting the regional IAC energy workshops.

The Study Panel appreciates the contribution of authors who prepared background papers that, together with the consultative workshops, provided the essential building blocks for the report. Those involved were John Ahearne, Robert U. Ayres, Isaias de Carvalho Macedo, Vibha Dhawan, J. B. Greenblatt, Jiang Yi, Liu Zhen Yu, Amory B. Lovins, Cedric Philibert, K. Ramanathan, Jack Siegel, Xu Zhihong, Qingshan Zhu, and Roberto Zilles.

The Study Panel is most grateful for the extraordinary contributions of Jos van Renswoude, Study Director, for organizing the entire study panel process, and along with Dilip Ahuja, Consultant, and Marika Tatsutani, Writer/Editor, for the successful completion of the report writing process.

The InterAcademy Council (IAC) Secretariat and the Royal Netherlands Academy of Arts and Sciences (KNAW) in Amsterdam, where IAC is headquartered, provided guidance and support for this study. In this regard, special mention is made of the assistance provided by John P. Campbell, IAC Executive Director; Albert W. Koers, IAC General Counsel; Stéphanie Jacometti, Communications Coordinator; and Margreet Haverkamp, Shu-Hui Tan, Floor van den Born, Ruud de Jong, and Henrietta Beers of the IAC Secretariat. Ellen Bouma, Publication Designer, and Sheldon I. Lippman, Editorial Consultant, prepared the final manuscript for publication.

The Study Panel gratefully acknowledges the leadership exhibited by the Government of China, the Government of Brazil, the William and Flora Hewlett Foundation, the Energy Foundation, the German Research Foundation (DFG), and the United Nations Foundation, which provided the financial support for the conduct of the study and the printing and distribution of this report.

Last but by no means least, the Study Panel thanks the InterAcademy Council Board and especially Bruce Alberts and Lu Yongxiang, IAC Co-Chairs, for providing the opportunity to undertake this important study.

Executive Summary

Making the transition to a sustainable energy future is one of the central challenges humankind faces in this century. The concept of energy sustainability encompasses not only the imperative of securing adequate energy to meet future needs, but doing so in a way that (a) is compatible with preserving the underlying integrity of essential natural systems, including averting dangerous climate change; (b) extends basic energy services to the more than 2 billion people worldwide who currently lack access to modern forms of energy; and (c) reduces the security risks and potential for geopolitical conflict that could otherwise arise from an escalating competition for unevenly distributed energy resources.

The sustainable energy challenge

The task is as daunting as it is complex. Its dimensions are at once social, technological, economic, and political. They are also global. People everywhere around the world play a role in shaping the energy future through their behavior, lifestyle choices, and preferences. And all share a significant stake in achieving sustainable outcomes.

The momentum behind current energy trends is enormous and will be difficult to check in the context of high levels of existing consumption in many industrialized countries; continued population growth; rapid industrialization in developing countries; an entrenched, capital-intensive and long-lived energy infrastructure; and rising demand for energy-related services and amenities around the world. Although wide disparities exist in per capita energy consumption at the country level, relatively wealthy households everywhere tend to acquire similar energy-using devices. Therefore, the challenge and the opportunity exists—in industrialized and developing countries alike—to address resulting energy needs in a sustainable manner through effective demand- and supply-side solutions.

The prospects for success depend to a significant extent on whether nations can work together to ensure that the necessary financial resources, technical expertise, and political will are directed to accelerating the deployment of cleaner and more efficient technologies in the world's rapidly industrializing economies. At the same time, current inequities that leave a large portion of the world's population without access to modern forms of energy and therefore deprived of basic opportunities for human and economic development must also be addressed.

This could be achieved without compromising other sustainability objectives, particularly if simultaneous progress is achieved toward introducing new technologies and reducing energy intensity elsewhere throughout the world economy. The process of shifting away from a business-as-usual trajectory will necessarily be gradual and iterative: because essential elements of the energy infrastructure have an expected life on the order of one to several decades, dramatic changes in the macroscopic energy landscape will take time. The inevitable *lag* in the system, however, also creates grounds for great urgency. In light of growing environmental and energy security risks, significant global efforts to transit to a different landscape must begin within the next ten years. Delay only increases the difficulty of managing problems created by the world's current energy systems, as well as the likelihood that more disruptive and costly adjustments will need to be made later.

The case for urgent action is underscored when the ecological realities, economic imperatives, and resource limitations that must be managed over the coming century are viewed in the context of present world energy trends. To take just two dimensions of the challenge—oil security and climate change—current forecasts by the International Energy Agency in its 2006 *World Energy Outlook* suggest that a continuation of business-as-usual trends will produce a nearly 40 percent increase in world oil consumption (compared to 2005 levels) and a 55 percent increase in carbon dioxide emissions (compared to 2004 levels) over the next quarter century (that is, by 2030). In light of the widely held expectation that relatively cheap and readily accessible reserves of conventional petroleum will peak over the next few decades and mounting evidence that the responsible mitigation of climate-change risks will require significant reductions in global greenhouse gas emissions within the same timeframe, the scale of the mismatch between today's energy trends and tomorrow's sustainability needs speaks for itself.

For this report, the Study Panel examined the various technology and resource options that are likely to play a role in the transition to a sustainable energy future, along with some of the policy options and research and development priorities that are appropriate to the challenges at hand. Its principal findings in each of these areas are summarized below followed by nine major conclusions with actionable recommendations reached by the Study Panel.

Energy demand and efficiency

Achieving sustainability objectives will require changes not only in the way energy is supplied, but in the way it is used. Reducing the amount of energy required to deliver various goods, services, or amenities is one way to address the negative externalities associated with current energy systems and provides an essential complement to efforts aimed at changing the mix of energy supply technologies and resources. Opportunities for improvement on the demand side of the energy equation are as rich and diverse as those on the supply side, and frequently offer significant near-term and long-term economic benefits. Widely varying per capita or per gross domestic product (GDP) levels of energy consumption across countries with comparable living standards—though certainly partly attributable to geographic, structural, and other factors—suggest that the potential to reduce energy consumption in many countries is substantial and can be achieved while simultaneously achieving significant quality-of-life improvements for the world's poorest citizens. For example, if measures of social welfare, such as the Human Development Index (HDI), are plotted against per capita consumption of modern forms of energy, such as electricity, one finds that some nations have achieved relatively high levels of well-being with much lower rates of energy consumption than other countries with a similar HDI, which is composed of health, education, and income indicators. From a sustainability perspective then, it is both possible and desirable to maximize progress toward improved social well-being while minimizing concomitant growth in energy consumption.

In most countries, energy intensity—that is, the ratio of energy consumed to goods and services provided—has been declining, albeit not at a rate sufficient to offset overall economic growth and reduce energy consumption in absolute terms. Boosting this rate of intensity decline should be a broadly held, public policy priority. From a purely technological standpoint, the potential for improvement is clearly enormous: cutting-edge advances in engineering, materials, and system design have made it possible to construct buildings that demonstrate zero-net energy consumption and vehicles that

achieve radically lower gasoline consumption per unit of distance traveled. The challenge, of course, is to reduce the cost of these new technologies while overcoming a host of other real-world obstacles—from lack of information and split incentives to consumer preferences for product attributes at odds with maximizing energy efficiency—that often hamper the widespread adoption of these technologies by the marketplace.

Experience points to the availability of policy instruments for overcoming barriers to investments in improved efficiency even when such investments, based on energy and cost considerations alone, are highly cost-effective. The improvements in refrigerator technology that occurred as a result of appliance efficiency standards in the United States provide a compelling example of how public policy intervention can spur innovation, making it possible to achieve substantial efficiency gains while maintaining or improving the quality of the product or service being provided. Other examples can be found in efficiency standards for buildings, vehicles, and equipment; in addition to information and technical programs and financial incentive mechanisms.

Energy supply

The world's energy supply mix is currently dominated by fossil fuels. Now, coal, petroleum, and natural gas together supply roughly 80 percent of global primary energy demand. Traditional biomass, nuclear energy, and large-scale hydropower account largely for the remainder. Modern forms of renewable energy play only a relatively small role at present (on the order of a few percent of the world's current supply mix). Energy security concerns—particularly related to the availability of relatively cheap, conventional supplies of petroleum and, to a lesser extent, of natural gas—continue to be important drivers of national energy policy in many countries and a potent source of ongoing geopolitical tensions and economic vulnerability. Nevertheless, environmental limits, rather than supply constraints, seem likely to emerge as the more fundamental challenge associated with continued reliance on fossil fuels. World coal reserves alone are adequate to fuel several centuries of continued consumption at current levels and could provide a source of petroleum alternatives in the future. Without some means of addressing carbon emissions, however, continued reliance on coal for a large share of the world's future energy mix would pose unacceptable climate-change risks.

Achieving sustainability objectives will require significant shifts in the current mix of supply resources toward a much larger role for low-carbon technologies and renewable energy sources, including advanced biofuels. The planet's untapped renewable energy potential, in particular, is enormous and widely distributed in industrialized and developing countries alike. In many settings, exploiting this potential offers unique opportunities to advance both environmental and economic development objectives.

Recent developments, including substantial policy commitments, dramatic cost declines, and strong growth in many renewable energy industries are promising. However, significant technological and market hurdles remain and must be overcome for renewable energy to play a significantly larger role in the world's energy mix. Advances in energy storage and conversion technologies and in enhancing long-distance electric transmission capability could do much to expand the resource base and reduce the costs associated with renewable energy development. Meanwhile, it is important to note that recent substantial growth in installed renewable capacity worldwide has been largely driven by the introduction of aggressive policies and incentives in a handful of countries. The expansion of similar commitments to other countries would further accelerate current rates of deployment and spur additional

investment in continued technology improvements.

In addition to renewable means of producing electricity, such as wind, solar, and hydropower, biomass-based fuels represent an important area of opportunity for displacing conventional petroleum-based transportation fuels. Ethanol from sugar cane is already an attractive option, provided reasonable environmental safeguards are applied. To further develop the world's biofuels potential, intensive research and development efforts to advance a new generation of fuels based on the efficient conversion of lignocellulosic plant material are needed. At the same time, advances in molecular and systems biology show great promise for generating improved biomass feedstocks and much less energy-intensive methods of converting plant material into liquid fuel, such as through direct microbial production of fuels like butanol.

Integrated *bio-refineries* could, in the future, allow for the efficient co-production of electric power, liquid fuels, and other valuable co-products from sustainably managed biomass resources. Greatly expanded reliance on biofuels will, however, require further progress in reducing production costs; minimizing land, water, and fertilizer use; and addressing potential impacts on biodiversity. Biofuels options based on the conversion of lignocellulose rather than starches appear more promising in terms of minimizing competition between growing food and producing energy and in terms of maximizing the environmental benefits associated with biomass-based transportation fuels

It will be equally important to hasten the development and deployment of a less carbon-intensive mix of fossil fuel-based technologies. Natural gas, in particular, has a critical role to play as a *bridge fuel* in the transition to more sustainable energy systems. Assuring access to adequate supplies of this relatively clean resource and promoting the diffusion of efficient gas technologies in a variety of applications is therefore an important public policy priority for the near to medium term.

Simultaneously, great urgency must be given to developing and commercializing technologies that would allow for the continued use of coal—the world's most abundant fossil-fuel resource—in a manner that does not pose intolerable environmental risks. Despite increased scientific certainty and growing concern about climate change, the construction of long-lived, conventional, coal-fired power plants has continued and even accelerated in recent years. The substantial expansion of coal capacity that is now underway around the world may pose the single greatest challenge to future efforts aimed at stabilizing carbon dioxide levels in the atmosphere. Managing the greenhouse gas 'footprint' of this existing capital stock, while making the transition to advanced conversion technologies that incorporate carbon capture and storage, thus represents a critical technological and economic challenge.

Nuclear technology could continue to contribute to future low-carbon energy supplies, provided significant concerns in terms of weapons proliferation, waste disposal, cost, and public safety (including vulnerability to acts of terrorism) can be—and are—addressed.

The role of government and the contribution of science and technology

Because markets will not produce desired outcomes unless the right incentives and price signals are in place, governments have a vital role to play in creating the conditions necessary to promote optimal results and support long-term investments in new energy infrastructure, energy research and development, and high-risk/high-payoff technologies. Where the political will exists to create the conditions for a sustainable energy transition, a wide vari-

ety of policy instruments are available, from market incentives such as a price or cap on carbon emissions (which can be especially effective in influencing long-term capital investment decisions) to efficiency standards and building codes, which may be more effective than price signals in bringing about change on the end-use side of the equation. Longer term, important policy opportunities also exist at the level of city and land-use planning, including improved delivery systems for energy, water, and other services, as well as advanced mobility systems.

Science and technology (S&T) clearly have a major role to play in maximizing the potential and reducing the cost of existing energy options while also developing new technologies that will expand the menu of future options. To make good on this promise, the S&T community must have access to the resources needed to pursue already promising research areas and to explore more distant possibilities. Current worldwide investment in energy research and development is widely considered to be inadequate to the challenges at hand.

Accordingly, a substantial increase—on the order of at least a doubling of current expenditures—in the public and private resources directed to advancing critical energy technology priorities is needed. Cutting subsidies to established energy industries could provide some of the resources needed while simultaneously reducing incentives for excess consumption and other distortions that remain common to energy markets in many parts of the world. It will be necessary to ensure that public expenditures in the future are directed and applied more effectively, both to address well-defined priorities and targets for research and development in critical energy technologies and to pursue needed advances in basic science. At the same time, it will be important to enhance collaboration, cooperation, and coordination across institutions and national boundaries in the effort to deploy improved technologies.

The case for immediate action

Overwhelming scientific evidence shows that current energy trends are unsustainable. Significant ecological, human health and development, and energy security needs require immediate action to effect change. Aggressive changes in policy are needed to accelerate the deployment of superior technologies. With a combination of such policies at the local, national, and international level, it should be possible—both technically and economically—to elevate the living conditions of most of humanity while simultaneously *addressing the risks* posed by climate change and other forms of energy-related environmental degradation and *reducing the geopolitical tensions and economic vulnerabilities* generated by existing patterns of dependence on predominantly fossil-fuel resources.

The Study Panel reached nine major conclusions, along with actionable recommendations. These conclusions and recommendations have been formulated within a holistic approach to the transition toward a sustainable energy future. This implies that not a single one of them can be successfully pursued without proper attention to the others. Prioritization of the recommendations is thus intrinsically difficult. Nonetheless, the Study Panel believes that, given the dire prospect of climate change, the following three recommendations should be acted upon **without delay and simultaneously**:

- Concerted efforts should be mounted to improve energy efficiency and reduce the carbon intensity of the world economy, including the worldwide introduction of price signals for carbon emissions, with consideration of different economic and energy systems in individual countries.
- Technologies should be developed and deployed for capturing and sequestering carbon from fossil fuels, particularly coal.
- Development and deployment of renewable energy technologies should be accelerated in an environmentally responsible way.

Taking into account the three urgent recommendations above, another recommendation stands out by itself as a moral and social imperative and should be pursued with all means available:

- The poorest people on this planet should be supplied with basic, modern energy services.

Achieving a sustainable energy future requires the participation of all. But there is a division of labor in implementing the various recommendations of this report. The Study Panel has identified the following principal 'actors' that must take responsibility for achieving results:

- Multi-national organizations (e.g., United Nations, World Bank, regional development banks)
- Governments (national, regional, and local)
- S&T community (and academia)
- Private sector (businesses, industry, foundations)
- Nongovernmental organizations (NGOs)
- Media
- General public

Conclusions, recommendations, actions

Based on the key points developed in this report, the Study Panel offers these conclusions with recommendations and respective actions by the principal actors.

CONCLUSION 1. Meeting the basic energy needs of the poorest people on this planet is a moral and social imperative that can and must be pursued in concert with sustainability objectives.

Today, an estimated 2.4 billion people use coal, charcoal, firewood, agricultural residues, or dung as their primary cooking fuel. Roughly 1.6 billion people worldwide live without electricity. Vast numbers of people, especially women and girls, are deprived of economic and educational opportunities without access to affordable, basic labor-saving devices or adequate lighting, added to the time each day spent gathering fuel and water. The indoor air pollution caused by traditional cooking fuels exposes millions of families to substantial health risks. Providing modern forms of energy to the world's poor could generate multiple benefits, easing the day-to-day struggle to secure basic means of survival; reducing substantial pollution-related health risks; freeing up scarce capital and human resources; facilitating the delivery of essential services, including basic medical care; and mitigating local environmental degradation. Receiving increased international attention, these linkages were a major focus of the 2002 World Summit for Sustainable Development in Johannesburg, which recognized the importance of expanded access to reliable and affordable energy services as a prerequisite for achieving the United Nation's Millennium Development Goals.

RECOMMENDATIONS

- Place priority on achieving much greater access of the world's poor to clean, affordable, high-quality fuels and electricity. The challenge of expanding access to modern forms of energy revolves primarily around issues of social equity and distribution—the fundamental problem is not one of inadequate global resources, unacceptable environmental damage, or unavailable technologies. Addressing the basic energy needs of the world's poor is clearly central to the larger goal of sustainable development and must be a top priority for the international community if some dent is to be made in reducing current inequities.
- Formulate policy at all levels, from global to village scale, with greater awareness of the substantial inequalities in access to energy services that now exist, not only between countries but between populations within the same country and even between households within the same town or village. In many developing countries, a small elite

uses energy in much the same way as in the industrialized world, while most of the rest of the population relies on traditional, often poor-quality and highly polluting forms of energy. In other developing countries, energy consumption by a growing middle class is contributing significantly to global energy demand growth and is substantially raising national per capita consumption rates, despite little change in the consumption patterns of the very poor. The reality that billions of people suffer from limited access to electricity and clean cooking fuels must not be lost in per capita statistics.

NEEDED ACTIONS

- Given the international dimension of the problem, multinational organizations like the United Nations and the World Bank should take the initiative to draw up a plan for eliminating the energy poverty of the world's poor. As a first step, governments and NGOs can assist by supplying data on the extent of the problem in their countries.
- The private sector and the S&T community can help promote the transfer of appropriate technologies. The private sector can, in addition, help by making appropriate investments.
- The media should make the general public aware of the enormity of the problem.

CONCLUSION 2. Concerted efforts must be made to improve energy efficiency and reduce the carbon intensity of the world economy.

Economic competitiveness, energy security, and environmental considerations all argue for pursuing cost-effective, end-use efficiency opportunities. Such opportunities may be found throughout industry, transportation, and the built environment. To maximize efficiency gains and minimize costs, improvements should be incorporated in a holistic manner and from the ground up wherever possible, especially where long-lived infrastructure is involved. At the same time, it will be important to avoid underestimating the difficulty of achieving nominal energy efficiency gains, as frequently happens when analyses assume that reduced energy use is an end in itself rather than an objective regularly traded against other desired attributes.

RECOMMENDATIONS

- Promote the enhanced dissemination of technology improvement and innovation between industrialized and developing countries. It will be especially important for all nations to work together to ensure that developing countries adopt cleaner and more efficient technologies as they industrialize.
- Align economic incentives—especially for durable capital investments—with long-run sustainability objectives and cost considerations. Incentives for regulated energy service providers should be structured to encourage co-investment in cost-effective efficiency improvements, and profits should be delinked from energy sales.
- Adopt policies aimed at accelerating the worldwide rate of decline in the carbon intensity of the global economy, where carbon intensity is measured as carbon dioxide equivalent emissions divided by gross world product, a crude measure of global well-being. Specifically, the Study Panel recommends immediate policy action to introduce meaningful price signals for avoided greenhouse gas emissions. Less important than the initial prices is that clear expectations be established concerning a predictable escalation of those prices over time. Merely holding carbon dioxide emissions constant over the next several decades implies that the carbon intensity of the world economy needs to decline at roughly the same rate as gross world product grows—achieving the absolute *reductions*

in global emissions needed to stabilize atmospheric concentrations of greenhouse gases will require the worldwide rate of decline in carbon intensity to begin outpacing worldwide economic growth.
- Enlist cities as a major driving force for the rapid implementation of practical steps to improve energy efficiency.
- Inform consumers about the energy-use characteristics of products through labeling and implement mandatory minimum efficiency standards for appliances and equipment. Standards should be regularly updated and must be effectively enforced.

NEEDED ACTIONS

- Governments, in a dialogue with the private sector and the S&T community, should develop and implement (further) policies and regulations aimed at achieving greater energy efficiency and lower energy intensity for a great variety of processes, services, and products.
- The general public must be made aware, by governments, the media, and NGOs of the meaning and necessity of such policies and regulations.
- The S&T community should step up its efforts to research and develop new, low-energy technologies.
- Governments, united in intergovernmental organizations, should agree on realistic price signals for carbon emissions—recognizing that the economies and energy systems of different countries will result in different individual strategies and trajectories—and make these price signals key components of further actions on reducing the carbon emissions.
- The private sector and the general public should insist that governments issue clear carbon price signals.

CONCLUSION 3. Technologies for capturing and sequestering carbon from fossil fuels, particularly coal, can play a major role in the cost-effective management of global carbon dioxide emissions. As the world's most abundant fossil fuel, coal will continue to play a large role in the world's energy mix. It is also the most carbon-intensive conventional fuel in use, generating almost twice as much carbon dioxide per unit of energy supplied than natural gas. Today, new coal-fired power plants—most of which can be expected to last more than half a century—are being constructed at an unprecedented rate. Moreover, the carbon contribution from coal could expand further if nations with large coal reserves like the United States, China, and India turn to coal to address energy security concerns and develop alternatives to petroleum.

RECOMMENDATIONS

- Accelerate the development and deployment of advanced coal technologies. Without policy interventions the vast majority of the coal-fired power plants constructed in the next two decades will be conventional, pulverized coal plants. Present technologies for capturing carbon dioxide emissions from pulverized coal plants on a retrofit basis are expensive and energy intensive. Where new coal plants without capture must be constructed, the most efficient technologies should be used. In addition, priority should be given to minimize the costs of future retrofits for carbon capture by developing at least some elements of carbon capture technology at every new plant. Active efforts to develop such technologies for different types of base plants are currently underway and should be encouraged by promoting the construction of full-scale plants that utilize the latest technology advances.

- Aggressively pursue efforts to commercialize carbon capture and storage. Moving forward with full-scale demonstration projects is critical, as is continued study and experimentation to reduce costs, improve reliability, and address concerns about leakage, public safety, and other issues. For capture and sequestration to be widely implemented, it will be necessary to develop regulations and to introduce price signals for carbon emissions. Based on current cost estimates, the Study Panel believes price signals on the order of US$100–150 per avoided metric ton of carbon equivalent (US$27–41 per ton of carbon dioxide equivalent) will be required to induce the widespread adoption of carbon capture and storage. Price signals at this level would also give impetus to the accelerated deployment of biomass and other renewable energy technologies.
- Explore potential retrofit technologies for post-combustion carbon capture suitable for the large and rapidly growing population of existing pulverized coal plants. In the near term, efficiency improvements and advanced pollution control technologies should be applied to existing coal plants as a means of mitigating their immediate climate change and public health impacts.
- Pursue carbon capture and storage with systems that co-fire coal and biomass. This technology combination provides an opportunity to achieve net *negative* greenhouse gas emissions—effectively removing carbon dioxide from the atmosphere.

NEEDED ACTIONS

- The private sector and the S&T community should join forces to further investigate the possibilities for carbon capture and sequestration and develop adequate technologies for demonstration.
- Governments should facilitate the development of these technologies by making available funds and opportunities (such as test sites).
- The general public needs to be thoroughly informed about the advantages of carbon sequestration and about the relative manageability of associated risks. The media can assist with this.

CONCLUSION 4. Competition for oil and natural gas supplies has the potential to become a source of growing geopolitical tension and economic vulnerability for many nations in the decades ahead. In many developing countries, expenditures for energy imports also divert scarce resources from other urgent public health, education, and infrastructure development needs. The transport sector accounts for just 25 percent of primary energy consumption worldwide, but the lack of fuel diversity in this sector makes transport fuels especially valuable.

RECOMMENDATIONS

- Introduce policies and regulations that promote reduced energy consumption in the transport sector by (a) improving the energy efficiency of automobiles and other modes of transport and (b) improving the efficiency of transport *systems* (e.g., through investments in mass transit, better land-use and city planning, etc.).
- Develop alternatives to petroleum to meet the energy needs of the transport sector, including biomass fuels, plug-in hybrids, and compressed natural gas, as well as—in the longer run—advanced alternatives, such as hydrogen fuel cells.
- Implement policies to ensure that the development of petroleum alternatives is pursued in a manner that is compatible with other sustainability objectives. Current methods for liquefying coal and extracting oil from unconventional sources, such as tar sands and shale oil, generate substantially higher levels of carbon dioxide and other pollutant emissions compared to conventional

petroleum consumption. Even with carbon capture and sequestration, a liquid fuel derived from coal will at best produce emissions of carbon dioxide roughly equivalent to those of conventional petroleum at the point of combustion. If carbon emissions from the conversion process are *not* captured and stored, total fuel-cycle emissions for this energy pathway as much as double. The conversion of natural gas to liquids is less carbon intensive than coal to liquids, but biomass remains the only near-term feedstock that has the potential to be truly carbon-neutral and sustainable on a long-term basis. In all cases, full fuel-cycle impacts depend critically on the feedstock being used and on the specific extraction or conversion methods being employed.

NEEDED ACTIONS

- Governments should introduce (further) policies and regulations aimed at reducing energy consumption and developing petroleum alternatives for use in the transport sector.
- The private sector and the S&T community should continue developing technologies adequate to that end.
- The general public's awareness of sustainability issues related to transportation energy use should be significantly increased. The media can play an important role in this effort.

CONCLUSION 5. As a low-carbon resource, nuclear power can continue to make a significant contribution to the world's energy portfolio in the future, but only if major concerns related to capital cost, safety, and weapons proliferation are addressed.

Nuclear power plants generate no carbon dioxide or conventional air pollutant emissions during operation, use a relatively abundant fuel feedstock, and involve orders-of-magnitude smaller mass flows, relative to fossil fuels. Nuclear's potential, however, is currently limited by concerns related to cost, waste management, proliferation risks, and plant safety (including concerns about vulnerability to acts of terrorism and concerns about the impact of neutron damage on plant materials in the case of life extensions). A sustained role for nuclear power will require addressing these hurdles.

RECOMMENDATIONS

- Replace the current fleet of aging reactors with plants that incorporate improved intrinsic (passive) safety features.
- Address cost issues by pursuing the development of standardized reactor designs.
- Understand the impact of long-term aging on nuclear reactor systems (e.g., neutron damage to materials) and provide for the safe and economic decommissioning of existing plants.
- Develop safe, retrievable waste management solutions based on dry cask storage as longer-term disposal options are explored. While long-term disposal in stable geological repositories is technically feasible, finding socially acceptable pathways to implement this solution remains a significant challenge.
- Address the risk that civilian nuclear materials and knowledge will be diverted to weapons applications (a) through continued research on proliferation-resistant uranium enrichment and fuel-recycling capability and on safe, fast neutron reactors that can burn down waste generated from thermal neutron reactors and (b) through efforts to remedy shortcomings in existing international frameworks and governance mechanisms.
- Undertake a transparent and objective re-examination of the issues surrounding nuclear power and their potential solutions. The results of such a re-examination should be used to educate the public and policymakers.

NEEDED ACTIONS

- Given the controversy over the future of nuclear power worldwide, the United Nations should commission—as soon as possible—a transparent and objective re-examination of the issues that surround nuclear power and their potential solutions. It is essential that the general public be informed about the outcome of this re-examination.
- The private sector and the S&T community should continue research and development efforts targeted at improving reactor safety and developing safe waste management solutions.
- Governments should facilitate the replacement of the current fleet of aging reactors with modern, safer plants. Governments and intergovernmental organizations should enhance their efforts to remedy shortcomings in existing international frameworks and governance mechanisms.

CONCLUSION 6. Renewable energy in its many forms offers immense opportunities for technological progress and innovation.

Over the next 30–60 years, sustained efforts must be directed toward realizing these opportunities as part of a comprehensive strategy that supports a diversity of resource options over the next century. The fundamental challenge for most renewable options involves cost-effectively tapping inherently diffuse and in some cases intermittent resources. Sustained, long-term support—in various forms—is needed to overcome these hurdles. Renewable energy development can provide important benefits in underdeveloped and developing countries because oil, gas, and other fuels are hard cash commodities.

RECOMMENDATIONS

- Implement policies—including policies that generate price signals for avoided carbon emissions—to ensure that the environmental benefits of renewable resources relative to non-renewable resources will be systematically recognized in the marketplace.
- Provide subsidies and other forms of public support for the early deployment of new renewable technologies. Subsidies should be targeted to promising but not-yet-commercial technologies and decline gradually over time.
- Explore alternate policy mechanisms to nurture renewable energy technologies, such as renewable portfolio standards (which set specific goals for renewable energy deployment) and 'reverse auctions' (in which renewable energy developers bid for a share of limited public funds on the basis of the *minimum* subsidy they require on a per kilowatt-hour basis).
- Invest in research and development on more transformational technologies, such as new classes of solar cells that can be made with thin-film, continuous fabrication processes. (See also biofuels recommendations #7.)
- Conduct sustained research to assess and mitigate any negative environmental impacts associated with the large-scale deployment of renewable energy technologies. Although these technologies offer many environmental benefits, they may also pose new environmental risks as a result of their low power density and the consequently large land area required for large-scale deployment.

NEEDED ACTIONS

- Governments should substantially facilitate the use—in an environmentally sustainable way—of renewable energy resources through adequate policies and subsidies. A major policy step in this direction would include implementing clear price signals for avoided greenhouse gas emissions.
- Governments should also promote research and development in renewable energy technologies by

supplying significantly more public funding.

- The private sector, aided by government subsidies, should seek entrepreneurial opportunities in the growing renewable energy market.
- The S&T community should devote more attention to overcoming the cost and technology barriers that currently limit the contribution of renewable energy sources.
- NGOs can assist in promoting the use of renewable energy sources in developing countries.
- The media can play an essential role in heightening the general public's awareness of issues related to renewable energy.

CONCLUSION 7. Biofuels hold great promise for simultaneously addressing climate-change and energy-security concerns.

Improvements in agriculture will allow for food production adequate to support a predicted peak world population on the order of 9 billion people with excess capacity for growing energy crops. Maximizing the potential contribution of biofuels requires commercializing methods for producing fuels from lignocellulosic feedstocks (including agricultural residues and wastes), which have the potential to generate five to ten times more fuel than processes that use starches from feedstocks, such as sugar cane and corn. Recent advances in molecular and systems biology show great promise in developing improved feedstocks and much less energy-intensive means of converting plant material into liquid fuel. In addition, intrinsically more efficient conversion of sunlight, water, and nutrients into chemical energy may be possible with microbes.

RECOMMENDATIONS

- Conduct intensive research into the production of biofuels based on lignocellulose conversion.
- Invest in research and development on direct microbial production of butanol or other forms of biofuels that may be superior to ethanol.
- Implement strict regulations to insure that the cultivation of biofuels feedstocks accords with sustainable agricultural practices and promotes biodiversity, habitat protection, and other land management objectives.
- Develop advanced bio-refineries that use biomass feedstocks to self-generate power and extract higher-value co-products. Such refineries have the potential to maximize economic and environmental gains from the use of biomass resources.
- Develop improved biofuels feedstocks through genetic selection and/or molecular engineering, including drought resistant and self-fertilizing plants that require minimal tillage and fertilizer or chemical inputs.
- Mount a concerted effort to collect and analyze data on current uses of biomass by type and technology (both direct and for conversion to other fuels), including traditional uses of biomass.
- Conduct sustained research to assess and mitigate any adverse environmental or ecosystem impacts associated with the large-scale cultivation of biomass energy feedstocks, including impacts related to competition with other land uses (including uses for habitat preservation and food production), water needs, etc.

NEEDED ACTIONS

- The S&T community and the private sector should greatly augment their research and development (and deployment) efforts toward more efficient, environmentally sustainable technologies and processes for the production of modern biofuels.
- Governments can help by stepping up public research and development funding and by adapting existing subsidy and fiscal policies so as to

favor the use of biofuels over that of fossil fuels, especially in the transport sector.
- Governments should pay appropriate attention to promoting sustainable means of biofuels production and to avoiding conflicts between biofuel production and food production.

CONCLUSION 8. The development of cost-effective energy storage technologies, new energy carriers, and improved transmission infrastructure could substantially reduce costs and expand the contribution from a variety of energy supply options.
Such technology improvements and infrastructure investments are particularly important to tap the full potential of intermittent renewable resources, especially in cases where some of the most abundant and cost-effective resource opportunities exist far from load centers. Improved storage technologies, new energy carriers, and enhanced transmission and distribution infrastructure will also facilitate the delivery of modern energy services to the world's poor—especially in rural areas.

RECOMMENDATIONS

- Continue long-term research and development into potential new energy carriers for the future, such as hydrogen. Hydrogen can be directly combusted or used to power a fuel cell and has a variety of potential applications, including as an energy source for generating electricity or in other stationary applications and as an alternative to petroleum fuels for aviation and road transport. Cost and infrastructure constraints, however, are likely to delay widespread commercial viability until mid-century or later.
- Develop improved energy storage technologies, either physical (e.g., compressed air or elevated water storage) or chemical (e.g., batteries, hydrogen, or hydrocarbon fuel produced from the reduction of carbon dioxide) that could significantly improve the market prospects of intermittent renewable resources, such as wind and solar power.
- Pursue continued improvements and cost reductions in technologies for transmitting electricity over long distances. High-voltage, direct-current transmission lines, in particular, could be decisive in making remote areas accessible for renewable energy development, improving grid reliability, and maximizing the contribution from a variety of low-carbon electricity sources. In addition, it will be important to improve overall grid management and performance through the development and application of advanced or 'smart' grid technologies that could greatly enhance the responsiveness and reliability of electricity transmission and distribution networks.

NEEDED ACTIONS

- The S&T community, together with the private sector, should have focus on research and development in this area
- Governments can assist by increasing public funding for research and development and by facilitating needed infrastructure investments.

CONCLUSION 9. The S&T community—together with the general public—has a critical role to play in advancing sustainable energy solutions and must be effectively engaged.
As noted repeatedly in the foregoing recommendations, the energy challenges of this century and beyond demand sustained progress in developing, demonstrating, and deploying new and improved energy technologies. These advances will need to come from the S&T community, motivated and supported by appropriate policies, incentives, and market drivers.

RECOMMENDATIONS

- Provide increased funding for public investments in sustainable energy research and development, along with incentives and market signals to promote increased private-sector investments.
- Effect greater coordination of technology efforts internationally, along with efforts to focus universities and research institutions on the sustainability challenge.
- Conduct rigorous analysis and scenario development to identify possible combinations of energy resources and end-use and supply technologies that have the potential to simultaneously address the multiple sustainability challenges linked to energy.
- Stimulate efforts to identify and assess specific changes in institutions, regulations, market incentives, and policy that would most effectively advance sustainable energy solutions.
- Create an increased focus on specifically energy-relevant awareness, education, and training across all professional fields with a role to play in the sustainable energy transition.
- Initiate concerted efforts to inform and educate the public about important aspects of the sustainable energy challenge, such as the connection between current patterns of energy production and use and critical environmental and security risks.
- Begin enhanced data collection efforts to support better decisionmaking in important policy areas that are currently characterized by a lack of reliable information (large cities in many developing countries, for example, lack the basic data needed to plan effectively for transportation needs).

NEEDED ACTIONS

- The S&T community must strive for better international coordination of energy research and development efforts, partly in collaboration with the private sector. It should seek to articulate a focused, collaborative agenda aimed at addressing key obstacles to a sustainable energy future.
- Governments (and intergovernmental organizations) must make more public funding available to not only boost the existing contribution from the S&T community but also to attract more scientists and engineers to working on sustainable energy problems.
- The why and how of energy research and development should be made transparent to the general public to build support for the significant and sustained investments that will be needed to address long-term sustainability needs.
- The S&T community itself, intergovernmental organizations, governments, NGOs, the media, and—to a lesser extent—the private sector should be actively engaged in educating the public about the need for these investments.

Lighting the way

While the current energy outlook is very sobering, the Study Panel believes that there are sustainable solutions to the energy problem. Aggressive support of energy science and technology must be coupled with incentives that accelerate the concurrent development and deployment of innovative solutions that can transform the entire landscape of energy demand and supply. Opportunities to substitute superior supply-side and end-use technologies exist throughout the world's energy systems, but current investment flows generally do not reflect these opportunities.

Science and engineering provide guiding principles for the sustainability agenda. Science provides the basis for a rational discourse about trade-offs and risks, for selecting research and development priorities, and for identifying new opportunities—openness is one of its dominant values. Engineering,

through the relentless optimization of the most promising technologies, can deliver solutions—learning by doing is among its dominant values. Better results will be achieved if many avenues are explored in parallel, if outcomes are evaluated with actual performance measures, if results are reported widely and fully, and if strategies are open to revision and adaptation.

Long-term energy research and development is thus an essential component of the pursuit of sustainability. Significant progress can be achieved with existing technology but the scale of the long-term challenge will demand new solutions. The research community must have the means to pursue promising technology pathways that are already in view and some that may still be over the horizon.

The transition to sustainable energy systems also requires that market incentives be aligned with sustainability objectives. In particular, robust price signals for avoided carbon emissions are critical to spur the development and deployment of low-carbon energy technologies. Such price signals can be phased in gradually, but expectations about how they will change over time must be established in advance and communicated clearly so that businesses can plan with confidence and optimize their long-term capital investments.

Critical to the success of all the tasks ahead are the abilities of individuals and institutions to effect changes in energy resources and usage. Capacity building, both in terms of investments in individual expertise and institutional effectiveness, must become an urgent priority of all principal actors: multi-national organizations, governments, corporations, educational institutions, non-profit organizations, and the media. Above all, the general public must be provided with sound information about the choices ahead and the actions required for achieving a sustainable energy future.

1. The sustainable energy challenge

Humankind has faced daunting problems in every age, but today's generation confronts a unique set of challenges. The environmental systems on which all life depends are being threatened locally, regionally, and at a planetary level by human actions. And even as great numbers of people enjoy unprecedented levels of material prosperity, a greater number remains mired in chronic poverty, without access to the most basic of modern services and amenities and with minimal opportunities for social (e.g., educational) and economic advancement. At the same time, instability and conflict in many parts of the world have created profound new security risks.

Energy is critical to human development and connects in fundamental ways to all of these challenges. As a result, the transition to sustainable energy resources and systems provides an opportunity to address multiple environmental, economic, and development needs. From an environmental perspective, it is becoming increasingly clear that humanity's current energy habits must change to reduce significant public health risks, avoid placing intolerable stresses on critical natural systems, and, in particular, to manage the substantial risks posed by global climate change. By spurring the development of alternatives to today's conventional fuels, a sustainable energy transition could also help to address the energy security concerns that are again at the forefront of many nations' domestic and foreign policy agendas, thereby reducing the likelihood that competition for finite and unevenly distributed oil and gas resources will fuel growing geopolitical tensions in the decades ahead. Finally, increased access to clean, affordable, high-quality fuels and electricity could generate multiple benefits for the world's poor, easing the day-to-day struggle to secure basic means of survival; enhancing educational opportunities; reducing substantial pollution-related health risks; freeing up scarce capital and human resources; facilitating the delivery of essential services, including basic medical care; and mitigating local environmental degradation.

Energy, in short, is central to the challenge of sustainability in all its dimensions: social, economic, and environmental. To this generation falls the task of charting a new course. Now and in the decades ahead no policy

The term 'sustainable energy' is used throughout this report to denote energy systems, technologies, and resources that are not only capable of supporting long-term economic and human development needs, but that do so in a manner compatible with (1) preserving the underlying integrity of essential natural systems, including averting catastrophic climate change; (2) extending basic energy services to the more than 2 billion people worldwide who currently lack access to modern forms of energy; and (3) reducing the security risks and potential for geopolitical conflict that could otherwise arise from an escalating competition for unevenly distributed oil and natural gas resources. In other words, the term 'sustainable' in this context encompasses a host of policy objectives beyond mere supply adequacy.

objective is more urgent than that of finding ways to produce and use energy that limit environmental degradation, preserve the integrity of underlying natural systems, and support rather than undermine progress toward a more stable, peaceful, equitable, and humane world. Many of the insights, knowledge, and tools needed to accomplish this transition already exist but more will almost certainly be needed. At bottom the decisive question comes down to this: *Can we humans collectively grasp the magnitude of the problem and muster the leadership, endurance, and will to get the job done?*

1.1 The scope of the challenge

Linkages between energy use and environmental quality have always been apparent, from the deforestation caused by fuelwood use even in early societies to the high levels of local air and water pollution that have commonly accompanied the early phases of industrialization. In recent decades, advances in scientific understanding and in monitoring and measurement capabilities have brought increased awareness of the more subtle environmental and human-health effects associated with energy production, conversion, and use. Fossil-fuel combustion is now known to be responsible for substantial emissions of air pollutants—including sulfur, nitrogen oxides, hydrocarbons, and soot—that play a major role in the formation of fine particulate matter, ground-level ozone, and acid rain; energy use is also a major contributor to the release of long-lived heavy metals, such as lead and mercury, and other hazardous materials into the environment. Energy-related air pollution (including poor indoor air quality from the use of solid fuels for cooking and heating) not only creates substantial public health risks, especially where emission controls are limited or nonexistent, it harms ecosystems, degrades materials and structures, and impairs agricultural productivity. In addition, the extraction, transport, and processing of primary energy sources such as coal, oil, and uranium are associated with a variety of damages or risks to land, water, and ecosystems while the wastes generated by some fuel cycles—notably nuclear electricity production—present additional disposal issues.

Although the most obvious environmental impacts from energy production and use have always been local, significant impacts—including the long-range transport of certain pollutants in the atmosphere—are now known to occur on regional, continental, and even transcontinental scales.

And at a global level, climate change is emerging as the most consequential and most difficult energy-environment linkage of all. The production and use of energy contributes more than any other human activity to the change in *radiative forcing* that is currently occurring in the atmosphere;[1] in fact, fossil-fuel combustion alone currently accounts for well over half of total greenhouse gas emissions worldwide (after accounting for different gases' carbon dioxide equivalent warming potential). Since the dawn of the industrial era, carbon dioxide levels in the atmosphere have increased by about 40 percent; going forward, trends in energy production, conversion, and use—more than any other factor within human control—are likely to determine how quickly those levels continue to rise, and how far. The precise implications of the current trajectory remain unknown, but there is less and less doubt that the risks are large and more and more evidence that human-induced global warming is already underway. In its recent, Fourth Assessment report, for example, the Intergovernmental Panel on Climate Change (IPCC) concluded that evidence for the warming of the Earth's climate system was now 'unequivocal' and identified a number of potential adverse impacts associated with continued warming, including increased risks to coasts, ecosystems, fresh-water resources, and human health (IPCC, 2007a: p. 5; and 2007b) . In this context, making the transition to lower-carbon energy options is widely acknowledged as a central imperative in the effort to reduce climate-change risks.

Another issue that will continue to dominate regional, national, and international energy policy debates over the next several decades is energy security. Defined as access to adequate supplies of energy when needed, in the form needed, and at affordable prices, energy security remains a central priority for all nations concerned with promoting healthy economic growth and maintaining internal as well as external stability. In the near to medium term, energy security concerns are almost certain to focus on oil and, to a lesser extent, on natural gas. As demand for these resources grows and as reserves of relatively cheap and readily accessible supplies decline in many parts of the world, the potential for supply disruptions, trade conflicts, and price shocks is likely to increase. Already, there is concern that the current environment of tight supplies and high and volatile prices is exacerbating trade imbalances, slowing global economic growth, and directly or indirectly complicating efforts to promote international peace and security. The problem is particularly acute for many

1 Radiative forcing is a measure of the warming effect of the atmosphere. It is typically expressed in watts per square meter.

developing countries that devote a large fraction of their foreign exchange earnings to oil imports, thus reducing the resources available to support investments needed for economic growth and social development.

Providing the energy services needed to sustain economic growth and, conversely, avoiding a situation where lack of access to such services constrains growth and development, remains a central policy objective for all nations, and an especially important challenge for developing nations given the substantial resource and capital investments that will be required. Within that larger context, a third important set of issues (in addition to the environmental and energy-security issues noted above) concerns the specific linkages between access to energy services, poverty alleviation, and human development. These linkages have recently drawn increased international attention and were a major focus of the 2002 World Summit for Sustainable Development in Johannesburg, which recognized the importance of expanded access to reliable and affordable energy services as a prerequisite for achieving the United Nation's Millennium Development Goals.[2] These linkages are discussed in detail in other reports (notably in the 2000 and 2004 World Energy Assessments undertaken by the United Nations Development Programme, United Nations Department of Economic and Social Affairs, and World Energy Council) and summarized in Box 1.1 (DFID, 2002).

In brief, substantial inequalities in access to energy services now exist, not only between countries but between populations within the same country and even between households within the same town or village. In many developing countries, a small elite uses energy in much the same way as in the industrialized world, while most of the rest of the population relies on traditional, often poor-quality and highly polluting forms of energy. It is estimated that today roughly 2.4 billion people use charcoal, firewood, agricultural residues, or dung as their primary cooking fuel, while some 1.6 billion people worldwide live without electricity.[3] Without

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2 Millenniun Development Goals (MDG) call for halving poverty in the world's poorest countries by 2015. According to a United Nations (2005: p. 8)) report, The link between energy services and poverty reduction was explicity identified by the World Summit for Sustainable Development (WSSD) in the Johannesbury Plan of Implementation (JPOI), which called for the international community to 'Take joint actions and improve efforts to work together at all levels to improve access to reliable and affordable energy services for sustainable development sufficient to facilitate the achievement of the MDGs, including the goal of halving the proportion of people in poverty by 2015, and as a means to generate other important services that mitigate poverty, bearing in mind that access to energy facilitates the eradication of poverty'.

3 Data on the numbers of people without access to modern energy services are at best highly

Box 1.1 Energy and the Millennium Development Goals

Energy services can play a variety of direct and indirect roles in helping to achieve the Millennium Development Goals:

To halve extreme poverty. Access to energy services facilitates economic development – micro-enterprise, livelihood activities beyond daylight hours, locally owned businesses, which will create employment – and assists in bridging the 'digital divide. '

To reduce hunger and improve access to safe drinking water. Energy services can improve access to pumped drinking water and provide fuel for cooking the 95 percent of staple foods that need cooking before they can be eaten.

To reduce child and maternal mortality; and to reduce diseases. Energy is a key component of a functioning health system, contributing, for example, to lighting operating theatres, refrigerating vaccines and other medicines, sterilizing equipment, and providing transport to health clinics.

To achieve universal primary education, and to promote gender equality and empowerment of women. Energy services reduce the time spent by women and children (especially girls) on basic survival activities (gathering firewood, fetching water, cooking, etc.); lighting permits home study, increases security, and enables the use of educational media and communications in schools, including information and communication technologies.

To ensure environmental sustainability. Improved energy efficiency and use of cleaner alternatives can help to achieve sustainable use of natural resources, as well as reduce emissions, which protects the local and global environment.

access to affordable, basic labor-saving devices or adequate lighting and compelled to spend hours each day gathering fuel and water, vast numbers of people, especially women and girls, are deprived of economic and educational opportunities; in addition, millions are exposed to substantial health risks from indoor air pollution caused by traditional cooking fuels. The challenge of expanding access to energy services revolves primarily around issues of social equity and distribution—the fundamental problem is not one of inadequate global resources or of a lack of available technologies. Addressing the basic energy needs of the world's poor is clearly central to the larger goal of sustainable development and must be a top priority for developing countries in the years ahead if some dent is to be made in reducing current inequities.

1.2 The scale of the challenge

The scale of the sustainable energy challenge is illustrated by a quick review of current consumption patterns and of the historic linkages between energy use, population, and economic growth. Human development to the end of the 18th century was marked by only modest rates of growth in population, per capita income, and energy use. As the Industrial Revolution gathered pace, this began to change. Over the last century alone, world population grew 3.8 times, from 1.6 to 6.1 billion people; worldwide average per capita income increased nine-fold (to around US$8,000 per person in 2000)[4]; annual primary energy use rose by a similar amount (ten-fold) to 430 exajoules (EJ); and fossil-fuel use alone increased twenty-fold.[5]

Throughout this period, energy use in many countries followed a common pattern. As societies began to modernize and shift from traditional forms of energy (such as wood, crop residues, and dung) to commercial forms of energy (liquid or gaseous fuels and electricity), their energy consumption per capita and per unit of economic output (gross domestic product) often grew rapidly. At a later stage of development,

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approximate and vary depending on the source consulted. Hence it is probably more appropriate to focus on the fact that available data point to a significant fraction of the world's population rather than on the specific numeric figures cited by different sources.

4 In 2000, the gross world product on a purchasing power parity basis was US$49 trillion (population 6.1 billion).

5 Estimates for 1900 vary from 37 to 50 EJ, an estimate of 40 EJ is used here; and estimates for 2000 vary from 400 to 440 EJ and an estimate of 430 EJ is used here [1 EJ equals 109 gigajoules (GJ); 1 GJ equals 0.17 barrels of oil equivalent equals 0.027 million cubic meters (mcm) gas equals 0.04 metric ton (mt) coal equals 0.28 megawatt-hour.]

however, further growth in energy consumption typically slowed as the market for energy-using devices reached a point of saturation and as wealthier economies shifted away from more energy-intensive manufacturing and toward a greater role for the less energy-intensive service sector. The rate of growth in energy consumption also diminished in some industrialized countries as a result of concerted energy efficiency and conservation programs that were launched in the wake of sharp oil price increases in the early 1970s. Figure 1.1 shows declining energy intensity trends for OECD and non-OECD countries over the last 18 years.

In recent years, the energy intensity of the world's industrialized economies has been declining at an average annual rate of 1.1 percent per year, while the energy intensity of the non-OECD economies has been declining, on average, even faster (presumably because these economies start from a base of higher intensity and lower efficiency). Because the rate of decline in energy intensity has generally not been sufficient to offset GDP growth, total energy consumption has continued to grow in industrialized countries and is growing even faster in many developing countries.

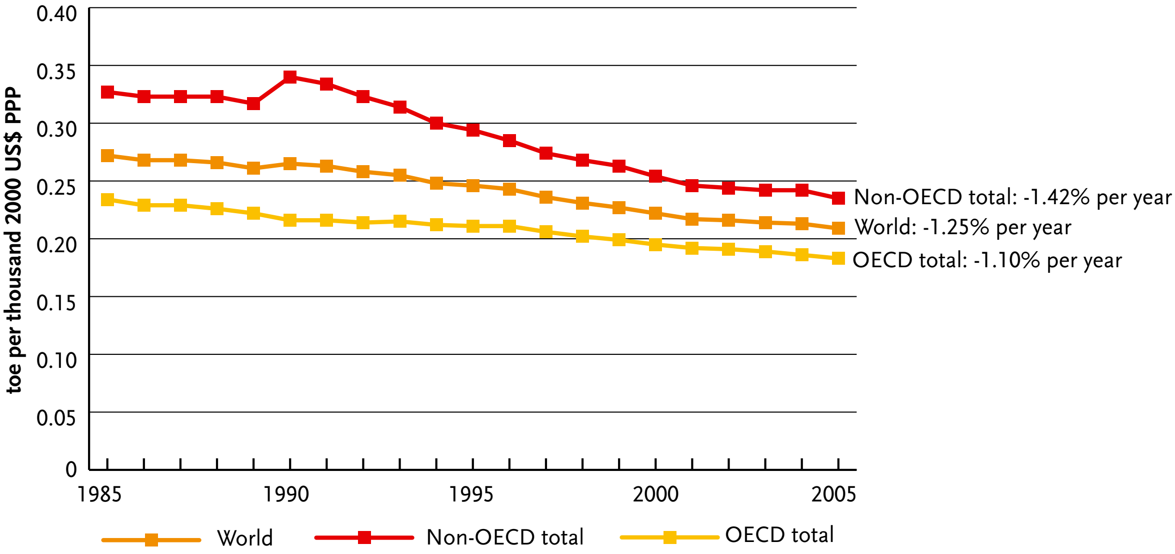

Figure 1.1 Energy intensity versus time, 1985-2005

Note: TPES is total primary energy supply; GDP is gross domestic product; PPP is purchasing power parity; toe is ton oil equivalent.

Source: IEA, 2005

Looking ahead, current projections suggest that the world's population will grow by another 50 percent over the first half of this century (to approximately 9 billion by 2050), world income will roughly quadruple,[6] and energy consumption will either double or triple, depending on the pace of future reductions in energy intensity. But projections are notoriously unreliable: patterns of development, structural economic shifts, population growth, and lifestyle choices will all have a profound impact on future trends. As discussed later in this report, even small changes in average year-to-year growth or in the rate of intensity reductions can produce very different energy and emissions outcomes over the course of several decades. Simply boosting the historical rate of decline in energy intensity from 1 percent per year to 2 percent per year on a global average basis, for example, would reduce energy demand in 2030 by 26 percent below the business-as-usual base case. Numerous engineering analyses suggest that intensity reductions of this magnitude could be achieved by concerted investments in energy efficiency over the next half century, but even seemingly modest changes in annual average rates of improvement can be difficult to sustain in practice, especially over long periods of time, and may require significant policy commitments.

Confronted with the near certainty of continued growth in overall energy demand, even with concerted efforts to further improve efficiency, reduce energy intensity, and promote a more equitable distribution of resources, the scale of the sustainability challenge becomes more daunting still when one considers the current mix of resources used to meet human energy needs. Figure 1.2 shows total primary energy consumption for the OECD countries, developing countries, and transition economies (where the latter category chiefly includes Eastern European countries and the former Soviet Union), while Figures 1.3 and 1.4 show global primary energy consumption and global electricity production, broken down by fuel source.

Non-renewable, carbon-emitting fossil fuels (coal, oil, and natural gas) account for approximately 80 percent of world primary energy consumption (Figure 1.3). Traditional biomass comprises the next largest share (10 percent) while nuclear, hydropower, and other renewable resources (including modern biomass, wind, and solar power), respectively, account for 6, 2, and 1 percent of the total. Figure 1.4 shows the mix of fuels used to generate electricity worldwide. Again, fossil fuels—primarily coal and

6 To a gross world product on a purchasing price parity basis of US$196 trillion (USDOE, 2006).

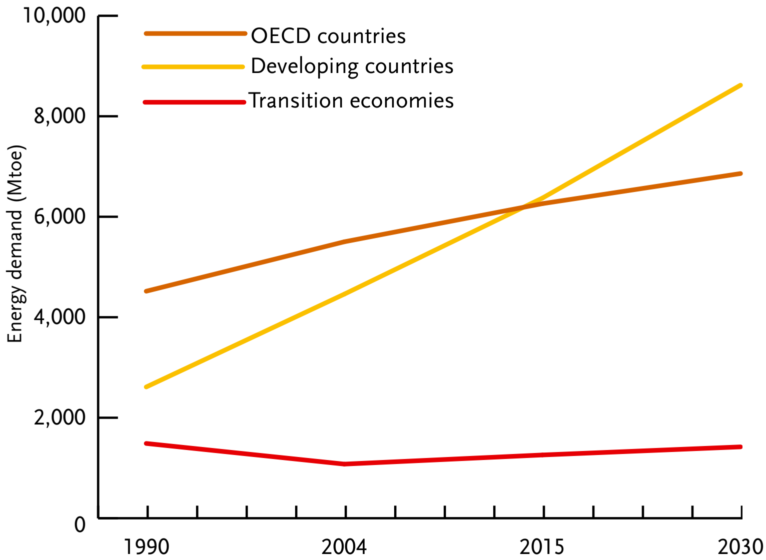

Figure 1.2 Regional shares in world primary energy demand, including business-as-usual projections

Note: 1 megaton oil equivalent (Mtoe) equals 41.9 petajoules.

Source: IEA, 2006

natural gas—dominate the resource mix, accounting for two-thirds of global electricity production. The nuclear and hydropower contributions are roughly equal at 16 percent of the total,[7] while non-hydro renewables account for approximately 2 percent of global production.

Most projections indicate that fossil fuels will continue to dominate the world's energy mix for decades to come, with overall demand for these fuels and resulting carbon emissions rising accordingly.[8]

Table 1.1 shows a reference case projection for future energy demand developed by the International Energy Agency (IEA) based largely on business-as-usual assumptions. It must be emphasized that these projections

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7 Note that Figure 1.3 shows the nuclear power contribution to primary energy supply as roughly three times the hydropower contribution, even though as noted in the text and in Figure 1.4 electricity production from these two sources worldwide is roughly equal. This is because the thermal energy generated at a nuclear power plant is included as primary energy in Figure 1.3 (an accounting convention that may be justified because this thermal energy could, in principle, be used).

8 Typically fossil fuel supply would double by 2050 accounting for over 60 percent of primary energy supply [IEA estimates for 2030 are 82 percent].

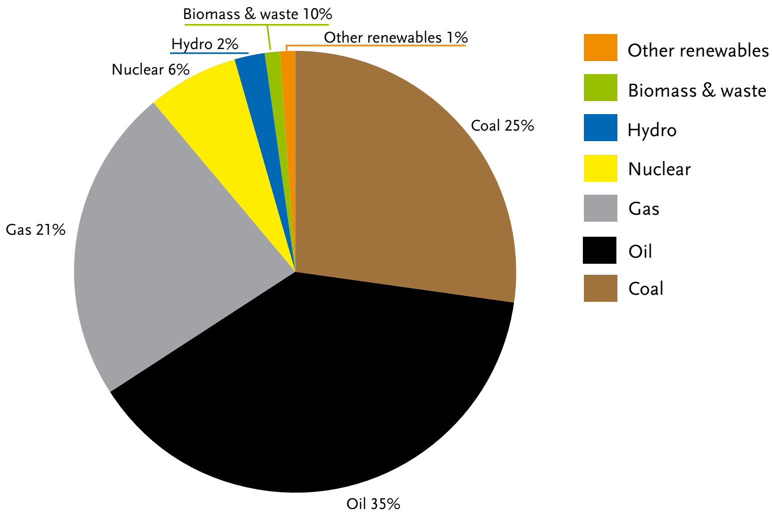

Figure 1.3 World primary energy consumption by fuel, 2004

Note: Total world primary energy consumption in 2004 was 11,204 megatons oil equivalent (or 448 exajoules).

Source: IEA, 2006

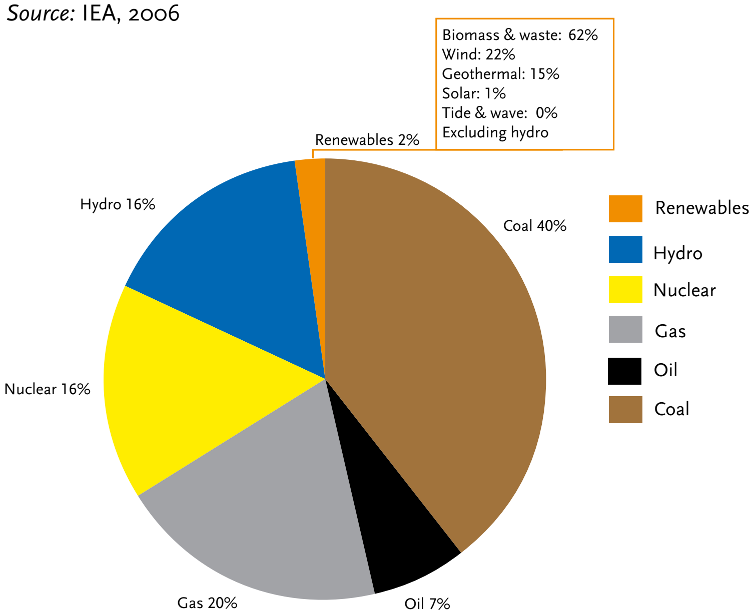

Figure 1.4 World electricity production by energy source, 2004

Note: Total world electricity production in 2004 was 17,408 terawatt-hours (or 63 exajoules).

Source: IEA, 2006.

Table 1.1 World primary energy demand by fuel

	Million ton oil equivalent (Mtoe)					Average annual growth rate
	1980	**2004**	**2010**	**2015**	**2030**	**2004-2030**
Coal	1,785	2,773	3,354	3,666	4,441	1.8%
Oil	3,107	3,940	4,366	4,750	5,575	1.3%
Gas	1,237	2,302	2,686	3,017	3,869	2.0%
Nuclear	186	714	775	810	861	0.7%
Hydro	148	242	280	317	408	2.0%
Biomass and waste	765	1,176	1,283	1,375	1,645	1.3%
Other renewables	33	57	99	136	296	6.6%
Total	7,261	11,204	12,842	14,071	17,095	1.6%

Note: 1 million ton oil equivalent equals 41.9 petajoules.

Source: IEA 2006

do not incorporate sustainability constraints (such as mitigation measures that might be necessary to manage climate risks)—as such, they are not intended to portray an inevitable future, much less a *desirable* one. Rather the usefulness of such projections lies in their ability to illuminate the consequences of allowing current trends to continue. For example, IEA's reference case projections assume moderate growth in the use of renewable energy technologies. But since non-hydro renewables accounted for only 2 percent of world electricity production in 2004, fossil-fuel consumption and global carbon emissions continue to grow strongly by 2030. Indeed current forecasts suggest that a continuation of business-as-usual trends will produce a roughly 55 percent increase in carbon dioxide emissions over the next two decades.

The implications of these projections, from a climate perspective alone, are sobering. If the trends projected by IEA for the next quarter century continue beyond 2030, the concentration of carbon dioxide in the atmosphere would be on track to reach 540–970 parts per million by 2100—anywhere from two to three times the pre-industrial concentration of 280 parts per million. By contrast, it is increasingly evident that the responsible mitigation of climate-change risks will require significant reductions in global greenhouse gas emissions by mid-century. As part of its Fourth Assessment Report, the IPCC has identified numerous adverse impacts on water supplies, ecosystems, agriculture, coasts, and public health that would be predicted (with 'high' or 'very high' confidence) to accompany

continued warming. Moreover, the current IPCC assessment places the onset for several of these 'key impacts' at a global mean temperature change of 2–3 degrees Celsius (IPCC, 2007a: p 13). The IPCC further estimates that limiting global warming to a 2–3 degrees Celsius change will require stabilizing atmospheric concentrations of greenhouse gases somewhere in the range of 450–550 parts per million in carbon dioxide equivalent terms. Based on numerous IPCC-developed scenarios, achieving stabilization within this range could require absolute reductions in global emissions of as much as 30–85 percent compared to 2000 levels by mid-century (IPCC 2007b: p 23-5). Hence, a major goal of this report is to offer recommendations for shifting the world's current energy trajectory through the accelerated deployment of more efficient technologies and sustainable, low-carbon energy sources.

The consequences of current trends are also troubling, however, from an energy security perspective given the longer-term outlook for conventional oil supplies and given the energy expenditures and environmental impacts it implies, for countries struggling to meet basic social and economic-development needs. Recent forecasts suggest that a continuation of business-as-usual trends will produce a nearly 40 percent increase in world oil consumption by 2030, at a time when many experts predict that production of readily accessible, relatively cheap conventional oil will be rapidly approaching (or may have already reached) its peak. Moreover, IEA reference case projections, though they anticipate a substantial increase in energy consumption by developing countries, assume only modest progress over the next several decades toward reducing the large energy inequities that now characterize different parts of the world. This is perhaps not surprising insofar as the IEA projections are based on extrapolating past trends into the future; as such they do not account for the possibility that developing countries might follow a different trajectory than industrialized countries.

1.3 The need for holistic approaches

Beyond the scope and scale of the issues involved, the challenge of moving to sustainable energy systems is complicated by several additional factors. First is the fact that different policy objectives can be in tension (or even at odds), especially if approached in isolation. For example, efforts to improve energy security—if they led to a massive expansion of coal use without concurrent carbon sequestration—could significantly exacerbate climate

risks. Similarly, emulating historic patterns of industrialization in developing countries could, in a 21st century context, create substantial environmental and energy-security liabilities. Achieving sustainability almost certainly requires a holistic approach in which development needs, social inequities, environmental limits, and energy security are addressed—even if they cannot always be resolved at the same time. Priorities should be set, by region and by country.

Extending basic energy services to the billions of people who now lack access to electricity and clean cooking fuels, for example, could be accomplished in ways that would have only minimal impact on current levels of petroleum consumption and carbon dioxide emissions (Box 1.2). Indeed, closer examination of the relationship between energy consumption and human well-being suggests that a more equitable distribution of access to energy services is entirely compatible with accelerated progress toward addressing energy-security and climate-change risks. Figure 1.6 compares per capita consumption of electricity in different countries in terms of their Human Development Index (HDI) — a composite measure of well-being that takes into account life expectancy, education, and GDP.[9] The figure indicates that while a certain minimum level of electricity services is required to support human development, further consumption above that threshold is not necessarily linked to a higher HDI. Put another way, the figure indicates that a relatively high HDI (0.8 and above) has been achieved in countries where per capita levels of electricity consumption differ by as much as six-fold.

In fact, U.S. citizens now consume electricity at a rate of roughly 14,000 kilowawtt hour per person per year while Europeans enjoy similar standards of living using, on average, only 7,000 kilowatt-hours per person per year.[10] Improvements in energy efficiency represent one obvious opportunity to leverage multiple policy goals, but there are others — most notably, of course, changing the energy supply mix. To take an extreme example: if the resources used to meet energy needs were characterized by zero or near-zero greenhouse gas emissions, it would be possible to address climate-change risks without any reductions in consumption per se. In

9 The HDI is calculated by giving one-third weight to life expectancy at birth, one-third weight to education (both adult literacy and school enrollment), and one-third weight to per capita GDP (adjusted for purchasing power parity). It is worth noting that a graph that simply compares per capita GDP to energy (or electricity) consumption would show a considerably more linear relationship (UNDP, 2006).

10 Per capita electricity consumption in some European countries, such as Sweden and Norway, is higher than in the United States.

Box 1.2 A focus on cooking in the developing world

Clean, efficient stoves represent a major opportunity to extend energy and public health benefits to the billions of people who rely on traditional fuels for their household cooking needs.

Household energy ladder. Over 2.4 billion people in developing countries still rely on solid biomass fuels for their cooking needs. This number increases to 3 billion when the use of various types of coal for cooking is included. In fact, the use of solid biomass fuels for cooking accounts for as much as 30–90 percent of primary energy consumption in some developing countries. As incomes rise, people generally upgrade from dirtier fuels (animal dung, crop residues, wood, charcoal, and coal) to liquid fuels (kerosene) to gaseous fuels (liquid petroleum gas, natural gas, and biogas) and finally, sometimes, to electricity. Conversely, when prices of liquid and gaseous petroleum-based fuels rise, people tend to downgrade again to solid fuels—at least for certain tasks. As households move up the energy ladder, the fuels and stoves they use tend to become cleaner, more efficient, and easier to control—but also more costly. Because solid-fuel combustion for cooking is often inefficient and poorly controlled, the cost per meal prepared is generally not a simple function of the cost of the fuel or stove technology used.

Health and environmental impacts. The use of traditional fuels for cooking, often under poorly ventilated conditions, is a significant public health issue in many developing counties (Figure 1.5). Globally, exposure to smoke from household fuel combustion is estimated to be responsible for 1.6 million deaths annually, a death toll almost as high as that from malaria. Small children are disproportionately affected: they account for roughly 1 million of these deaths each year, usually from acute lower respiratory infections. Women are the next most affected group: they account for most of the remaining deaths, primarily from chronic pulmonary obstructive diseases (WHO, 2002).In addition to generating high levels of air pollution, extensive reliance on some traditional solid fuels—notably wood—can lead to unsustainable harvesting practices that in turn contribute to deforestation and generate other adverse impacts on local ecosystems. Moreover, some recent research suggests that biomass fuels used in cooking, even when they are harvested renewably (as crop residues and animal dung invariably are), can generate even higher overall greenhouse gas emissions than petroleum-fuel alternatives when emissions of non-carbon dioxide pollutants from incomplete combustion are accounted for (Smith and others, 2005).

Saving energy and saving lives. Several strategies have been tried in various places around the world to reduce the adverse impacts of cooking with solid fuels. Typically they combine simultaneous efforts to address three areas of opportunity: reducing exposure, reducing emissions, and using cleaner fuels. Options for reducing exposure include increasing ventilation, providing stoves with hoods or chimneys, and changing behavior. Options for reducing emissions include improving combustion efficiency, improving heat transfer efficiency, or preferably both. Fuel upgrades can involve switching to briquettes or charcoal (which creates problems of its own) and biogas. Several countries have subsidized shifts to kerosene and liquid petroleum gas in an effort to help poor households 'leapfrog' up the energy ladder. Smith (2002) has shown that if even a billion people switched from solid biomass cooking fuels to liquid petroleum gas, this would increase global emissions of carbon dioxide from fossil fuels by less than 1 percent. Emissions of greenhouse gases on an equivalent basis might actually decrease. Subsidizing cleaner fuels, however, suffers from several important drawbacks: it is expensive (India's expenditures for liquid petroleum gas subsidies exceed all its expenditures for education); it is inefficient (government subsidies often end up benefiting households that do not need them); and it can actually increase household spending on energy as subsidized fuels get diverted to other uses (for example, kerosene and liquid petroleum gasare often diverted to transportation uses). Some countries, notably China, have implemented very successful programs to replace traditional cookstoves with cleaner models. Elsewhere, as in India, such programs have had mixed results.

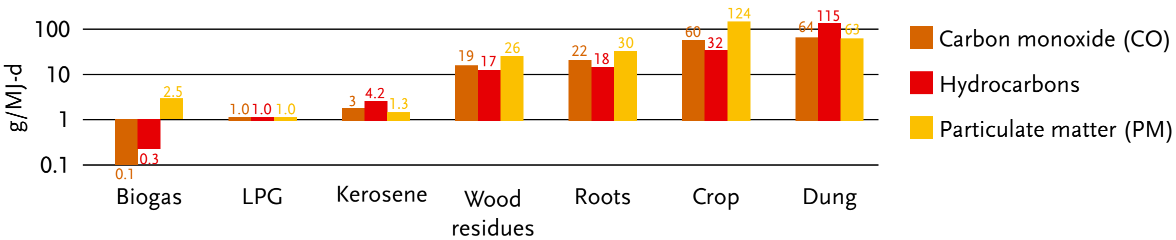

Figure 1.5 The energy ladder: Relative pollutant emissions per meal

Note: Health-damaging pollutants per unit energy delivered: ratio of emissions to liquid petroleum gas (LPG). Using a log scale in Figure 1.5, the values are shown as grams per megajoule (g/MJ-d) delivered to the cooking pot.

Source: Smith and others, 2005.

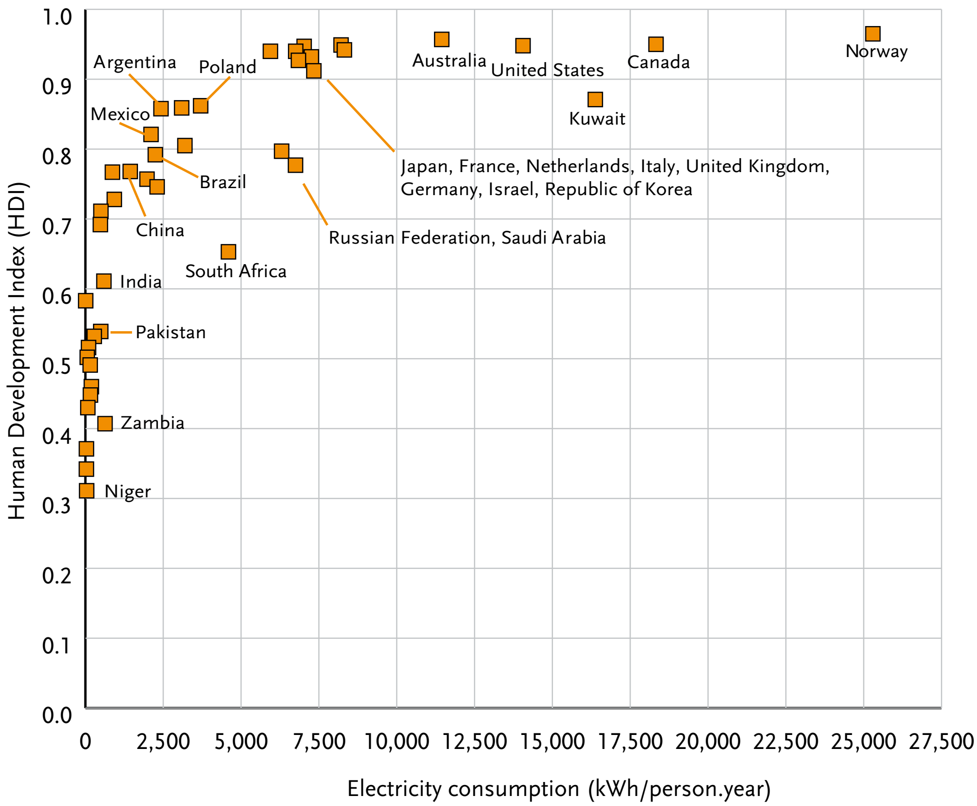

Figure 1.6 Relationship between human development index (HDI) and per capita electricity consumption, 2003 – 2004

Note: World average HDI equals 0.741. World average per capita annual electricity consumption, at 2,490 kWh per person.year, translates to approximately 9 gigajoules (GJ)/person.year [10,000 kilowatts (kWh) = 36 GJ]

Source: UNDP, 2006.

reality, of course, some combination of demand reductions and changes in the supply mix will almost certainly be necessary to meet the sustainability challenges of the coming century. Meanwhile, deploying renewable and other advanced, decentralized energy technologies can improve environmental quality, reduce greenhouse gas emissions, stimulate local economic development, reduce outlays for fuel imports, and make it more feasible to extend energy services to poor households, especially in remote rural areas.

Other factors complicate the sustainable energy challenge and further

underscore the need for holistic policy approaches. A high degree of inertia characterizes not only the Earth atmosphere climate system but also much of the energy infrastructure that drives energy-usage patterns, as well as the social and political institutions that shape market and regulatory conditions. Because the residence times of carbon dioxide and other greenhouse gases in the atmosphere are on the order of decades to centuries, atmospheric concentrations of greenhouse gases cannot be reduced quickly, even with dramatic cuts in emissions. Similarly, the momentum behind current energy consumption and emissions trends is enormous: the average automobile lasts more than ten years; power plants and buildings can last 50 years or longer; and major roads and railways can remain in place for centuries. The growth that has recently occurred in worldwide wind and solar energy capacity is heartening, but there are very few examples of new energy forms penetrating the market by indefinitely sustaining growth rates of more than 20 percent per year. Fundamental changes in the world's energy systems will take time, especially when one considers that new risks and obstacles almost always arise with the scaling up the deployment of new technologies, even if these risks and obstacles are hardly present when the technologies are first introduced. As a result, the process of transition is bound to be iterative and shaped by future developments and scientific advances that cannot yet be foreseen.

Precisely because there are unlikely to be any 'silver-bullet' solutions to the world's energy problems, it will be necessary to look beyond primary energy resources and production processes to the broader systems in which they are embedded. Improving the overall sustainability of these systems requires not only appropriate market signals—including prices that capture climate change impacts and other externalities associated with energy use—but may also demand higher levels of energy-related investment and new institutions. Most current estimates of energy sector investment go only so far as delivered energy, but investments in the devices and systems that use energy—including investments in buildings, cars or airplanes, boilers or air conditioners—will arguably matter as much, if not more.[11] In all likelihood, much of the required investment can be taken up in normal capital replacement processes. With estimated world income in 2005 of US$60 trillion (based on purchasing power parity) and an average capital investment rate close to US$1 trillion per month, there should be substantial scope to accelerate the deployment of improved technologies.

11 For example, IEA estimates of cumulative energy industry investments for 2004 2030 amount to US$17 trillion.

1.4 Summary points

The multiple linkages between energy, the environment, economic and social development, and national security complicate the task of achieving sustainable outcomes on the one hand and create potentially promising synergies on the other.

- **The scope and scale of the sustainable energy challenge require innovative, systemic solutions as well as new investments in infrastructure and technology**. Much of the infrastructure investment will need to happen anyway, but in most places the market and regulatory environment is not currently providing the feedback signals necessary to achieve a substantial shift in business-as-usual patterns. And by several measures, current worldwide investment in basic energy research and development is not adequate to the task at hand.[12]
- **Change will not come overnight.** Essential elements of the energy infrastructure have expected life of the order of one to several decades. That means the energy landscape of 2025 may not look that different from the energy landscape of today. Nevertheless, it will be necessary within the next decade to initiate a transition such that by 2020 new policies are in place, consumer habits are changing, and new technologies are gaining substantial market share.
- **The problem of unequal access to modern energy services is fundamentally a problem of distribution, not of inadequate resources or environmental limits.** It is possible to meet the needs of the 2 billion-plus people that today lack access to essential modern forms of energy (i.e., either electricity or clean cooking fuels) while only minimally changing the parameters of the task for everyone else. For example, it has been estimated that it would cost only US$50 billion to ensure that all households have access to liquid petroleum gas for cooking. Moreover, the resulting impact on global carbon dioxide emissions from fossil-fuel use would be on the order of 1or 2 percent (IEA, 2004; 2006). Reducing current inequities is a moral and social imperative and can be accomplished in ways that advance other policy objectives.
- **A substantial course correction cannot be accomplished in the time-frame needed to avoid significant environmental and energy-security risks if developing countries follow the historic energy trajectory of already industrialized countries.** Rich countries, which have consumed more than their share of the world's endowment of resources and of the

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12 Public investment in energy research and development (R&D) in 2005, by OECD and non-OECD countries, has been estimated at US$9 billion, or a mere 3.2 percent of all public R&D expenditures. Historically, private investment in energy R&D, as a percent of energy expenditures, has also been low compared with other technology sectors.

absorptive capacity of the planet's natural systems, have the ability and obligation to assist developing countries in 'leapfrogging' to cleaner and more efficient technologies.

- **To succeed, the quest for sustainable energy systems cannot be limited to finding petroleum alternatives for the transport sector and low-carbon means of generating electricity—it must also include a set of responsible and responsive demand-side solutions.** Those solutions must address opportunities at the city level (with special focus on the use of energy and water), new energy-industrial models (incorporating modern understanding of industrial ecology), and advanced mobility systems. In addition, it will be necessary to focus on opportunities at the point of end-use (cars, appliances, buildings, etc.) to implement the widest range of energy-saving options available. Most of the institutions that frame energy policy today have a strong supply-side focus. The needs of the 21st century call for stronger demand-side institutions with greater country coverage than is, for example, provided by the IEA with its largely indusrialized country membership.
- **Given the complexity of the task at hand and the existence of substantial unknowns, there is value in iterative approaches that allow for experimentation, trying out new technologies at a small scale and developing new options.** Science and engineering have a vital role to play in this process and are indispensable tools for finding humane, safe, affordable, and environmentally responsible solutions. At the same time, today's energy challenges present a unique opportunity for motivating and training a new generation of scientists and engineers.
- **The experience of the 20th century has demonstrated the power of markets for creating prosperous economies.** Market forces alone however will not create solutions to shared-resource problems that fall under the 'tragedy-of-the-commons' paradigm (current examples include international fishing, water and air pollution, and global warming emissions).[13] Governments have a vital role to play in defining the incentives, price signals, regulations, and other conditions that will allow the market to deliver optimal results. Government support is also essential where markets would otherwise fail to make investments that are in society's

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13 Tragedy of the commons refers to a situation where free access to a finite resource inevitably leads to over-exploitation of the resource because individuals realize private benefits from exploitation, whereas the costs of over-exploitation are diffuse and borne by a much larger group. As applied to the problem of climate change, the finite resource is the absorptive capacity of the Earth s atmosphere. As long as there is no restriction on emitting greenhouse gases and as long as the private cost to individual emitters does not reflect the public harm caused by their actions, overall emissions will exceed the amount that would be optimal from the standpoint of the common good.

long-term best interest; examples include certain types of infrastructure, basic research and development, and high-risk, high-payoff technologies.

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2. Energy demand and efficiency

The sustainability challenges outlined in Chapter 1 are enormous and will require major changes, not only in the way energy is supplied but in the way it is used. Efficiency improvements that reduce the amount of energy required to deliver a given product or provide a given service can play a major role in reducing the negative externalities associated with current modes of energy production. By moderating future demand growth, efficiency improvements can also 'buy time' to develop and commercialize new energy-supply solutions; indeed, enhanced efficiency may be essential to making some of those solutions feasible in the first place. The infrastructure hurdles and resource constraints that inevitably arise when scaling up new energy systems become much more manageable if energy losses are minimized all the way down the supply chain, from energy production to the point of end use.

The argument for end-use efficiency improvements is especially compelling when such improvements can (a) be implemented cost-effectively—in the sense that investing in the efficiency improvement generates returns (in future energy-cost savings) similar to or better than that of competing investments—and (b) result in the same level and quality of whatever service is being provided, whether that is mobility, lighting, or a comfortable indoor environment. In such cases, boosting energy efficiency is (by definition) less costly than procuring additional energy supplies; moreover, it is likely to be even more advantageous from a societal perspective when one takes into account the un-internalized environmental and resource impacts associated with most supply alternatives. Past studies, many of them based on a bottom-up, engineering analysis of technology potential, have concluded that cost-effective opportunities to improve end-use efficiency are substantial and pervasive across a multitude of energy-using devices—from buildings to cars and appliances—that are already ubiquitous in industrialized economies and being rapidly acquired in many developing ones. Skeptics caution, however, that such studies have often failed to account for, or have accounted only inadequately for, the power of human preferences and appetites, as well as for the complicated trade-offs and linkages that exist between the deployment of energy-saving technologies and long-term patterns of energy consumption and demand.

A comprehensive treatment of these trade-offs and linkages, together with a detailed analysis of how much end-use efficiency improvement could be achieved in different parts of the world within specified cost and time parameters is beyond the scope of this study. Such assessments must be approached with humility under any circumstances, given the difficulty of anticipating future technological advances and their impact on human behavior, tastes, and preferences. Modern life is full of examples of technologies that have improved quality of life and enhanced productivity for millions of people, while also directly or indirectly creating demand for wholly new products and services. Rapidly advancing frontiers in electronics, telecommunications, and information technology have had a particularly profound influence in recent decades and can be expected to continue generating new opportunities for efficiency gains along with new forms of economic activity and consumption. As noted in Chapter 1, over the last two decades, technology improvements have produced a modest (somewhat more than 1 percent per year on average) but steady decline in the energy intensity of the world economy—where intensity is measured by the ratio of economic output (gross world product) to primary energy consumption. This decline, however, has not been sufficient to offset growth in economic output and worldwide energy consumption in absolute terms has continued to rise.

Chapter 2 reviews, in broad terms, some of the technology opportunities that exist for boosting energy efficiency specific end-use sectors, along with some of the chief policy mechanisms that have been used at different times and in different contexts to promote such improvements[14]. It should be acknowledged at the outset that because the best data available on these topics are from Europe, Japan, and the United States much of the discussion in this chapter reflects an industrialized country bias. Nevertheless, the findings presented here are likely to be broadly relevant given similarities in the energy conversion and end-use technologies that have tended to be widely adopted around the world as economies industrialize and as personal incomes, at least for wealthy elites, rise. Around the world, people turn out to want much the same things—from refrigerators and air conditioners to televisions and cars. The near-universal desire for similar goods and amenities creates both a challenge and an opportunity to transfer technology improvements and lessons learned. Rapidly developing economies, in particular, have an opportunity to 'leapfrog' to more efficient technolo-

14 Unless otherwise specified, data used in this chapter are derived from the IEA (2004a and 2006a) World Energy Outlook reports

gies, which tend to produce larger benefits and be more cost-effective when they are incorporated from the ground up rather than being retrofitted at a later date in existing buildings, infrastructure, equipment, or processes. Moreover, the economic rationale for incorporating efficiency improvements is likely to be especially compelling—despite the fact that this is frequently disregarded—in the early phases of industrialization when energy-intensive basic materials tend to consume a larger share of economic resources.

In both industrialized and developing country contexts, however, market drivers alone are unlikely to deliver the full potential of cost-effective, end-use efficiency improvements, in part because of the well-documented existence of pervasive informational, organizational, behavioral, and other barriers. Real-world experience suggests that these barriers can be substantially reduced if the political will exists to shift the balance of information and incentives. How much of the gap between realized efficiency gains and engineering estimates of cost-effective potential can be explained by true market failures has been extensively debated, but it is clear that energy-saving opportunities often remain untapped, even in instances where efficiency improvements are cost-effective and offer favorable payback periods or high rates of return. It is already technically possible and cost-effective, for example, to construct buildings that meet or exceed modern standards of illumination, temperature control, and air quality using one-half the energy of conventional buildings. With further research and development to reduce costs and improve systems integration, the closer to 90 percent energy savings that have been achieved in individual demonstration buildings could likely be achieved in many new commercial structures. But wholesale changes in construction practices are unlikely to occur (or will occur only gradually) without concerted policy interventions.

In sum, efforts to improve the efficiency of downstream energy use must be seen as an essential complement to the transformation of upstream energy production and conversion systems. Both will be necessary to achieve sustainability objectives and both require action by governments to better align private incentives with public objectives.[15] As a first step it

15 A recent rise in energy prices especially for oil and natural gas can be expected to stimulate additional energy-efficiency investment throughout the global economy, especially if higher prices are sustained. But depending on the electricity supply mix, electricity prices are unlikely to be proportionately affected. Thus in the buildings sector, and even in other sectors that are more directly affected by oil and natural gas prices (e.g., transportation and industry) the overall effect of recent price increases is unlikely to be sufficient to fully overcome the market barriers to efficiency. A further consideration that could affect the argument for policy

will be important to recognize that opportunities for change on the demand-side are as rich as opportunities on the supply side and can produce equal or even larger benefits in many cases. Methods for directly comparing supply- and demand-side options have been developed for the electric utility sector under the rubric of integrated resource planning; in principle such methods could be applied in other planning contexts and in corporate decisionmaking. (An important supporting development in the utility sector has been the effort, in some jusridictions, to de-couple profits from energy sales so as to better align the incentives of energy-services providers with societal objectives.) At present, however, no industry is organized to deliver energy-efficiency improvements on the scale that exists for delivering energy carriers (such as oil, gas, or electricity). Finding business models for investing in and profiting from efficiency improvements therefore remains a key challenge. Energy services companies may fill some of this need.[16] In addition, several large corporations have recently initiated substantial in-house efforts to improve efficiency and reduce their energy costs.

2.1 Assessing the potential for energy-efficiency improvements

Improvements in the efficiency of energy transformation and use have long been tightly linked to the development of modern industrial societies. Almost two and a half centuries ago, the Watt steam engine improved on the efficiency of previous designs by a factor of three or more, ushering in a revolution in the practical application of steam power. This development led to any number of sweeping societal and technological improvements, but it also had the effect of increasing demand for coal. In fact, changes in the efficiency and precision with which energy can be put to use have played at least as large a role in driving the social transformations associated with industrialization as has the simple expansion of available energy supplies.

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intervention is that high prices can be expected to induce fuel switching along with reduced consumption. To the extent that fuel switching shifts consumption to more carbon-intensive fuels like coal, the effect of higher prices will not be automatically congruent with sustainability objectives.

16 Energy services companies are usually small companies that identify energy savings in enterprises through auditing and then perform the retrofitting measures needed either with their own capital or with capital made available by a financial institution. The investment is recovered by savings in the energy bill of the enterprise.

The technological and social dynamics that determine energy demand are of central importance to managing energy systems. Total demand for primary energy resources depends on both the efficiency of the processes used to convert primary energy to useful energy and the intensity with which useful energy is used to deliver services. For example, total demand for a primary resource like coal depends not only on the efficiency with which coal is converted to electricity (where efficiency is a dimensionless quantity that reflects the ratio of energy output to energy input in the conversion process),[17] but also on the intensity with which electricity is used to deliver services such as lighting or refrigeration.

Maximum energy savings can be achieved by comprehensively exploiting opportunities to improve conversion efficiencies and reduce end-use intensity throughout the energy supply chain, ideally also taking into account the lifecycle properties and content of different products, as well as the potential for substituting alternative products or services (Figure 2.1). To what extent theoretically available efficiency gains will be captured, however, depends on a number of factors. A first issue is obviously cost: many, if not most, consumer and company decisions are driven first and foremost by bottom-line considerations. Even where efficiency improvements are highly cost-effective (in the sense that the higher first cost of the more efficient technology is quickly recouped in energy-cost savings), they may be adopted only slowly; some of the reasons for this are reviewed in the discussion of market barriers in the next section.

Other factors that affect the uptake of new technology have to do with the social and economic systems in which energy use is embedded. Simply

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17 Maximum potential efficiency in this sense is governed by the first law of thermodynamics that essentially states energy is conserved (i.e., cannot be created or destroyed) and therefore the amount of energy lost in a closed system cannot be greater than the amount of energy gained in that system. The maximum efficiency of heat engines is governed by the second law of thermodynamics, which states that energy systems tend toward increased entropy. These physical laws are useful for determining the limits of what is possible in terms of the energy required to drive a given process. For example, capturing carbon dioxide from the atmosphere and concentrating it into a stream of gas that can be pumped underground for sequestration entails a reduction in entropy. Hence, the laws of thermodynamics allow one to calculate the minimum energy input that would be required to implement this process. The quality and monetary value of different forms of energy is also important, however. For example, when the chemical energy contained in the bonds of natural gas molecules is converted to lower-quality (thermal) energy in heated water, some ability to produce work (higher-quality energy) is lost. Thus, calculations of theoretical energy efficiency potential, only partly capture the economics of energy use since not all forms of energy have equal monetary value. Waste heat from a power plant is clearly not as valuable as the high temperature heat used to turn a steam turbine while the liquid fuels used for transportation because they have extremely high value in those applications are seldom used for space heating or electricity generation

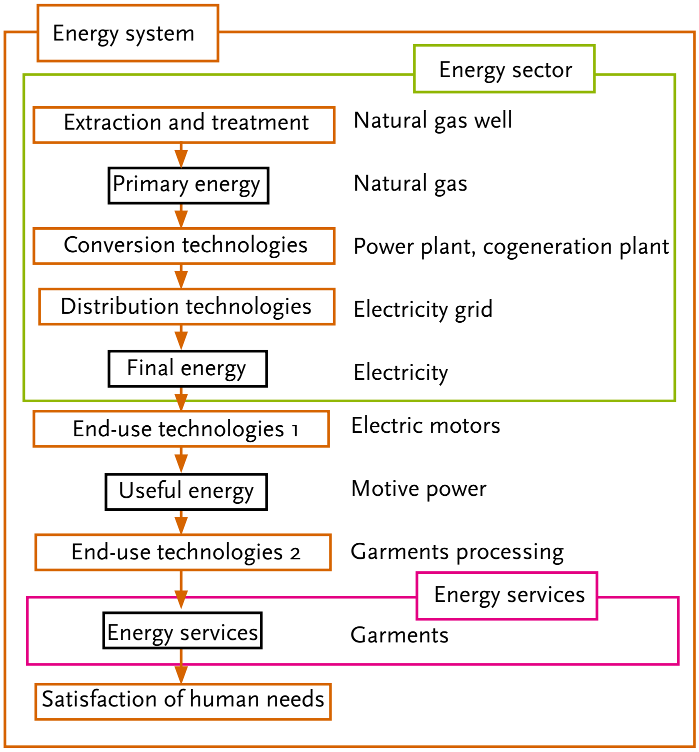

Figure 2.1 The energy chain

Note: Energy flow is shown from extraction of primary energy to provision of needed services.

Source: UNDP, UNDESA, and WEC, 2004.

replacing an incandescent light bulb, which typically produces 10–15 lumens per watt, with a compact fluorescent that delivers over 50 lumens per watt will generate significant and readily quantifiable energy savings. But far greater intensity reductions (as well as ancillary energy and cost savings from, for example, downsizing space-cooling equipment) can often be achieved by deploying comprehensive strategies that also make use of improved lighting design, better sensors and controls, and natural light. Which lighting technologies and systems are adopted—and how much of this technical potential is ultimately realized—will depend, of course, on a host of other factors, among them human preferences for particular color-spectra, spatial distributions, and ratios of direct to indirect illumination. Such preferences are often culturally determined, at least in

part, and can change over time. At the same time, continued technology development can overcome intial trade-offs between increased efficiency and other product attributes.

Further complexities arise when assessing the potential for energy intensity reductions in the transport sector. As with lighting (and leaving aside for a moment the larger intensity reductions that could undoubtedly be achieved through better urban planning and public transportation systems), it is technically possible to deliver personal mobility for as little as one-tenth the primary energy consumption currently associated with each passenger-kilometer of vehicle travel.[18] Despite significant technology advances, however, average passenger-car fuel-economy has not changed much, at least in part because improved efficiency has been traded off against other vehicle attributes, such as interior volume, safety, or driving performance (e.g., acceleration). The situation is further complicated by the fact that energy—while obviously critical to the provision of mobility and other services—is only one of many factors that play a role in determining how those services are provided: fuel costs, for example, may comprise only a relatively small percentage of total transportation expenditures.

Similar arguments may be generalized across many kinds of energy systems. Technology innovations play a central role by enabling reductions in energy use, but their effect on overall energy consumption is often difficult to predict. Put in microeconomic terms, such innovations shift the production function for various services (such as mobility or illumination) and change the amounts of various inputs (energy, material, labor) required to produce a given level of satisfaction (utility). Typically, technology innovations create opportunities to save energy, save other inputs, or increase utility (Figure 2.2).

Actual outcomes depend on how users take advantage of these opportunities. In some cases, technological innovations that could be used to reduce energy consumption are directed to other objectives: automotive technology, for example, has advanced dramatically in recent decades, but much of this improvement has been used to increase vehicle size and power. At a macro-economic level, technology improvements that boost efficiency and productivity can also be expected to stimulate economic growth, thereby contributing to potentially higher levels of overall

18 Obviously, other constraints, such as the desired speed and comfort of travel and real-world driving conditions in different settings, will also affect theoretically attainable fuel-economy performance.

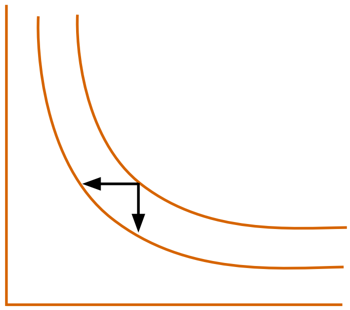

Figure 2.2 Technology innovation and the production function

Note: Technological innovation allows the same service to be delivered with less energy and other inputs. The outermost curve shows the original production iso-quant which describes the trade-off between energy requirements and other inputs needed to deliver a given level of energy service (such as illumination). Technological innovation moves the curve toward the origin enabling the same service to be produced with a reduction in energy use or other inputs, or both.

consumption in the long run, albeit at a lower level of energy intensity. Simple economic theory suggests that if efficiency improvements reduce the energy-related costs of certain activities, goods, or services, consumption of those activities, goods, or services would be expected to rise.

Further complicating matters is the tendency in modernizing economies toward ever more conversion from primary forms of energy (such as biomass, coal, or crude oil) to more useful or refined forms of energy (such as electricity and vehicle fuel). On the one hand, these conversion processes themselves generally entail some inevitable efficiency losses; on the other hand these losses may be offset by much more efficient end uses. Historically, the move to electricity certainly had an enormous impact on end-use efficiencies and on the range of amenities and activities available to people.

How significant these 'rebound' or 'take-back' effects are in reality, and to what extent they offset the energy savings that result from efficiency improvements, has been extensively debated in the relevant literature. In industrialized countries, observations and theory suggest that (a) improvements in energy efficiency have indeed reduced the growth of energy demand over the last few decades, and (b) the economic stimulus from efficiency improvements has not played a significant role in stimulating energy consumption. This result is not unexpected, since energy costs are relatively small when compared to total economic activity for most indus-

trialized countries.[19] The situation may be less clear over longer time scales and in developing-country contexts, where there may be unmet demand for energy services and where energy costs represent a larger fraction of the economic costs of services. In these cases, energy-cost savings may be invested in expanding energy supply or other essential services and it is more plausible that macroeconomic feedbacks will offset some of the demand reductions one might otherwise expect from efficiency improvements.

This debate misses an essential point: improvements in energy efficiency will lead to some complex mixture of reduced energy use and a higher standard of living.[20] Given that economic growth to support a higher standard of living is universally regarded as desirable and necessary, especially for the world's poor, concomitant progress toward improved efficiency and lower carbon intensity is clearly preferable to a lack of progress in terms of advancing broader sustainability objectives. Put another way, if growth and development are needed to improve people's lives, it would be better—for a host of reasons—if this growth and development were to occur efficiently rather than inefficiently and with lower rather than higher emissions of carbon dioxide.

Today, even countries at similar levels of development exhibit a wide range of overall energy and carbon intensities (i.e., energy consumed or carbon emitted per unit of economic output). This variation is a function not only of technological choices but of different economic structures, resource endowments, climatic and geographic circumstances, and other factors. On the whole, past experience suggests that energy-efficiency improvements do tend to accompany technological progress, albeit not at a pace sufficient to offset overall growth in demand. Moreover, the efficiency gains realized by the marketplace absent policy intervention usually fall well short of engineering estimates of cost-effective potential. Before exploring specific pros-

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19 Both theory and empirical studies have shown that in general only a small portion of the energy savings is lost to increased consumption. This is understood by the following example. Suppose an individual s consumption habits are such that he or she typically spends 10 percent of income on energy. Assume that a large investment in insulation, efficient furnace, and appliances reduces the person s total energy use by 25 percent. This translates into 2.5 percent of income, of which if past patterns of consumption hold only 10 percent or 0.25 percent might be spent on additional energy use. See also Schipper and Grubb (2000), p. 367-88.

20 What matters, from an environmental or energy-security perspective, is final emissions or fuel consumption. Because the relationship between efficiency improvements and reduced emissions or fuel consumption is not straightforward, additional policy measures may be needed to ensure that desired objectives in terms of absolute energy saved or tons of carbon avoided are being achieved.

pects for further energy-intensity reductions in different end-use sectors it is useful to review, in general terms, some of the likely reasons for this gap.

2.2 Barriers to realizing cost-effective energy savings

New technologies or methods for improving the efficiency of energy use are often not adopted as quickly or as extensively as might be expected based on cost-effectiveness considerations alone. In some cases, more efficient models may not be available in combination with other characteristics that consumers value more; in other cases, a company may forego efficiency improvements that would have very rapid economic payoffs because of the risk of interfering with complex manufacturing processes. Entrenched habits and cultural and institutional inertia can also present formidable barriers to change, even in relatively sophisticated companies with substantial energy expenses. Regulatory or market conditions sometimes create additional impediments: for example, rules that forbid small-scale end-users from selling power they generate back to the grid may inhibit the deployment of efficient technologies for on-site co-generation of heat and electricity. In sum, institutional, behavioral, or other barriers to the adoption of cost-effective, energy-efficient technologies are widespread and have been extensively documented in the energy-policy literature. Because most policy options for promoting energy efficiency are aimed at addressing one or more of these barriers, it is important to understand where and why they arise and where the most effective points of leverage for overcoming them might lie.

The role of institutional or other non-economic barriers to energy efficiency varies greatly between sectors. Large industries that are directly involved in energy production or conversion (such as the electric utility industry) and other industries that use energy intensively (such as the aluminum, steel, and cement industries) typically possess the institutional capacity to analyze their energy use, assess the potential impact of new technologies, and implement cost-effective improvements. Moreover, their motivation to understand and manage their energy needs is usually stronger because energy accounts for a larger share of their overall production costs. In such industries, the uptake of new energy technologies includes such salient barriers as the following:

- Complexity of process integration coupled with the high cost of system outages. The managers of large complex facilities, such as steel factories, place a very high value on reliability and may be reluctant to assume the operating risks associated with adopting new technologies.

- Regulatory hurdles, such as the necessity of complying with new environmental and safety permits, which may limit the adoption of new technologies. In the United States, some utilities have asserted that permitting requirements slowed the introduction of new technologies for coal-fired power plants.
- Existence of disincentives to capital investments in efficiency-enhancing retrofits compared to investments in new production capacity.
- Slow pace of turnover for some types of capital stock, arising in part from the two factors listed above, which plays a role in limiting the uptake of new technologies.

In contrast to energy-intensive industries, individual consumers, small businesses, and other end-users (including industries with low energy intensity) often lack the information and institutional capability to analyze and manage their energy use. Moreover, they are unlikely to acquire this information and capability because energy—in terms of cost and importance—often rates fairly low relative to other considerations. For individual consumers and small businesses, in particular, prominent barriers to the uptake of new energy technologies include the following:

- *Split incentives and lack of clear market signals.* Homebuilders and developers often do not include cost-effective energy technologies because real estate markets lack effective means to quantify resulting energy savings and efficiently recoup the added capital cost from buyers. Similarly, landlords lack incentives to invest in more efficient appliances if their tenants will be paying building energy costs. The same problem accounts for the fact that many electronic devices consume unnecessarily large amounts of power even when turned off or in stand-by mode. Manufacturers have no incentive to reduce these losses when the resulting impact on energy use and operating costs is invisible to the consumer at the point of purchase.
- *Lack of information and analytical capacity.* This lack may prevent end-users from effectively managing their energy consumption even when markets for applicable energy technologies exist. For example, if more end-users of electricity had access to real-time metering and faced real-time pricing they would shift consumption to off-peak hours. This would allow for more efficient utilization of generation resources and enhance grid reliability; it could potentially also facilitate increased reliance on

certain low-carbon energy sources, such as wind and nuclear power, that would otherwise be underutilized at night.[21]

- *Lack of access to capital*. The adoption of high-capital-cost technologies could slow without access to capital. Many low-income families in North America continue to use relatively costly and inefficient electric heat and hot water systems, even though switching to natural gas could pay for itself within a few years. In many cases, these families lack the up-front capital to purchase new gas appliances. Capital constraints are, of course, also likely to be an issue in many developing country contexts where poor households may face discount rates as high as 60 percent or more.
- *The difficulty of integrating complex systems*. The difficulty of integrating complex systems might create impediments for small users. Designing and operating highly efficient buildings requires tight integration between various building subsystems, both during the design phase and in later operation.

A variety of policies have been developed and implemented to address these barriers, including building and appliance standards, targeted technology incentives, research and development initiatives, consumer-information programs, and utility-sponsored demand-management programs. These options are reviewed in the sector-specific discussions that follow.

2.3 The buildings sector

Global consumption of primary energy to provide heating, cooling, lighting, and other building-related energy services grew from 86 exajoules in 1971 to 165 exajoules in 2002—an average annual growth rate of 2.2 percent per year (Price and others, 2006). Energy demand for commercial buildings grew about 50 percent faster than for residential buildings during the period. Energy use in buildings has also grown considerably faster in developing countries than in industrialized countries over the last three decades: the annual average growth rate for developing countries was 2.9 percent from 1971 to 2002, compared to 1.4 percent for industrialized countries. Overall, 38 percent of all primary energy consumption (not counting traditional biomass) is used globally to supply energy services in buildings.

21 In situations where baseload capacity is dominated by coal-fired power plants, on the other hand, peak shifting might not be beneficial from an emissions standpoint (especially if the marginal power source during peak hours is less carbon-intensive than the marginal power source during off-peak hours).

Energy demand in buildings is driven by population growth, the addition of new energy-using equipment, building and appliance characteristics, climatic conditions, and behavioral factors. The rapid urbanization that is occurring in many developing countries has important implications for energy consumption in the building sector. Most of the population growth that is projected to occur worldwide over the next quarter century is expected to occur in urban areas. And as millions of apartments and houses are added to accommodate a growing population, they in turn create new demand for energy to power lights, appliances, and heating and cooling systems. Structural changes in the economy, such as the expansion of the service sector, can produce more rapid demand growth in the commercial buildings sector.

It is important to make a distinction between what can be achieved in individual buildings and what can be achieved for the buildings sector as a whole in a given country. In the case of individual buildings, very large energy savings are possible and have been demonstrated. Numerous examples exist where heating energy use has been reduced to less than 10 percent of the average for the existing building stock through such measures as high insulation, passive solar design, low infiltration, measures to reduce heating and cooling loads, as well as efficient heating and cooling systems (Havey, 2006). Building designs that result in very low energy consumption are becoming the norm for new construction, such as in Germany and Austria, with 'passive houses' that rely on renewable energy sources and consume little or no outside energy close behind. Recently, there has even been discussion of so-called 'energy-plus houses' that could actually deliver power back to the grid. If these advances prove broadly transferable, they could create substantial new opportunities for promoting sustainability objectives, especially in settings where the building stock is expanding rapidly. Similarly, appliances are available that use 50 percent less energy than typical appliances. Obtaining large energy reductions in residential buildings generally does not require special expertise; the more complex systems in large commercial buildings, by contrast, place greater demands on designers, engineers, and building operators.

In any case, maximizing the energy efficiency of buildings is a complex undertaking that requires a high degree of integration in architecture, design, construction, and building systems and materials. For this reason, the best results are generally achievable in new buildings where energy and ecological considerations can be incorporated from the ground up. In countries with a rapidly expanding building stock, it may therefore make

sense to introduce differential policies specifically targeted to new construction. In many industrialized countries, on the other hand, the population of existing buildings is far larger than the number of new buildings added each year. Creative policies may be needed to capture cost-effective retrofit opportunities in these buildings given the different deployment hurdles and typically higher costs that apply. Achieving a broad transformation of the building stock in different contexts will require that the technologies, human skills, financial incentives, and regulatory requirements needed to capture efficiency opportunities in new and existing structures are widely disseminated.

Residential buildings

It is difficult to compare the energy performance of buildings in different countries because of data limitations (related to energy use at the end-use level), climate variations, and different construction practices that are not quantified. The best data source for an inter-comparison of European countries, the IEA covers 11 of its highest energy-using members. The IEA data indicate that appliances and lighting account for 22 percent of total household energy consumption on an end-use basis and approximately 32 percent of primary energy consumption (that is, taking into account primary energy consumption to generate electricity). Space heating accounts for the largest share of energy consumption in residential buildings: about 40 percent of total primary energy demand (IEA, 2004b).

Potential for efficiency improvements in space heating and cooling for residential buildings has several options, including the following:

- using more efficient heating and cooling equipment,
- increasing thermal insulation,
- using passive solar techniques to collect heat,
- reducing infiltration of outside air or losses of conditioned air to unconditioned space,
- using more efficient thermal distribution systems,
- using active solar collectors, and
- changing behavior (e.g., temperature set points).

In some countries, more efficient heating and cooling systems have been mandated through building codes or appliance standards. At the same time, improved construction practices and building energy standards—that led to multiple glazings, higher insulation levels, and reduced air infiltration—have reduced per-square-foot heating, ventilation, and air conditioning loads in new buildings in many countries around the world. In

some instances, the addition of low-tech options, such as ceiling fans, can be used to reduce air conditioning requirements. And in a few cases, policies have been introduced to reduce building energy consumption through behavioral changes. To reduce air conditioning loads, for example, some Chinese cities have adopted regulations that prohibit residents from setting thermostats below 26 degrees Celsius during the summertime.

Appliances are the second major contributor to energy demand in residential buildings. The evolution of refrigerator technology in the United States represents a major energy-efficiency success story. Figure 2.3 shows trends in average refrigerator energy use, price, and volume in the United States over the last half century. The peak of electricity use occurred in the middle 1970s. Thereafter, as the State of California set efficiency standards

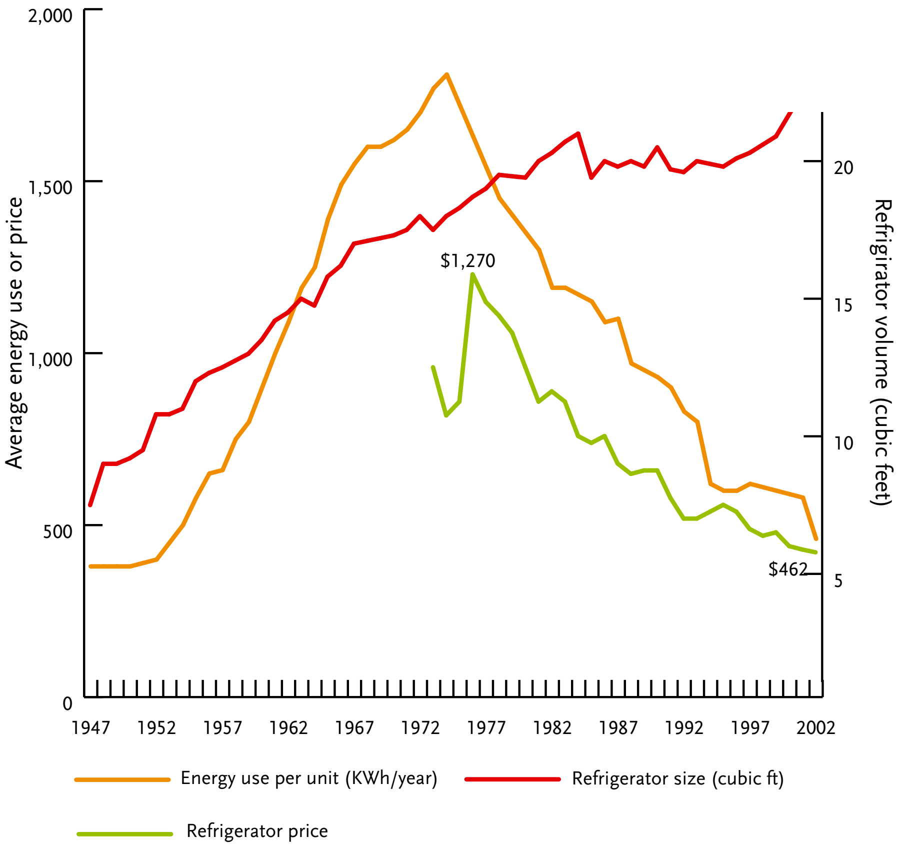

Figure 2.3 Refrigerator energy use in the United States over time

Source: David Goldstein, Natural Resources Defense Council

and as the U.S. Congress debated setting a federal standard, energy use in refrigerators began to decline very significantly. Efficiency improvements were realized using available technologies: improved insulation (using blowing agents), better compressors, and improved seals and gaskets. The industry did not need to develop new refrigerants to achieve these gains. Average refrigerator energy consumption declined dramatically in the late 1970s in anticipation of the California standards; federal standards, when they were introduced several years later, were more stringent than the California standards. Throughout this period, the size of new refrigerators increased, but their price fell.

The changes in energy consumption depicted in Figure 2.3 are significant. The annual electricity consumption of the average refrigerator declined from 1,800 kilowatt-hours per year to 450 kilowatt-hours per year between 1977 and 2002, even as volume increased by more than 20 percent and prices declined by more than 60 percent. It has been estimated that the value of U.S. energy savings from 150 million refrigerators and freezers were close to US$17 billion annually.

The potential to reduce energy consumption by other household appliances, though not as dramatic as in the case of refrigerators, is nonetheless substantial. Horizontal-axis clothes-washing machines, for example, require substantially less water and energy than vertical-axis machines. Homes and commercial buildings now have a large and growing number of 'miscellaneous' energy-using devices, such as televisions, other audiovisual equipment, computers, printers, and battery chargers. Many of these devices use—and waste—significant amounts of power when in standby mode; in fact, standby losses from miscellaneous electronic equipment have been estimated to account for 3–13 percent of residential electricity use in OECD countries. In many cases, significant energy savings could be achieved by redesigning these types of devices so as to minimize standby losses.[22]

Commercial buildings

The two most important sources of energy demand in U.S. commercial buildings, as illustrated in Figure 2.4, are space heating, ventilation, and air conditioning (HVAC) systems, which account for 31 percent of total

22 It is possible to reduce most standby losses to 1-2 watts from 5-25 or more watts. Documenting the magnitude of the possible savings is difficult, however, because of the large variety of standby losses (Lebot and others, 2000). The IEA (2006b) report, Raising the Profile of Energy Efficiency in China, provides an interesting case study of standby power efficiency.

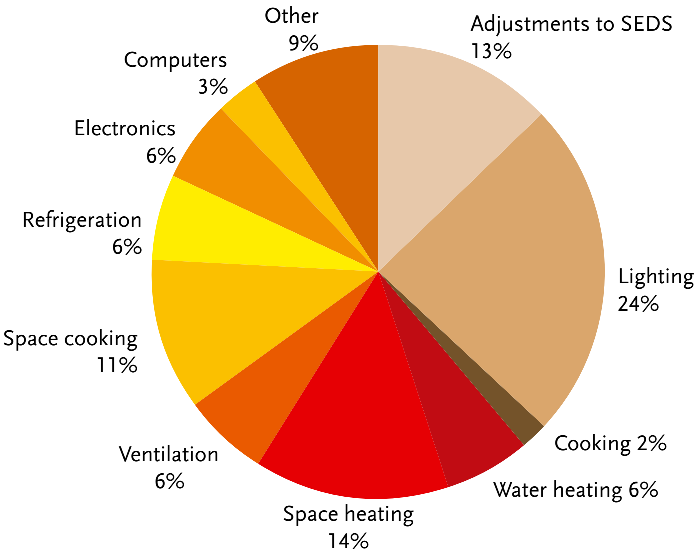

Figure 2.4 Shares of primary energy use in U.S. commercial buildings

Note: Total energy consumption: 17.49 quadrillion British thermal units (equal to 18.45 EJ). Building energy consumption in the industrial sector is excluded. The portion of Figure 2.4 labeled Adjustment to SEDS (State Energy Data Systems) represents uncertainty in the numbers shown. Data from 2003.

Source: USDOE, 2005.

building primary energy use; and lighting, which accounts for 24 percent of total building primary energy use. The results for large commercial buildings in many other countries are thought to be similar to those for the United States, although no such statistical breakdown is available for other IEA member nations or for the developing world, The term 'commercial buildings' covers a wide range of structures, including government buildings, commercial office buildings, schools, hospitals, houses of worship, shops, warehouses, restaurants, and entertainment venues.

Large energy-saving opportunities exist in the commercial-building sector. In hot and humid climates, cooling loads can be reduced by addressing the building envelope—including window coatings and shading—and by employing energy-efficient lighting (which produces less waste heat). In many cases, low-technology options, such as incorporating

traditional design features or painting flat rooftops white to increase their reflectivity, can produce substantial reductions in cooling loads. Building-integrated solar photovoltaics represent another option for reducing grid-electricity consumption in commercial buildings, among the points discussed in Chapter 3. And regardless of climate, more efficient equipment is available for all of the major commercial-building end-uses shown in Figure 2.4.

The most significant efficiency opportunities for commercial buildings in the future involve system integration. An example is daylighting, in which sensors measure light entering the perimeter areas of a building and actuators control the level of artificial lighting. This can reduce lighting energy consumption in perimeter areas by 75 percent and produce additional savings by reducing cooling loads. Numerous studies and real-world applications have shown such daylighting systems to be highly cost-effective when evaluated on the basis of lifecycle costs (that is, taking into account operating cost savings over the life of the building as well as up-front capital cost). Because of their perceived complexity, however, they have had only limited penetration in the market.

Inspecting all elements of a building to ensure that they are working properly—a process known as building commissioning—often produces large savings. Frequently, buildings are not constructed the way they were designed and commissioning can identify and rectify such problems, reducing energy consumption by 10–30 percent or more. Even where buildings are constructed as specified, commissioning can 'tune up' the HVAC systems. Still greater energy savings can be achieved in commercial buildings through 'continuous commissioning' which involves real-time monitoring of overall HVAC performance and all other building systems and adjusting system controls based on the monitoring results. Just as daylighting has been slow to gain commercial acceptance, the complexities of continuous commissioning will need to be overcome before it is widely adopted.

Policies for promoting energy efficiency in buildings

Many countries have adopted policies to promote energy efficiency in buildings; two of the most common are appliance efficiency standards and building energy codes. In some countries, utility companies have also played a major role in providing incentives, information, or technical assistance to promote end-use efficiency improvements. Finally, governments or financial institutions can provide financial incentives, including low– or mid-cost loans for energy-efficiency investments in both retrofit

and original building construction projects. Loans at slightly below market value can stimulate increased use of energy-efficiency services providers, such as energy service companies (ESCO), and are likely to be particularly attractive when the builder/retrofitter is also the owner and operator of the building and thus stands to benefit from reduced energy costs over time. This is often the case for buildings owned by government, major corporations, universities, and other such large institutions.

Appliance standards have been especially effective: they are relatively easy to enforce, usually involve only a small number of manufacturers, and produce energy savings without requiring consumers to spend time and effort to avoid purchasing an inefficient model. To produce continued technology improvements and efficiency gains, however, appliance standards must be rigorous and must be updated periodically. Building codes are important since they have an effect on the overall, lifetime energy consumption of structures that will last many decades. For building codes to succeed, however, building designers and builders must be educated and requirements must be enforced. Other types of programs, such as utility demand-side management or Japan's Top Runner (Box 2.1), can serve as an important complement to building codes and appliance standards by providing incentives for further efficiency gains beyond the minimums established via mandatory standards.

Box 2.1 Japan's Top Runner Program

In 1999, Japan introduced an innovative addition to its existing Energy Conservation Law. The Top Runner Program is designed to promote ongoing efficiency improvements in appliances, machinery, and equipment used in the residential, commercial and transportation sectors.

This is how the program works. Committees composed of representatives from industry, academia, trade unions, and consumer groups identify the most efficient model currently on the market in a particular product category. The energy performance of this 'top runner ' model is used to set a target for all manufacturers to achieve within the next four to eight years. To meet the target, manufacturers must ensure that the weighted average efficiency of all the models they offer in the same product category meet the top runner standard. In this way, the program offers more flexibility than minimum efficiency standards for all products: manufacturers can still sell less efficient models, provided they more than compensate with higher efficiency in other models. By continually resetting targets based on best-in-class performance, this approach to benchmarking progressively raises the bar for average efficiency performance.

Although manufacturers are only obliged to 'make efforts ' to reach the target, the Top Runner Program has achieved good results in Japan. The government's chief leverage lies in its ability to publicize a company's failure to meet the targets, or to make a good faith effort to meet targets, which in turn would put a company's brand image at risk. Typically, the targets set in different product categories are indexed to other product attributes (such as vehicle weight, screen size in the case of a television, or power in the case of an air conditioner). In some cases additional categories have been created to accommodate certain product functions that may not be cost-effective in combination with the most advanced efficiency features or to reflect price distinctions (e.g., one target for low-cost, high-efficiency models and a separate target for high-cost, high-efficiency models). This additional flexibility is designed to ensure that consumers retain a wide range of choices.

Japan's Top Runner Program includes a consumer information component, in the form of a labeling system. Individual product models that do not meet the target can remain on the market, but receive an orange label. Models that do meet the target receive a green label.

For more information, see Energy Conservation Center, Japan, website: www.eccj.or.jp

2.4 Industrial energy efficiency

The industrial sector accounts for 37 percent of global primary energy consumption; hence, it represents a major area of opportunity for efficiency improvements. This sector is extremely diverse and includes a wide range of activities from extracting natural resources and converting them into raw materials, to manufacturing finished products. The industrial sector can be broadly defined as consisting of energy-intensive industries (e.g., iron and steel, chemicals, petroleum refining, cement, aluminum, pulp and paper) and light industries (e.g., food processing, textiles, wood products, printing and publishing, metal processing). Energy-intensive industries account for more than half of the sector's energy consumption in most countries.

Trends in industrial-sector energy consumption

Primary energy consumption in the industrial sector grew from 89 exajoules in 1971 to 142 exajoules in 2002 at an average annual growth rate of 1.5 percent (Price and others, 2006). Primary energy consumption in developing countries, which accounted for 43 percent of worldwide industrial-sector primary energy use in 2002, grew at an average rate of 4.5 percent per year over this time period. Industrialized countries experienced much slower average growth (0.6 percent per year), while primary energy consumption by the industrial sector in the countries that make up the former Soviet Union and Eastern and Central Europe actually declined at an average rate of 0.4 percent per year.

Industrial energy consumption in a specific country or region is driven by the level of commodity production, the types of commodities produced, and the energy efficiency of individual production facilities. Historically, the energy efficiency of this sector has been closely tied to overall industrial efficiency (Japan being perhaps the prime example of a country that achieved high levels of industrial efficiency in part by using energy very efficiently). In general, production of energy-intensive commodities like iron, steel, and cement is declining or stable in most industrialized countries and is on the rise in most developing countries where infrastructure and housing is being added at a rapid rate. For example, between 1995 and 2005, steel production declined at an average annual rate of 0.3 percent in the United States, while growing at an annual rate of 1.0 percent in Japan and 14 percent in China (USGS, 2006).

The amount of energy consumed to produce one unit of a commodity is determined by the types of production processes involved, the vintage of

the equipment used, and the efficiency of various conversion processes within the production chain, which in turn depends on a variety of factors, including operating conditions. Industrial energy intensity varies between different types of commodities, individual facilities, and different countries depending upon these factors.

Steel, for example, can be produced using either iron ore or scrap steel. Best practice energy intensity for producing hot rolled steel from iron ore is 19.5 gigajoules per ton, while the production of the same product using scrap steel only requires 4.3 gigajoules per ton (Worrell and others, 2007). The energy intensity of the Chinese steel industry declined over the decade from 1990 to 2000, despite an increased share of primary steel production, indicating that production efficiencies improved as small, old, inefficient facilities were closed or upgraded and newer facilities were constructed. In the future, Chinese steel production will likely continue to become more efficient as Chinese producers adopt advanced casting technologies, improved furnaces, pulverized coal injection, and increased recovery of waste heat.

In the Indian cement industry, a shift away from inefficient wet kilns toward more efficient semi-dry and dry kilns, together with the adoption of less energy-intensive equipment and practices, has produced significant efficiency gains (Sathaye and others, 2005). Similarly, the energy intensity of ammonia production in current, state-of-the-art plants has declined by more than 50 percent. Developing countries now produce almost 60 percent of the world's nitrogen fertilizer and many of the most recently constructed fertilizer plants in these countries are highly energy efficient.

Energy-efficiency potential in the industrial sector

Industrial producers, especially those involved in energy-intensive activities, face stronger incentives to improve efficiency and reduce energy consumption than most end-users in the buildings or transportation sectors. Important drivers include the competitive pressure to minimize overall production costs, the desire to be less vulnerable to high and volatile energy prices, the need to respond to environmental regulatory requirements, and growing consumer demand for more environmentally friendly products.

Opportunities to improve industrial energy efficiency are found throughout this diverse sector (deBeer and others, 2001). At the facility level, more efficient motor and pumping systems can typically reduce energy consumption by 15–20 percent, often with simple payback periods of

around two years and internal rates of return around 45 percent. It has been estimated that use of high-efficiency motor-driven systems, combined with improvements to existing systems, could reduce electricity use by motor-driven systems in the European Union by 30 percent (De Keulenaer, 2004), while the optimization of compressed air systems can result in improvements of 20–50 percent (McKane and Medaris, 2003). Assessments of steel, cement, and paper manufacturing in the United States have found cost-effective savings of 16–18 percent (Worrell and others, 2001); even greater savings can often be realized in developing countries where old, inefficient technologies are more prevalent (WEC, 2004). A separate assessment of the technical potential for energy-efficiency improvements in the steel industry found that energy savings of 24 percent were achievable by 2010 using advanced but already available technologies such as smelt reduction and near net shape casting (de Beer and others, 2000).

In addition to the potential that exists based on currently available improvements, new and emerging technologies for the industrial sector are constantly being developed, demonstrated, and adopted. Examples of emerging technologies that could yield further efficiency improvements include direct reduced iron and near net shape casting of steel, separation membranes, black liquor gasification, and advanced cogeneration. A recent evaluation of over 50 such emerging technologies—applicable to industries as diverse as petroleum refining; food processing; mining; glass-making; and the production of chemicals, aluminum ceramics, steel, and paper—found that over half of the technologies promised high energy savings, many with simple payback times of three years or less (Martin and others, 2000). Another analysis of the long-term efficiency potential of emerging technologies found potential savings of as much as 35 percent for steelmaking and 75–90 percent for papermaking over a longer time horizon (de Beer, 1998; and de Beer and others, 1998).

In an encouraging sign of the potential for further efficiency gains in the industrial sector, some companies that have effectively implemented technology improvements and reduced their energy costs are creating new lines of business in which they partner with other energy-intensive companies to disseminate this expertise.

Policies to promote industrial-sector energy efficiency

Among the barriers to improved efficiency, those of particular importance in the industrial sector are investment and profitability barriers, informa-

tion and transaction costs, lack of skilled personnel, and slow capital stock turnover. The tendency of many companies to believe they are already operating as efficiently as possible may constitute a further barrier: a survey of 300 firms in the Netherlands, for example, found that most viewed themselves as energy efficient even when profitable improvements are available (Velthuijsen, 1995). Uncertainties related to energy prices or capital availability are another common impediment—they often result in the application of stringent criteria and high hurdle rates for energy efficiency investments. Capital rationing is often used within firms as an allocation means for investments, especially for small investments such as many energy efficiency retrofits. These difficulties are compounded by the relatively slow turnover rate of capital stock in the industrial sector and by a strong aversion to perceived risks associated with new technologies, especially where these risks might affect reliability and product quality.

Many policies and programs have been developed and implemented with the aim of improving industrial energy efficiency (Galitsky and others, 2004). Almost all industrialized countries seek to address informational barriers through a combination of individual-plant audit or assessment reports, benchmarking, case studies, factsheets, reports and guidebooks, and energy-related tools and software. The U.S. Department of Energy provides confidential assessment reports through its Industrial Assessment Centers for smaller industrial facilities and has just initiated an Energy Savings Assessment Program that provides free assessments for 200 of the country's most energy-intensive manufacturing facilities (USDOE, 2006).

Benchmarking provides a means to compare energy use within one company or plant to that of other similar facilities producing similar products. This approach can be used to compare plants, processes, or systems; it can also be applied to a class of equipment or appliances, as is done in Japan's Top Runner Program (Box 2.1). The Netherlands has established negotiated 'benchmarking covenants' under which participating companies agree to reach performance goals that would put them within the top 10 percent of most efficient plants in the world or make them comparable to one of the three most efficient producing regions of the world (where regions are defined as geographic areas with a production capacity similar to the Netherlands). In return, participating companies are exempt from further government regulations with respect to energy consumption or carbon dioxide emissions. In addition, the Dutch government requires companies that have not yet achieved the rank of top 10 percent most efficient (or top 3 regionally) by 2006 to implement all economically feasible

energy conservation measures by 2012, defined as those measures that generate enough savings to cover the costs of borrowed capital (Ministry of Economic Affairs, 1999).

Target-setting, where governments, industrial sectors, or individual companies establish overarching energy-efficiency or emissions-reduction goals, can provide a valuable framework for reporting energy consumption and undertaking efficiency improvements. The Chinese government, for example, recently issued a policy aimed at reducing that country's energy intensity (economy-wide energy consumption per unit of GDP) by 20 percent over the next five years. The policy includes energy-savings quotas for local governments. At the company level, governments can offer financial incentives, supporting information, rewards, publicity, and relief from other environmental or tax obligations in exchange for meeting certain targets. Where this approach has been used, progress toward negotiated targets is closely monitored and reported publicly, typically on an annual basis. In the United Kingdom, for example, energy-intensive industries have negotiated Climate Change Agreements with the government. The reward for meeting agreed-upon targets is an 80 percent discount on energy taxes. During the first target period for this program (2001–2002), total realized reductions were three times higher than the target (Pender, 2004); during the second target period, average reductions were more than double the target (DEFRA, 2005). Companies often did better than expected, in part because the targets they negotiated typically reflected a belief that they were already energy efficient (DEFRA, 2004). Finally, a number of large multi-national corporations have recently undertaken ambitious voluntary initiatives to improve energy efficiency and reduce greenhouse gas emissions.

Many countries provide *energy management assistance* by supporting standardized energy management systems, promotional materials, industry experts, training programs, and some form of verification and validation assistance for companies interested in tracking and reporting energy use and/or greenhouse gas emissions. Incentives can also be provided via award and recognition programs. Efficiency standards can be effectively applied to certain types of standardized equipment that are widely used throughout the industrial sector.

Fiscal policies—such as grants or subsidies for efficiency investments, subsidized audits, loans, and tax relief—are used in many countries to promote industrial-sector energy-efficiency investments. Worldwide, the most popular approach involves subsidized audit programs. Although public loans are less popular than outright energy efficiency subsidies,

innovative funding mechanisms such as can be provided through energy services companies, guarantee funds, revolving funds, and venture capital funds are growing in popularity. Similarly, many countries offer tax relief in the form of accelerated depreciation, tax reductions, and tax exemptions to promote efficiency improvements. In general, financial incentive mechanisms should be designed to avoid subsidizing technologies that are already profitable. Continued subsidies may be justified in some cases, however, to achieve the economies of scale necessary to make sustainable technologies affordable in a developing country context.

2.5 Transportation energy efficiency

The transportation sector accounts for 22 percent of global energy use and 27 percent of global carbon emissions. In the major energy-using industrialized countries (specifically the 11 highest energy using IEA countries), nearly all (96 percent) of transportation energy comes from petroleum fuels, such as gasoline (47 percent) and diesel (31 percent). Road vehicles account for about three-quarters of all transportation energy use; roughly two-thirds of transport energy is used for passenger mobility while one-third is used to move freight (Price and others, 2006).

Trends in transportation-sector energy consumption

Transportation energy use has grown considerably faster in developing countries than in industrialized countries over the last three decades—the average annual rate of growth over the period from 1971 to 2002 was 4.8 percent for developing countries and 2 percent for industrialized countries. In absolute terms, however, industrialized countries still consume about twice as much energy (56 exajoules) for transportation as do developing countries (26 exajoules).

Transportation energy consumption in a specific country or region is driven by the amount of passenger and freight travel, the distribution of travel among various transportation modes, and the energy efficiency of individual vehicles or modes of transport. Figure 2.5 shows the distribution of energy use by mode of transport in the United States and illustrates the dominance of light-duty road vehicles (including automobiles, sport utility vehicles, pickups, minivans, and full-size vans) in terms of overall energy consumption. Similar patterns obtain in other countries, although a greater number of light-duty vehicles in Europe operate on diesel fuel.[23]

23 This is in part because EU environmental regulations allow for greater tailpipe emissions of nitrogen oxides; diesel engines are more efficient than spark-ignition gasoline engines, but generally produce higher nitrogen-oxide emissions.

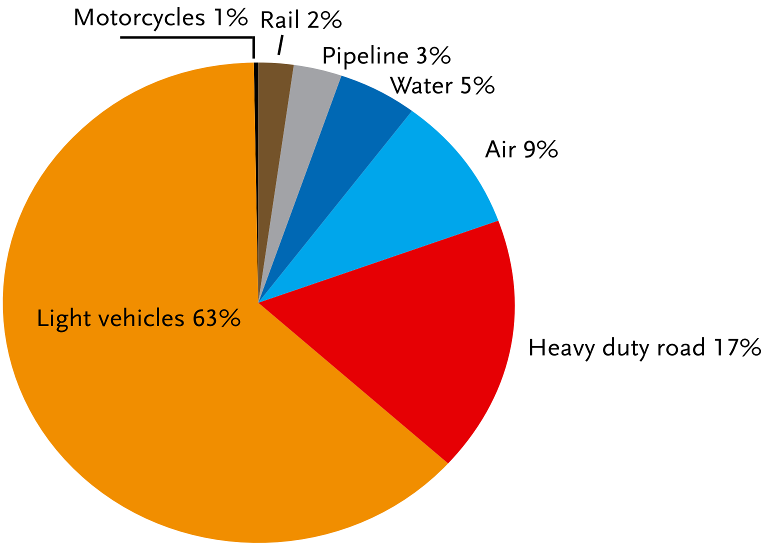

Figure 2.5 U.S. transportation energy consumption by mode, 2005

Note: Total U.S. transportation energy consumption in 2005 was 27,385 trillion British thermal units.

Source: Davis and Diegel, 2006.

Energy-efficiency potential in the transportation sector

Overall demand for transportation services generally and personal vehicle travel specifically can be influenced by patterns of development and land-use planning, as well as by the availability of public transportation, fuel costs, government policies (including congestion, parking, and roadway fees), and other factors. Different modes of transport also have very different energy and emissions characteristics—as a means of moving freight, for example, rail transport is as much as ten times more energy-efficient per kilometer as road transport. Some of the policy options available for advancing sustainability objectives in the transportation sector are politically difficult to enact while others (notably land-use planning) are difficult to affect except over long periods of time—although substantial opportunities may exist in developing countries where new development is occurring at a rapid clip and land-use patterns are not already heavily determined by existing infrastructure. Several strategies for reducing travel demand are discussed in general terms in the next section.

At the level of individual vehicles, three types of approaches can be used to reduce energy consumption.[24] The first is to reduce the load on the engine, thereby reducing the amount of energy required to move the vehicle. The second is to increase drive-train efficiency and capture energy losses (especially in braking). A third is to increase the engine load factor—that is, the amount of time the engine operates near its rated or maximum power output for a given speed. If the primary objective is to reduce greenhouse gas emissions, then a fourth approach (beyond improving efficiency) is to switch to a less carbon-intensive fuel. (Alternative-fuel options could include electricity or biofuels; the latter is discussed in a later section of this report).

For road vehicles, load on the engine can be minimized by reducing vehicle mass, aerodynamic drag, and tire-rolling resistance. Mass reductions can be achieved by replacing conventional steel in the bodies and engines of vehicles with materials that are equally strong, but significantly lighter in weight. A 10 percent reduction in vehicle weight can improve fuel economy by 4–8 percent. Increased use of lightweight but very strong materials, such as high-strength steel, aluminum, magnesium, and fiber-reinforced plastics, can produce substantial weight reductions without compromising vehicle safety. Such advanced materials are already being used in road vehicles; their use is growing, but they generally cost more than conventional materials. Smaller engines, capable of operating at high revolutions per minute or with turbo-charge for additional power, can also be used, as can smaller and lighter transmissions. Aerodynamic drag can be reduced through more streamlined body design but may also introduce trade-offs in terms of stability in crosswinds. Technologies that turn the engine off when idling can also produce energy savings.

Some technologies, both commercially available and under development, can be used to increase the drive-train efficiency of road vehicles. Examples include multi-valve overhead camshafts, variable valve lift and timing, electromechanical valve throttling, camless-valve actuation, cylinder deactivation, variable compression ratio engines, continuously variable transmissions, and low-friction lubricants. In addition, new types of highly efficient drive-trains—such as direct injection gasoline and diesel engines, and hybrid electric vehicles—are now in production.

24 Note that changes in vehicle operation or maintenance, such as driving at a lower speed or keeping tires properly inflated, can also reduce energy consumption. These approaches, since they cannot be engineered into the vehicle and remain under the control of the operator are not discussed in this report. Nevertheless, the opportunity exists for governments to influence certain operating norms via policy (e.g., lower speed limits).

Several studies have estimated the overall potential increase in fuel economy that could be achieved through the use of multiple technologies in light-duty vehicles. These estimates range from a 25–33 percent increase in fuel economy at no incremental cost (NRC, 2002) to a 61 percent increase in fuel economy using parallel hybrid technology at an incremental vehicle cost of 20 percent (Owen and Gordon, 2003).

Hybrid-electric vehicles, which utilize both a conventional internal combustion engine and an electric motor in the drive-train, have immediate potential to reduce transportation energy use, mainly from shutting down the engine when stopped, recovering braking losses to recharge the battery, and allowing for the engine to be downsized by supplementing with electric power during acceleration. In the United States, the market for hybrid vehicles has grown rapidly in the last few years: the number of hybrid vehicles sold more than doubled between 2004 and 2005 and grew a further 28 percent between 2005 and 2006.[25]

In current production hybrids, the batteries are charged directly from the onboard engine and from regenerative braking. 'Plug-in' hybrids could also be charged from the electricity grid thereby further reducing petroleum use (especially if the vehicles are primarily used for short commutes). Such vehicles would require a larger battery and longer recharge times. Pairing this technology with clean, low-carbon means of producing electricity could also produce substantial environmental benefits. Widespread commercialization of plug-in hybrids would depend on the development of economical batteries that can sustain thousands of deep discharges without appreciable loss of energy storage capacity. It could also depend on whether on-grid, battery-charging patterns would require a substantial expansion of available electric-generating capacity.

Over a longer timeframe, substantial reductions in oil consumption and conventional pollutant emissions, along with near-zero carbon emissions, could potentially be achieved using hydrogen fuel-cell vehicles. In general, the specific environmental benefits of this technology will depend on how the hydrogen is produced: if a large part of the objective is to help address climate change risks, the hydrogen will have to be produced using low-carbon resources, or—if fossil sources are used—in combination with carbon capture and sequestration. Meanwhile, recent studies conclude that

25 In 2000, just under 7,800 hybrid vehicles were sold in the United States; by 2006, sales had reached more than 254,500. Nevertheless, hybrids at 1.5 percent of vehicle sales in 2006 still constitute only a small fraction of the U.S. car market. Toyota Motor Company accounts for the majority of hybrids sold in the United States (R.L.Polk & Co, 2007).

several significant technical barriers will need to be surmounted before hydrogen fuel-cell vehicles can be viable in large numbers. Chief among these barriers are the durability and cost of the fuel cell, the cost of producing hydrogen, the cost and difficulty of developing a new distribution infrastructure to handle a gaseous transportation fuel, and the challenge of developing on-board storage systems for hydrogen (NRC/NAE, 2004; TMC/MIRI, 2004). In one effort to begin demonstrating hydrogen technology, Daimler Chrysler has developed a fleet of hydrogen fuel-cell buses that are are now in use in several cities around the world.

Motorcycles and two- and three-wheel scooters are already relatively efficient compared to cars, but in urban areas where two-stroke engines are heavily used they make a substantial contribution to air pollution. Conventional pollutant emissions from this category of transport vehicles can be reduced substantially, and efficiency can be further improved using some of the engine technologies developed for light vehicles Honda estimates that a prototype hybrid-electric scooter could reduce energy use by roughly 30 percent in stop-and-go driving, while producing even larger reductions in conventional pollutant emissions (Honda, 2004).

The main opportunity for reducing energy consumption in heavy-duty diesel trucks is through body improvements to reduce aerodynamic drag. Electric or hybrid-electric drive-train technologies are not considered practical for heavy-duty vehicle applications, although fuel cells may well be. However, hybrid-electric systems are well-suited for stop-and-go driving by buses and delivery vehicles in urban areas; studies have found that fuel economy improvements ranging from 10 percent (Foyt, 2005) to 57 percent (Chandler and others, 2006) could be achieved using hybrid technology in these applications.

For rail engines, advances have been made in reducing aerodynamic drag and weight, and in developing regenerative brakes (at railside or onboard) and higher efficiency motors. A 1993 Japanese report illustrates how a train with a stainless-steel car body, inverter control, and regenerative braking system could cut electricity use in half over a conventional train (JREast Group, 2003). Alternative power plants are also a possibility for rail travel.

Today's aircraft are 70 percent more fuel-efficient per passenger-kilometer than the aircraft of 40 years ago; most of this improvement has come from increasing passenger capacity but gains have also been achieved by reducing weight and improving engine technology. Options for further reducing energy use in aviation include laminar flow technology and

blended wing bodies,[26] both of which reduce air drag, and further engine improvements and weight reductions. Airplane manufacturer Boeing claims that its new 787 family of aircraft will achieve a 20 percent improvement in fuel economy, in part through the extensive use of composite materials (Boeing, 2007). Other, longer-term options include larger aircraft, use of unconventional fuels or blends, and new engines using liquid hydrogen fuel.

Obviously, the overall efficiency of road, air, and rail transport also depends to a considerable extent on utilization: higher occupancy ratios on buses, trains, and airplanes will result in lower energy consumption or emissions per passenger-mile.

Technology options for reducing energy use in the shipping industry include hydrodynamic improvements and machinery; these technologies could reduce energy use by 5–30 percent on new ships and 4–20 percent when retrofitted on old ships. Since ship engines have a typical lifetime of 30 years or more, the introduction of new engine technologies will occur gradually. A combination of fleet optimization and routing changes could produce energy savings in the short term; reducing ship speed would also have this effect but may not be a realistic option given other considerations. It has been estimated that the average energy intensity of shipping could be reduced by 18 percent in 2010, and by 28 percent in 2020, primarily via reduced speed and eventually new technology. This improvement would not, however, be enough to overcome additional energy use from projected demand growth (shipping is estimated to grow 72 percent by 2020). Inland ferries and offshore supply ships in Norway are using natural gas in diesel ship engines and achieving a 20 percent reduction in energy use, but this option is limited by access to liquefied natural gas and cost. Where natural gas is available and especially where the gas would otherwise be flared, use of liquefied natural gas as a ship fuel could produce significant emissions reductions. Large sails, solar panels, and hydrogen fuel cells are potential long-term (2050) options for reducing ship-related energy use and carbon emissions.

Policies to promote transportation-sector energy efficiency

The primary policy mechanisms available to promote energy efficiency in transportation include new vehicle standards, fuel taxes and economic incentives, operational restrictions, and land-use planning.

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26 The blended wing body is an advanced aircraft body design that combines efficient high-lift wings with a wide airfoil-shaped body. This design enables the aircraft body to contribute to lift, thereby improving fuel economy.

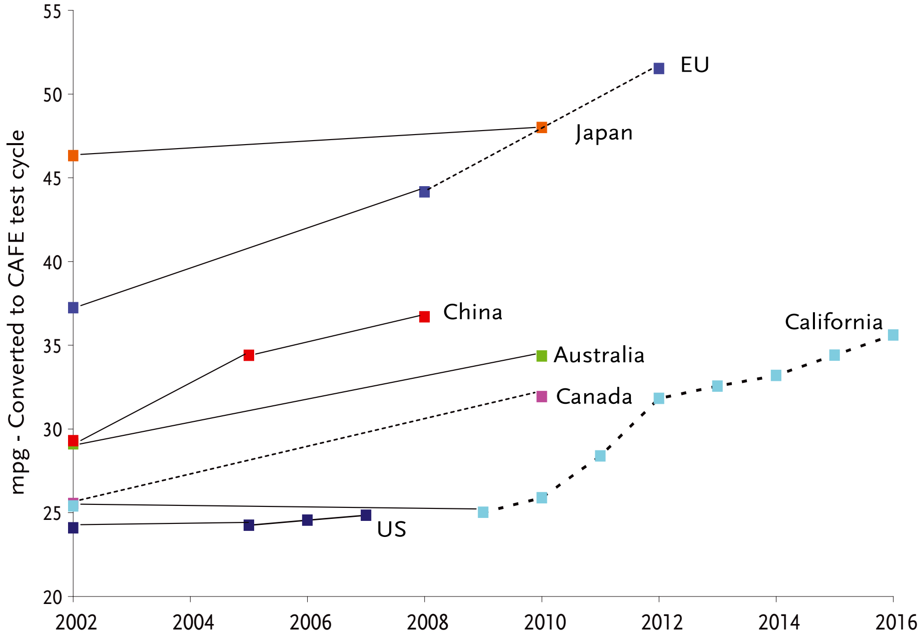

Figure 2.6 Comparison of auto fuel efficiency by auto fuel economy standards among countries, normalized to U.S. test procedure

Note: Y-axis shows miles per gallon (mpg) according to Corporate Average Fuel Economy (CAFE) standards [1 mpg equals 0.425 kilometers per liter]. Dotted lines denote proposed standards. Japan has recently announced that it wants to implement even tougher standards, which would put it on par with the EU beyond 2014 (An and others, 2007).

Source: An and Sauer, 2004.

Many countries now have efficiency standards for new light-duty vehicles, typically in the form of performance standards that are applied to the average efficiency (or fuel economy) of a manufacturer's fleet (Figure 2.6). This flexibility allows manufacturers to offer models with a range of fuel-economy characteristics. The introduction of fuel-economy standards in the late 1970s led to substantial efficiency gains in the U.S. automobile fleet throughout the 1980s, but it has proved politically difficult to increase the standards over time to reflect advances in vehicle technology. In fact, fuel economy standards in the United States have remained largely unchanged for the last two decades. Meanwhile, the growing market share of minivans, sport utility vehicles, and pickup trucks—which are designated as 'light trucks' and are therefore subject to a considerably lower fleet-average standard—has actually produced a decline in the effective

fuel economy standard for passenger vehicles in the United States since the 1980s.[27] Finally, because such standards generally apply to new vehicles only and because the average life of a passenger vehicle is 13 years (the average life of large diesel engines is even longer), there is a substantial lag time between the adoption of standards and appreciable improvements in fleet-wide efficiency.

Some jurisdictions regulate emissions from heavy-truck engines, and some have prescriptive standards that require four-stroke engines in motorcycles, snowmobiles, or personal watercraft. However, these standards are aimed at conventional-pollutant emissions rather than at reducing fuel use or carbon emissions. No countries have fuel-economy standards for aircraft, shipping, or locomotives, although some are developing standards that limit the emissions of pollutants other than carbon. In some cases, significant reductions in emissions and energy consumption can be achieved simply through mode-shifting (e.g., transporting freight by rail rather than by heavy truck).

Fuel taxes give operators an additional economic incentive to reduce energy use. In many respects fuel taxes are preferable to efficiency standards. They apply immediately to both old and new vehicles, across all transportation modes. They also leave consumers with great flexibility in how to respond, either by opting for more efficient vehicles or by changing their travel patterns, or both. Several EU member states have imposed large gasoline taxes for decades while such taxes have been extremely difficult to implement in the United States. And although fuel taxes have many theoretical advantages from the standpoint of economic efficiency, experience to date suggests they need to be quite high (given the relative price inelasticity of travel demand and the fact that fuel costs are often a small fraction of transportation-related expenses) to produce significant changes in consumers' transportation choices or fuel consumption patterns.

'Feebates' have been proposed in the United States (and to achieve other environmental goals in other countries) as an alternative policy to surmount the political obstacles associated with both fuel-economy standards and fuel taxes. Fees would be levied on sales of vehicles with relatively poor fuel economy, while rebates would be given for sales of vehicles with high fuel economy. Most of the proposals are revenue neutral (i.e., the total rebate outlay would cover the total fee revenue). Although feebates

27 The U.S light truck average fuel economy standard remained below 21 miles per gallon during the 1990s; it was recently raised so that a standard of 22.2 miles per gallon will take effect in 2007.

have been proposed in several U.S. jurisdictions, they have never been enacted.

Another proposal for promoting light-duty vehicle efficiency is to transfer fixed vehicle costs—such as liability insurance, registration fees, and emission inspection fees—into variable costs based on the number of miles driven per year. Such a policy would provide direct incentives to drivers to reduce their miles driven and should result in reductions in urban congestion and air pollution as well as energy use. As yet, however, no jurisdiction has adopted this strategy, although the Netherlands expects to introduce a system like this in 2007/2008.

A more severe approach to managing transportation demand is to impose restrictions on where and when vehicles can operate. A mild form of this approach involves restricting the use of certain highway lanes to vehicles with at least two or three occupants during peak commute times. Another option that may be feasible in some settings is 'congestion pricing' whereby differential tolls are charged for road use at different times of day. Revenues from congestion pricing can in turn be used to subsidize mass transit. Several cities have imposed more severe restrictions on downtown centers, mostly as a means of reducing congestion and emissions of smog-forming pollutants. Singapore was the first large city to impose limits on automobiles in its central business district, requiring cars to purchase and display special permits to enter the area during business hours. This program, combined with an excellent subway system, has been successful in reducing congestion. A more recent program has been implemented by the City of London. It is similar to the approach pioneered by Singapore and has proved quite successful: an estimated 18 percent reduction in traffic in the zone has produced a 30 percent reduction in congestion, a 20 percent reduction in carbon dioxide emissions, and 16 percent reductions in nitrogen-oxide and particulate matter emissions (Transport for London, 2005).

Changes in land-use planning represent a long-term policy option that nonetheless can have a significant impact on energy consumption. Zoning and development policies that encourage high-density housing and well-mixed residential, retail, and business areas can dramatically reduce the number and length of trips taken in private automobiles. Such policies can also help ensure that future development is amenable to more efficient or environmentally friendly transportation modes, such as public transit, bicycling, or even walking. Public transit can make a significant contribution to energy and environmental objectives (while also reducing conges-

tion and urban air pollution and increasing mobility for low-income and elderly citizens) so long as ridership on buses and trains is consistently high. Again, dense and well-mixed development is critical.

2.6 Summary points

The energy intensity of the world's industrialized and developing economies—in terms of total energy consumed per unit of economic output—has been declining steadily over the last several decades as technology has improved and as a greater share of wealth is derived from less energy-intensive activities. Taken together, however, these intensity declines have not been sufficient to offset population increases and economic growth; overall energy consumption has steadily increased—in nearly all nations and for the world as a whole. Moreover, despite evidence that the technical potential for further energy-intensity reductions is enormous, there is evidence that country-level intensities are converging over time and may not, absent further policy intervention, continue to decline at the same rate as in recent decades. Some experts warn that rising material standards of living could, at some point and in some cases, begin to reverse past declines with potentially sobering implications for the prospect of achieving long-term, global sustainability goals.

Given the significant technical potential that exists to achieve further, cost-effective intensity reductions and given the critical importance of relieving current and projected stresses on the world's energy systems, concerted policy action to maximize the contribution of demand-side options along with supply-side solutions is justified.

- **Governments should aggressively pursue cost-effective opportunities to improve energy efficiency and reduce energy intensity throughout their economies.** Policies that have proved highly effective in different contexts and should be considered include appliance and equipment efficiency standards, including vehicle fuel-economy standards; building codes; financial mechanisms (for example, fuel taxes, tax incentives for efficiency investments, and feebates); information and technical assistance programs, including labeling for consumer products and energy audit programs; procurement policies; support for utility programs, including enabling regulatory reforms, where applicable; and support for efficiency-related research and development. The availability of low-cost capital and other financial incentives to promote deployment and innovation in energy efficiency improvements is essential.

- **Facilitating technology transfer from industrialized to developing countries is particularly important.** The importance of the technology transfer is so that countries with rapidly expanding infrastructure, building stock, manufacturing capacity, and penetration of energy-using devices can 'leapfrog' to more efficient technologies. Opportunities for efficiency improvement tend to be largest and most cost-effective when they are incorporated from the ground up rather than in later retrofit applications. Ensuring that developing countries modernize their economies as efficiently as possible is crucial to manage the considerable sustainability challenges that will otherwise accompany continued global economic growth.

- **Applied social science combined with explicit policy experimentation could plausibly deliver dramatic improvement in our understanding of (a) the determinants of energy demand, (b) the effectiveness of policies designed to facilitate the adoption of energy efficient technologies, and (c) the role of efficiency improvements in moderating demand.** Governments should actively support such research both through funding and, perhaps more importantly, by enabling policy experiments to measure the effectiveness of energy-efficiency programs.

- **Barriers to the adoption of potentially cost-effective energy technologies often arise from the difficulty of effectively quantifying and aggregating myriad small opportunities for improvement and, particularly in buildings, on the need for performance monitoring, intelligent management, and integration of diverse systems.** Information technologies combined with inexpensive monitoring systems might overcome some of these barriers delivering consistent energy savings to users that would otherwise have been unattainable without expert intervention. Such options should be aggressively pursued. In addition, it will be important to develop business models for identifying and implementing cost-effective energy efficiency improvements, perhaps building on experience to date with energy service companies.

- **While a R&D push must be balanced with market pull, there should be an accelerated focus on the development of energy-efficient technologies in the following areas:**
  a. Batteries that can make plug-in hybrids widely commercial (more robust to abuse), and can take many thousands of deep discharges without loss of storage capacity;

b. Low-cost LED (light-emitting diode) lighting with a color-rendering index that is appealing to consumers;
c. Tools for designing energy-efficient residential and commercial buildings; and
d. Low-cost, efficient fuel cells that can run on natural gas for dispersed applications (home, industrial, and commercial).

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3. Energy supply

Even with concerted efforts to exploit energy-efficiency opportunities and other demand-side solutions, the world's energy needs are enormous and almost certain to continue growing as developing economies industrialize and as rising standards of living in many societies lead to increased demand for modern consumer goods, services, and amenities.

For most of human history, animals and biomass supplied the vast bulk of human energy needs. With the advent of the Industrial Revolution roughly two centuries ago, humans began to turn increasingly to hydrocarbons as their primary source of energy, marking a profound shift that brought with it an era of unprecedented technological, socio-economic, and cultural change. Today, as concerns about environmental sustainability and energy security mount, the necessity of a third transition—to a new generation of energy supply technologies and resources—seems increasingly inevitable, if still not quite imminent. Even as the world remains largely dependent on coal, oil, and natural gas, early elements of that transition are beginning to come into view.

This chapter reviews the supply-side energy technologies and resources that are likely to play a role in the transition to a sustainable energy future. Separate sections cover fossil fuels, nuclear power, non-biomass renewable resources, and biomass energy. In general, the focus is on supply-side solutions that could make an appreciable contribution to meeting world energy needs in the next 20 to 40 years. Longer-term options, such as nuclear fusion, methane hydrates, and hydrogen (as an energy carrier) are discussed briefly but do not receive extensive treatment here.

3.1 Fossil fuels

Fossil fuels—coal, petroleum, natural gas, and their byproducts—supply approximately 80 percent of the world's primary energy needs today. Use of these fuels drives industrialized economies and has become integral to virtually every aspect of productive activity and daily life throughout the modern world. Yet almost from the beginning, humanity's steadily grow-

ing dependence on fossil fuels has been a source of anxiety as well as prosperity. As early as 1866, when the Industrial Age was just getting underway, the British author Stanley Jevons wondered how long his country's coal reserves would last. Coal turned out to be a more abundant resource than Jevons could have imagined, but similar questions have long been asked about the world's petroleum and natural gas supply. More recently, concerns about global climate change have emerged as a new—and perhaps ultimately more limiting—constraint on the long-term sustainability of current patterns of fossil-fuel use.

Those patterns suggest that fossil fuels will continue to play a dominant role in the world's energy mix for at least the next several decades, even with concerted efforts to promote energy efficiency and non-carbon alternatives. How to manage and improve humanity's use of coal, petroleum, and natural gas resources during the transition to a more sustainable energy future—and in particular, whether it is possible to do so in ways that begin to mitigate climate change and energy security risks while also responding to the urgent energy needs of developing countries—is therefore a key question for policymakers and political leaders the world over. This section describes the specific challenges that exist today in connection with each of the major fossil fuel options. A significant portion of the discussion focuses on the prospects for a new generation of climate-friendly coal technologies because of the unique potential they hold for advancing multiple economic, development, energy security, and environmental policy objectives.

Status of global fossil-fuel resources

As context for this discussion, it is useful to begin by reviewing the status of fossil fuel resources in relation to current and projected patterns of consumption. Table 3.1 shows proved reserves of natural gas, oil, and coal relative to current levels of consumption and relative to estimates of the total global resource endowment for each fuel. Proved reserves reflect the quantity of fuel that industry estimates, with reasonable certainty based on available geological and engineering data, to be recoverable in the future from known reservoirs under existing economic and operating conditions. Proved reserves generally represent only a small fraction of the total global resource base. Both figures tend to shift over time as better data become available and as technological and economic conditions change. In the case of oil, for example, estimated reserves grew for much of the last half century because improved extraction capabilities and new discoveries more than kept pace with rising consumption. This has begun to change

Table 3.1 Consumption, reserves, and resources of fossil fuels

	Consumption (EJ)				Proven reserves (EJ) end 2006[b]	Lifetime of proven reserves (years) at present consumption	Consumption to date (1860-2006) as a share of proven reserves	Resource base (ZJ)[a]	Lifetime of resource base (years)
	1860 – 1998[a]	1999 – 2006[b]	1860 – 2006[a,b]	2006[b]					
Oil	5,141	1,239	6,380	164	6,888	41	92%	32.4	198
Natural gas	2,377	785	3,163	109	7,014	63	45%	49.8	461
Coal	5,989	878	6,867	130	19,404	147	35%	199.7	1,538

Note: Under *Resource base*, 1 zettajoule (ZJ) equals 103 exajoules (EJ). Resources are defined as concentrations of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form that economic extraction is potentially feasible. The *Resource base* includes proven reserves plus additional (conventional and unconventional) resources. Unconventional resources could extend lifetime of oil, gas, and coal by a factor of 5-10, but their extraction will involve advanced technologies, higher costs, and possibly serious environmental problems

Sources: (a) UNDP, UNDESA, WEC, 2000: Table 5.7. (b) BP, 2007

in recent years, however, prompting concern that oil production could peak within the next few decades leading to a period of inevitable decline in available supplies.

Global coal supplies—both in terms of known reserves and estimated total resources—are far more abundant than global supplies of conventional oil and natural gas (Table 3.1); for the latter fuels, the ratio of known conventional reserves to current consumption is on the order of 40–60 years, whereas known coal reserves are adequate to support another 150 years at 2006 rates of consumption. Obviously, any estimate of known reserves—since reserves are a measure of the resource base that is economically retrievable using current technology—is subject to change over time: as prices rise and/or technology improves, estimated reserves can grow. Nevertheless, price and supply pressures are likely to continue to affect oil and natural gas markets over the next several decades (Table 3.1). The inclusion of unconventional resources greatly expands the potential resource base, especially for natural gas, if estimates of 'additional occurrences'—that is, more speculative hydrocarbon deposits that are not yet technically accessible for energy purposes, such as methane hydrates—are included. This will be discussed further in the section on unconventional resources.

In sum, near-term energy security and supply concerns are mostly relevant for oil and, to a lesser extent, for natural gas. These concerns are serious given the central role both fuels now play in the global energy economy. With the notable exception of Brazil, which uses substantial quantities of ethanol as a vehicle fuel, transportation systems throughout the world continue to rely almost exclusively on petroleum products. The rapid modernization of large developing countries like China and India, combined with stagnant or falling vehicle fuel-economy in major consuming countries like the United States and continued growth in freight and air transport, has sharply increased global oil demand in recent years, straining the capacity of producing countries and generating strong upward pressure on oil prices. Most of the world's proven reserves of conventional oil are concentrated in a few large deposits in a few regions of the globe, most notably, of course, in the Middle East. Natural gas, meanwhile, is already an important source of energy in many parts of the world and—as the cleanest and least carbon-intensive fossil-fuel option—has an important role to play in mitigating greenhouse gas and other pollutant emissions in the transition to a next generation of energy technologies. Though remaining natural gas reserves are more widely distributed around the world than oil reserves, regional supply constraints and high prices are beginning to affect gas markets as well, driving investments to develop new resources and to expand global capacity for producing and transporting liquefied natural gas.

Defining the sustainability challenge for fossil fuels

For oil and natural gas, ther efore, the immediate policy challenge consists of finding ways to enhance and diversify supplies in an environmentally acceptable manner while, at the same time, reducing demand through improved end-use efficiency and increased use of alternatives such as biomass-based fuels (these topics are covered elsewhere in this report). Overall, however, the estimates in Table 3.1 suggest that resource adequacy per se is not likely to pose a fundamental challenge for fossil fuels within the next century and perhaps longer. Coal, in particular, is abundant—both globally and in some of the nations that are likely to be among the world's largest energy consumers in the 21st century (including the United States, China, and India). At present, coal is used primarily to generate electricity (the power sector accounts for more than 60 percent of global coal combustion) and as an energy source for the industrial sector (e.g., for steel production). More recently, rising oil and natural gas prices have generated renewed interest in using coal as a source of alternative liquid fuels.

Without substantial technology improvements, however, increased reliance on coal to meet a wider array of energy needs—while perhaps positive from an energy security standpoint—would have serious environmental implications. Coal combustion in conventional pulverized-coal steam-electric power plants and coal conversion to liquid or gaseous fuels using conventional methods—that is, without carbon capture and sequestration—generates substantially larger quantities of carbon dioxide than does the direct combustion of oil or natural gas. Of course, the carbon generated in the process of converting coal to liquid fuel can theoretically be captured and sequestered (although few if any recent proposals for coal-to-liquids production provide for carbon capture). The carbon in the resulting liquid fuel is still released, however, when the fuel is combusted, generating in-use greenhouse gas emissions similar to those associated with conventional gasoline or diesel fuel. From a climate perspective, therefore, coal-to-liquids technology generates emissions that are—at best—roughly equivalent to those of the conventional fuels it replaces. If carbon dioxide is not captured and sequestered as part of the conversion process, coal-to-liquids generate as much as two times the full fuel-cycle emissions of conventional petroleum.

Thus, climate impacts, more than resource depletion, are likely to emerge as the most important long-term constraint on fossil-fuel use in general, and coal use in particular. Current means of utilizing fossil fuels all produce emissions of carbon dioxide, the primary greenhouse gas directly generated by human activities. Today's known reserves total more than twice the cumulative consumption that occurred between 1860 and 1998 (Table 3.1). Even if future consumption of fossil fuels were limited to today's known reserves, the result of burning these fuels (absent measures to capture and sequester resulting carbon dioxide emissions) would be to release more than double the amount of carbon that has already been emitted to the atmosphere. Accordingly, much of the remainder of this discussion focuses on the prospects for a new generation of coal technologies that would allow for continued use of the world's most abundant fossil-fuel resource in a manner compatible with the imperative of reducing climate-change risks.

Coal consumption is expected to grow strongly over the next several decades primarily in response to rapidly increasing global demand for electricity, especially in the emerging economies of Asia. At present, coal supplies nearly 40 percent of global electricity production; as a share of overall energy supply, coal use is expected to remain roughly constant or even decline slightly, but in absolute terms global coal consumption is

expected to increase by more than 50 percent over the next quarter century— from 2,389 million tons oil equivalent in 2002 to 3,601 million tons oil equivalent in 2030, according to the most recent IEA (2006) reference case forecast. Increased consumption is all but inevitable given that coal is by far the most abundant and cheapest resource available to China and India as these countries continue industrializing and seek to raise living standards for hundreds of millions of people. China alone is expanding its coal-based electric-generating capacity by some 50 gigawatts per year, or the equivalent of roughly one large (1 gigawatt) power plant per week. At 1.9 billion metric tons in 2004, its coal use already exceeds that of the United States, Japan, and the European Union combined. At the annual growth rate of 10.9 percent in 2005, China's coal consumption could double in seven years. India is in a similar situation with rapid economic growth and a population that is expanding more quickly than China's.

Advanced coal technology options

Today's dominant coal-using technologies involve the direct combustion of finely ground, or pulverized, coal in steam boilers. Older coal plants and coal plants in much of the developing world operate at relatively low rates of efficiency and generate large quantities of sulfur dioxide, nitrogen oxides, soot, and mercury as well as carbon dioxide. These pollutants create substantial public health risks, especially where emissions remain largely unregulated (as is the case in many developing countries). In some parts of the world, emissions from coal-fired power plants also contribute to pollution transport problems that transcend national and even continental borders. In addition, coal mining itself typically produces substantial local environmental impacts and poses significant health and safety risks to miners. Over time, pulverized coal technology has improved to achieve electricity-production efficiencies in excess of 40 percent and sophisticated pollution control technologies have been developed that can reliably reduce sulfur, nitrogen, particulate, and toxic air emissions by 97 percent or more. Importantly, these technologies do not reduce carbon dioxide emissions, which remain essentially uncontrolled in current conventional coal applications.

Significant environmental benefits can therefore be achieved simply by raising the efficiency of conventional pulverized coal plants (thereby reducing fuel consumption and carbon emissions per unit of electricity generated) and by adding modern pollution controls. Figure 3.1 plots the average

conversion efficiency of coal-fired power plants in different countries over time. The graph shows that several countries have achieved significant improvements in average efficiency over the last decade, but that further progress has slowed or plateaued in several cases. Remaining variation in average power-plant performance across different countries suggests there is room for further gains and that substantial carbon reductions can be achieved from efficiency improvements at conventional coal plants. Meanwhile, a new generation of coal technologies offers promise for further improving efficiency, generating useful co-products, and enhancing opportunities for cost-effective carbon capture and sequestration.

Two technologies that improve on conventional pulverized coal technology have been under development for some time and are already in commercial use worldwide. So-called 'supercritical' systems generate steam at very high pressure, resulting in higher cycle efficiency and lower emissions. Currently, about 10 percent of orders for new coal-fired plants are for supercritical steam systems. Of the more than 500 units of this type that already exist, most are in the countries of the former Soviet Union, Europe, and Japan. Another technology, known as fluidized-bed combus-

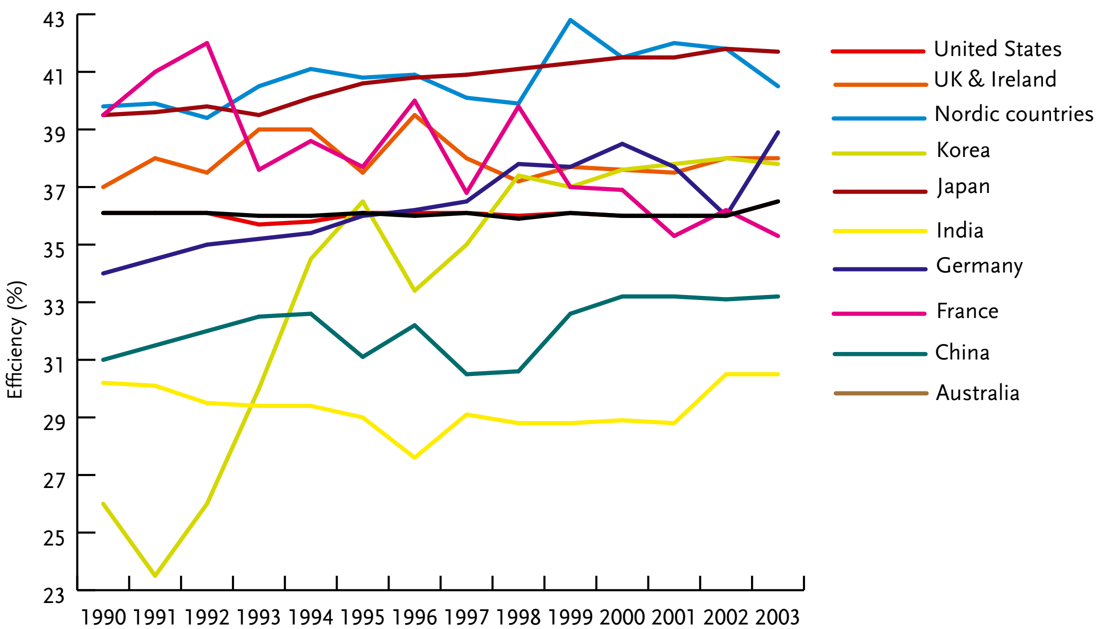

Figure 3.1 Efficiency of coal-fired power production

Source: Graus and Worrell, 2006.

tion, was developed as early as the 1960s. By combusting coal on a hot bed of sorbent particles, this technology capitalizes on the unique characteristics of fluidization to control the combustion process. Fluidized-bed combustion can be used to burn a wide range of coals with varying sulfur and ash content while still achieving advanced levels of pollution control; currently, some 1,200 plants around the world use this technology. Fluidized-bed systems have actually become less common in power plant applications, however, because the technology is best suited for smaller-scale applications (e.g., 30 megawatt units).

In contrast to supercritical or fluidized-bed systems, further advances in coal technology are likely to involve first gasifying the coal rather than burning it directly in pulverized form. Gasification converts coal (or potentially any carbon-containing material) into a synthesis gas composed primarily of carbon monoxide and hydrogen. The gas, in turn, can be used as a fuel to generate electricity; it can also be used to synthesize chemicals (such as ammonia, oxy-chemicals, and liquid fuels) and to produce hydrogen. Figure 3.2 describes the potential diversity of applications for coal gasification technology in schematic form.

Gasification technology itself is well developed (worldwide, some 385 modern gasifiers were in operation in 2004), but historically it has been used primarily in industrial applications for the production of chemicals, with electricity generation as a secondary and subordinate process. More recently, interest has focused on coal-based integrated gasification combined cycle (IGCC) technology as an option for generating electricity.

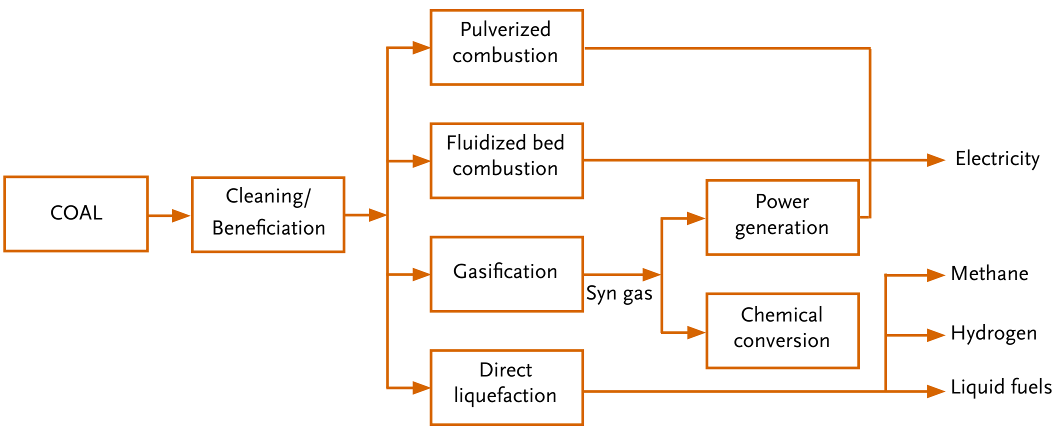

Figure 3.2 From coal to electricity and usable products

The gasification process not only allows for very low emissions of conventional pollutants, it facilitates carbon capture and sequestration and allows for the simultaneous production of valuable co-products, including liquid fuels. Given that high levels of pollution control can also be achieved in state-of-the-art pulverized coal plants, the latter two attributes provide the primary motivation for current interest in coal IGCC.

The first IGCC power plant was tested in Germany in the 1970s, but commercial-scale applications of this technology for electricity generation remain limited to a handful of demonstration facilities around the world. This situation may change significantly in the next few years, given rapidly growing interest in IGCC technology and recent announcements of a new round of demonstration plants in the United States and elsewhere. At the same time, concerns about cost, reliability, and lack of familiarity with IGCC technology in the electric power industry are likely to continue to present hurdles for some time. Cost estimates vary, but run as much as 20–25 percent higher for a new coal IGCC plant compared to a conventional pulverized coal plant, particularly if the conventional plant lacks modern pollution controls for sulfur and nitrogen oxide emissions. In addition, gasification-based processes are more sensitive to coal quality; from a cost perspective, the use of coals with lower heating values further disadvantages IGCC technology relative to the conventional alternatives. This may be a significant issue in countries like China and India that have large deposits of relatively poor-quality coal.

The higher cost of coal IGCC technology can obviously create a major impediment in some developing countries where access to capital may be constrained and where competing economic and development needs are particularly urgent. Often, advanced coal systems are also more complicated to construct and operate and more difficult to maintain. This need not be an impediment per se (apart from the cost implications) since construction and operation can usually be outsourced to large multinational companies, but the need to rely on outside parts and expertise may be viewed as an additional disadvantage by some countries. To overcome these obstacles, some countries have adopted incentives and other policies to accelerate the demonstration and deployment of IGCC technology, but the vast majority of new coal plants proposed or under construction in industrialized and developing countries alike still rely on pulverized coal technology. Given that each new facility represents a multidecade commitment in terms of capital investment and future emissions (power plants are typically expected to have an operating life as long as 75 years), the importance of accelerating the market penetration of advanced

coal technologies is difficult to overstate.

Future efforts to speed the deployment of cleaner coal technologies generally and IGCC technology in particular will be affected by several factors: the cost of competing low-emission options, including post-combustion carbon capture and sequestration for conventional coal technologies as well as natural gas and renewable technologies; the existence of continued support in the form of incentives, public funding for related research and development (R&D) activities, and favorable regulatory treatment; and—perhaps most importantly—the evolution of environmental mandates, especially as regards the control of greenhouse gas emissions.[28] The next section of this chapter provides a more detailed discussion of the prospects for different coal technologies—including conventional pulverized coal technology and oxy-fuel combustion as well as coal gasification—in combination with carbon capture and sequestration. Among other things, it suggests that for power production alone (that is, leaving aside opportunities to co-produce liquid fuels), the cost advantages of familiar pulverized coal technology relative to IGCC could largely offset the cost disadvantages of post-combustion carbon capture. Another important finding is that sequestration is not currently expected to pose any insurmountable challenges, either from the standpoint of available geologic repositories or from the standpoint of the technology needed to capture, transport, and inject carbon waste streams. Nevertheless, carbon capture and sequestration will generally represent an added cost (except perhaps in some instances where it can be used for enhanced oil recovery) and experience with sequestration systems at the scale necessary to capture emissions from commercial power plants remains limited at present.

Whichever technology combination proves most cost-effective and attractive to the investors, the price signals associated with future carbon constraints will need to be predictable and sufficient in magnitude to overcome remaining cost differentials when those cost differentials reflect not only the cost and risk premium associated with advanced coal technologies but the cost and feasibility of capturing and sequestering carbon. Progress toward reducing those cost differentials would greatly enhance the pros-

28 The gasification process also facilitates the capture of conventional air pollutants, like sulfur and nitrogen oxides. Regulatory requirements pertaining to the control of these and other pollutants (like mercury) could therefore also affect the cost competitiveness of IGCC systems relative to conventional pulverized coal systems. Given that effective post-combustion control technologies for most of these non-greenhouse gas emissions are already well-demonstrated and commercially available, carbon policy is likely to be a decisive factor governing future IGCC deployment.

pects for a successful transition toward sustainable energy systems given the relative abundance and low cost of the world's coal resource base. Besides providing electricity, advanced coal gasification systems with carbon capture and sequestration could become an important source of alternative transportation fuels.

Technologies already exist for directly or indirectly (via gasification) converting solid hydrocarbons such as coal to liquid fuel. Such coal-to-liquids systems may become increasingly attractive in the future, especially as countries that are coal-rich but oil-poor confront rising petroleum prices. Unfortunately, existing liquefaction processes are energy intensive, require large quantities of water, and generate very substantial carbon emissions. Modern, integrated gasification systems that produce both electricity and clean-burning liquid fuels offer the potential to greatly improve overall cycle efficiency and environmental performance, especially if coupled with cost-effective carbon capture and sequestration.

In the near future, new coal IGCC facilities are most likely to be constructed in the United States, Japan, and—to a lesser extent, given relatively small growth in overall coal capacity—the European Union. Some developing countries, notably China and India, have also expressed strong interest in this technology. In sum, knowledgeable observers express different degrees of optimism (or pessimism) about the prospects for accelerated diffusion of advanced coal technologies, but there is little disagreement about the nature of the obstacles that stand in the way or about how much may be at stake in successfully overcoming them.[29]

Carbon capture and sequestration

Successful development of carbon capture and sequestration technology could dramatically improve prospects for achieving the goal of reducing greenhouse gas emissions. From a technical standpoint, several options exist for separating and capturing carbon either before or after the point of fuel combustion. In addition, the magnitude of potentially suitable storage capacity in geologic repositories worldwide is thought to be sufficient to accommodate many decades (and perhaps centuries) of emissions at current rates of fossil-fuel use. At the same time, however, substantial hurdles must be overcome: large-scale efforts to capture and sequester carbon will add cost, will require additional energy and new infrastructure (including pipelines to transport the carbon dioxide to sequestration sites

29 For additional information on advanced coal technologies, see the MIT (2001) report, *The Future of Coal*.

and wells to inject it underground), may necessitate new institutional and regulatory arrangements, and may have difficulty winning public acceptance. Operational experience to date with some of the requisite systems for implementing carbon capture and sequestration has come primarily from the chemical processing, petroleum refining, and natural gas processing industries and from the use of compressed carbon dioxide for enhanced oil recovery. Several demonstration projects specifically aimed at exploring carbon capture and sequestration as a greenhouse gas-reduction strategy are now proposed or underway and two industrial-scale facilities are currently implementing carbon dioxide storage for the sole purpose of avoiding emissions to the atmosphere. Nevertheless, large-scale deployment of such systems is likely to continue to be slow—except in those instances where enhanced oil recovery provides favorable economic opportunities—without compelling regulatory or market signals to avoid carbon dioxide emissions.

CARBON CAPTURE

The most straightforward way to capture carbon from fossil energy systems is to recover it after combustion from the flue gases of large combustors such as power plants. On a volume basis, carbon dioxide typically accounts for between 3 percent (in the case of a natural gas combined-cycle plant) and 15 percent (for a coal combustion plant) of the flow of exhaust gases from such facilities. Though several options for post-combustion capture are available, the preferred approach exploits a reversible chemical reaction between an aqueous alkaline solvent (usually an amine) and carbon dioxide.

Because this approach involves separating carbon dioxide at relatively low concentrations from a much larger volume of flue gases, and because the regeneration of amine solvent and other aspects of the process are energy intensive, post-combustion carbon capture carries significant cost and energy penalties. According to a IPCC (2005) literature review, the fuel requirements for a new steam electric coal plant with an amine scrubber are anywhere from 24–40 percent higher than for the same plant venting carbon dioxide. Put another way, carbon capture reduces the efficiency of the power plant such that its electricity output per unit of fuel consumed is reduced by 20–30 percent.

Another approach, known as oxy-fuel combustion uses oxygen instead of air for combustion producing an exhaust stream that consists primarily of water and carbon dioxide. This option is still under development. A third

approach is to separate carbon prior to combustion by first converting the subject fuel to a synthesis gas composed primarily of carbon monoxide and hydrogen. The carbon monoxide in the synthesis gas is then reacted with steam to form more hydrogen and carbon dioxide. Typically, carbon dioxide is removed from the synthesis gas using a physical solvent that does not chemically bind the carbon dioxide as amines do. At that point, the favored approach for electricity production is to burn the remaining hydrogen-rich synthesis gas in a gas turbine/steam turbine combined-cycle power plant. Alternatively, the process can be adjusted to leave a higher carbon-to-hydrogen ratio in the syngas and then convert it, using Fischer-Tropsch or other chemical processes, to synthetic liquid fuels.

Efforts to explore pre-combustion carbon capture have mostly focused on IGCC technology to generate power using coal, petcoke or other petroleum residues, or biomass. The gasification process offers potential benefits—and some offsetting cost savings—with respect to conventional-pollutant control. On the other hand, it remains for now more expensive and—until more experience is gained with full-scale demonstration plants—less familiar than conventional combustion systems in power plant applications. However, interest in advanced coal systems has intensified significantly in recent years; and the marketplace for IGCC technology, at least in some parts of the world, now appears to be evolving rapidly.

Coal IGCC accounts for less than 1 gigawatt-electricity out of the 4 gigawatts- electricity of total IGCC capacity that has been built—most of the rest involves gasification of petroleum residues. While there has been only modest experience with coal IGCC without carbon capture, experience with gasification and capture-related technologies in the chemical process and petroleum-refining industries makes it possible to estimate capture costs for coal IGCC with about the same degree of confidence as for conventional steam-electric coal plants. Importantly, the decisive advantage of coal IGCC in terms of carbon capture is for bituminous coals, which have been the focus of most studies. The situation is less clear for subbituminous coals and lignites, for which very few IGCC analyses have been published. More study is needed to clarify the relative ranking of carbon capture and sequestration technologies for lower-quality coals.

The IPCC (2005) literature review summarized available information on carbon capture and sequestration costs. It concluded that available methods could reduce carbon dioxide emissions by 80–90 percent and that, across all plant types, the addition of carbon capture increases electricity production costs by US$12–36 per megawatt-hour. The IPCC review

further concluded that the overall cost of energy production for fossil-fuel plants with carbon capture ranged from US$43–86 per megawatt-hour. The cost for avoiding carbon dioxide emissions (taking into account any extra energy requirements for the capture technology and including the compression but not the transport of captured carbon dioxide) ranged from US$13–74 per metric ton of carbon dioxide.

According to the IPCC, most studies indicated that 'IGCC plants are slightly more costly without capture and slightly less costly with capture than similarly sized [pulverized coal] plants, but the differences in cost for plants with [carbon dioxide] capture can vary with coal type and other local factors.' Moreover, 'in all cases, [carbon dioxide] capture costs are highly dependent upon technical, economic and financial factors related to the design and operation of the production process or power system of interest, as well as the design and operation of the [carbon dioxide] capture technology employed. Thus, comparisons of alternative technologies, or the use of [carbon capture and storage] cost estimates, require a specific context to be meaningful.' In other words, no clear winner has yet emerged among competing options for carbon capture—on the contrary, a healthy competition is currently underway between different technologies—and it is likely that different approaches will prove more cost-effective in different contexts and for different coal types.

Carbon sequestration

Three types of geological formations are being considered for sequestering carbon dioxide: depleted oil and gas fields; deep salt-water filled formations (saline formations); and deep unminable coal formations (Figure 3.3). These formations occur in sedimentary basins, where layers of sand, silt, clay, and evaporate have been compressed over geological time to form natural, impermeable seals capable of trapping buoyant fluids, such as oil and gas, underground. Most experience to date with the technologies needed for carbon sequestration has come from the use of carbon dioxide for enhanced oil recovery in depleted oil fields—an approach that is likely to continue to offer significant cost-advantages in the near term, given current high oil prices. As a long-term emissions-reduction strategy, however, carbon sequestration would need to expand beyond enhanced oil or natural gas recovery to make use of saline formations, which have the largest storage potential for keeping carbon dioxide out of the atmosphere.

Research organizations have undertaken local, regional, and global assessments of potential geologic sequestration capacity since the early

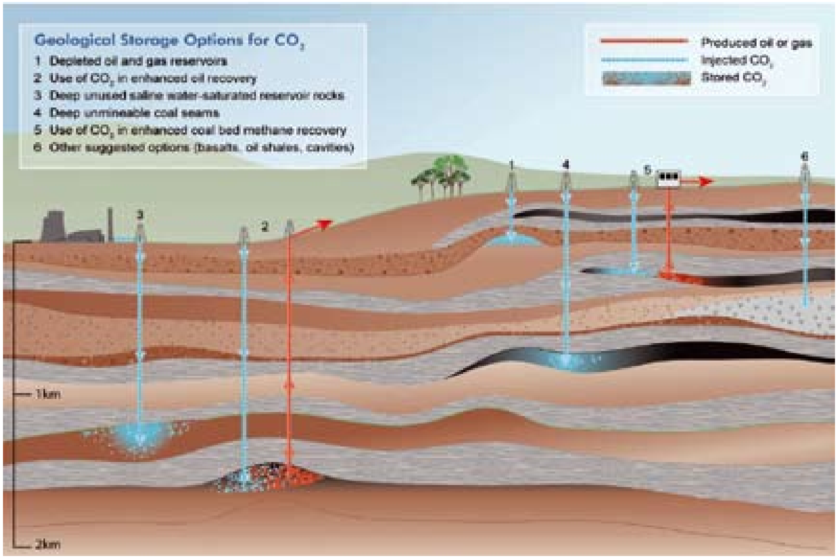

Figure 3.3 Schematic illustration of a sedimentary basin with a number of geological sequestration options

Source: IPCC, 2005

1990s (IPCC, 2005). In general, the most reliable information is available from oil and gas reservoirs; the least reliable information is available for coal seams. The reliability of capacity estimates for saline formations varies, depending on the quality of geological information available and the method used to calculate capacity. Table 3.2 summarizes the most current assessment of sequestration capacity. Saline formations have the largest potential capacity, but the upper estimates are highly uncertain, due both to a lack of accepted methodology for assessing capacity and a lack of data, especially for some parts of the world such as China, Latin America, and India). Overall, current estimates suggest that a minimum of about 2,000 gigatons of carbon dioxide sequestration capacity is available worldwide; roughly equivalent to 100 years of emissions at the current global emissions rate of roughly 24 gigatons per year.[30]

30 The amount of carbon dioxide storage capacity available underground should not be considered a fixed quantity. Rather, pore space for storage in sedimentary formations is like any other fuel or mineral reserve where the quantity available over time is likely to increase as science and technology improve and as the price people are willing to pay for the resource rises.

Table 3.2 World-wide CO2 geological sequestration capacity estimates

Reservoir type	Lower estimate of storage capacity ($GtCO_2$)	Upper estimate of storage capacity ($GtCO_2$)
Oil and gas fields	675[a]	900[a]
Unminable coal seams (enhance coal-bed methane)	3–15	200
Deep saline formations	1,000	Uncertain, but possibly 10^4

(a)These estimates would increase by 25 percent if undiscovered reserves were included. *Note:* GtCO2 refers to gigatons carbon dioxide.

Source: IPCC, 2005

There are several reasons to think that carbon dioxide sequestration can be essentially permanent. The existence of natural reservoirs of oil, gas, and carbon dioxide by itself is indicative. Further evidence comes from extensive experience with methods for injecting and storing fluids underground in other industrial contexts and from more recent experience with several early demonstration projects. Finally, the existence of several natural trapping mechanisms, which together tend to diminish the likelihood of leakage over time, and results from computer simulation models provide grounds for additional confidence in the ability to achieve very long-term storage in underground reservoirs.

In its recent assessment, the IPCC concluded that the fraction of carbon dioxide retained in appropriately selected and managed geological reservoirs is 'very likely to exceed 99% over 100 years, and is likely to exceed 99% over 1,000 years' (IPCC, 2005). Past experience also indicates that the risks associated with geologic sequestration are likely to be manageable using standard engineering controls, although regulatory oversight and new institutional capacities will likely be needed to enhance safety and to ensure robust strategies for selecting and monitoring sites. Employed on a scale comparable to existing industrial analogues, the risks associated with carbon capture and sequestration are comparable to those of today's oil and gas operations.

Even after the carbon dioxide is injected, long-term monitoring will be important for assuring effective containment and maintaining public confidence in sequestration facilities. While carbon dioxide is generally regarded as safe and non-toxic, it is hazardous to breathe at elevated concentrations and could pose risks if it were to accumulate in low-lying, confined, or poorly ventilated spaces. Past experience suggests that leakage or surface releases are most likely to occur at the injection site or at older, abandoned wells that were

not properly sealed; fortunately, several methods exist for locating such leaks and monitoring injection wells. Nevertheless, public acceptance of underground carbon sequestration in light of the potential for leakage and associated safety risks could emerge as a significant issue—especially in the early phases of deployment—and will need to be addressed.

Cost penalties for carbon capture and sequestration can be broken down into capture costs (which include drying and compressing the carbon dioxide), costs for transporting carbon dioxide to storage sites, and storage costs. The 2005 IPCC literature review arrived at an average, overall cost figure of US$20–95 per ton of carbon dioxide captured and sequestered based on the following estimates: capture costs ranging from US$15–75 per ton; pipeline transport costs ranging from US$1–8 per ton (US$2–4 per ton per 250 kilometers of onshore pipeline transport); geologic storage costs of US$0.5–8.0 per ton (excluding opportunities for enhanced oil recovery); and monitoring costs of US$0.1–0.3 per ton.

Planned and existing carbon capture and sequestration projects

The first commercial amine scrubber plant to employ post-combustion carbon dioxide capture has been operating in Malaysia since 1999. This plant recovers approximately 200 tons of carbon dioxide per day for urea manufacture (equivalent to the emission rate for a 41 megawatts-thermal coal combustor). An IGCC plant with carbon capture has not yet been built and, as noted previously, experience with coal IGCC systems for power generation (even without carbon capture and sequestration) remains limited. The first example of an IGCC unit with capture and sequestration is likely to be a 500 megawatts-electricity unit that will gasify petroleum coke at the Carson refinery in southern California and use the captured carbon dioxide for enhanced oil recovery in nearby onshore oil fields. The project will be carried out by BP and Edison Mission Energy and is scheduled to come on line early in the next decade.

In terms of geological sequestration for the purpose of avoiding carbon emissions to the atmosphere, two industrial-scale projects are operating today: a ten year old project in the Norwegian North Sea and a more recent project in Algeria. A third project in Norway is expected to be operational in late 2007. (Industrial-scale geologic sequestration is also being implemented at the Weyburn project in Canada, but in this case for purposes of enhanced oil recovery.) To date, all of these projects have operated safely with no indication of leakage. Plans for new sequestration projects are now being announced at a rate of several each year, with plans for further large-

scale applications announced in Australia, Norway, the United Kingdom, and the United States (as part of the FutureGEN consortium). In addition, dozens of small-scale sequestration pilot projects are underway worldwide and more are expected. For example, the U.S. Department of Energy has sponsored seven Regional Sequestration Partnerships to conduct 25 sequestration pilot tests in different geological formations; similar pilot tests are being carried out in Australia, Canada, Germany, Japan, the Netherlands, and Poland.

Looking ahead, enhanced oil recovery may offer the most promising near-term opportunities for carbon capture and sequestration. Carbon dioxide, mostly from natural sources, is already being used to support about 200,000 barrels per day of incremental oil production in the United States. This has already produced valuable experience with many aspects of the technology needed for successful transport and sequestration—including experience with carbon dioxide pipelines. As a result, costs for the technologies required to capture carbon dioxide at large power plants or other energy facilities are already low enough to be competitive where there are enhanced oil recovery opportunities nearby (Williams and others, 2006a; and 2006b). The economic potential for carbon dioxide-enhanced oil recovery is substantial (e.g., enough to support 4 million barrels per day of crude oil production for 30 years in the United States alone). Although coupling gasification energy and enhanced oil recovery projects will not always be feasible, this niche opportunity could nevertheless be significant enough to gain extensive early experience and 'buy down' technology costs for both gasification energy and carbon capture and storage technologies, even before a climate change mitigation policy is put into place.

Unconventional resources, including methane hydrates

The world's petroleum and natural gas resource base is considerably larger if unconventional sources of these fuels are included (noted in Table 3.1). In the case of petroleum, unconventional resources include heavy oil, tar sands, and oil shale. It has been estimated that if these resources could at some point be economically recovered in an environmentally acceptable fashion, the hemispheric balance of global petroleum resources would shift substantially. Interest in exploiting unconventional resources has grown of late as a direct result of high oil and natural gas prices and in response to energy security concerns that have heightened interest in options for diversifying global oil supplies and widening the gap between

available production capacity and demand. At present, Canada is producing about 1 million barrels per day of unconventional oil from tar sands, and Venezuela has started to tap its substantial heavy oil reserves.

Current technologies for extracting unconventional oil may not, however, be sustainable from an environmental standpoint. Depending on the type of resource being accessed and the technologies used, current extraction methods are highly energy-intensive and thus generate significantly higher greenhouse gas emissions compared to conventional oil production. In many cases they also produce substantial air, water, and ground surface pollution. Unless technologies can be developed that address these impacts and unless the environmental costs of extraction (potentially including carbon capture and sequestration) are included, efforts to develop unconventional oil supplies are unlikely to be environmentally sustainable.

Other fossil-fuel related technologies that could impact the longer-term supply outlook for conventional fuels, with potentially important implications for energy-security and sustainability objectives, include technologies for enhanced oil recovery, for collecting coal bed methane, for accessing 'tight gas' (natural gas that is trapped in highly impermeable, hard rock or non-porous sandstone or limestone), and for the underground gasification of coal.

The situation for methane hydrates is more complex and remains, for now, more speculative given that the technologies needed to tap this resource have not yet been demonstrated. Hydrates occur under certain high-pressure and low-temperature conditions when molecules of gas become trapped in a lattice of water molecules to form a solid, ice-like structure. Huge deposits of methane hydrate are thought to exist in the Arctic region, both on- and off-shore, and in other locations below the ocean floor (typically at depths ranging from 300–1,000 meters). These hydrates hold some promise as a future source of energy, both because the size of the potential resource base is enormous and because natural gas (methane) is a relatively clean-burning fuel with lower carbon density than oil or coal. Ironically, however, there is also concern that the same deposits could play a negative role in accelerating climate change if warming temperatures cause the hydrates to break down, producing large, uncontrolled releases of methane—a potent warming gas—directly to the atmosphere.

Technologies for exploiting methane hydrates are in the very early stages of development. As in conventional oil production, likely methods could involve depressurization, thermal stimulation, or possibly solvent injec-

tion. The fact that hydrates are stable only within a narrow band of temperature and pressure conditions complicates the technology challenge and creates some potential for significant unintended consequences (e.g., destabilizing sea beds or generating large accidental releases of methane to the atmosphere). At present, both the opportunities and the risks are poorly understood, and technologies for economically accessing the methane trapped in naturally occurring hydrates have yet to be demonstrated. Japan currently leads global efforts to remedy this gap and has created a research consortium with the aim of developing technologies feasible for commercial-scale extraction by 2016.

In summary: Fossil fuels

Dependence on fossil fuels for a dominant share of the world's energy needs is at the core of the sustainability challenge humanity confronts in this century. The combustion of natural gas, oil, and coal generates carbon dioxide emissions along with other damaging forms of air pollution. The world's steadily expanding stock of coal-fired power plants is expected to create significant climate liabilities for decades to come. At the same time, the prospect of an intensifying and potentially destabilizing global competition for relatively cheap and accessible oil and natural gas supplies is again stoking urgent energy security concerns in many parts of the world. For many poor countries, meanwhile, outlays for oil and other imported fuel commodities consume a large share of foreign exchange earnings that could otherwise be used to invest in economic growth and social development.

In this context, the fundamental problem with fossil fuels is not primarily that they are in short supply. Coal in particular is relatively inexpensive and abundant worldwide and it is already being looked to as an alternative source of liquid and gaseous fuel substitutes in the context of tightening markets and rising prices for oil and natural gas. Unfortunately, expanded reliance on coal using today's technologies would add substantially to rising levels of greenhouse gases in the atmosphere, creating a major source of environmental as well as (given the potential consequences of global warming) social and economic risk.

Managing these risks demands an urgent focus on developing economical, low-carbon alternatives to today's conventional fuels, along with new technologies for using fossil fuels that substantially reduce their negative impacts on environmental quality and public health. The availability of cost-effective methods for capturing and storing carbon dioxide emissions,

in particular, would significantly improve prospects for achieving sustainability objectives in this century and should be the focus of sustained research, development, and deployment efforts in the years ahead. Current trends in fossil-fuel consumption are unlikely to change, however, without a decisive shift in market and regulatory conditions. Government policies must be re-aligned: subsidies for well-established conventional fuels should be phased out and firm price signals for avoided greenhouse gas emissions—of sufficient magnitude to offset cost differentials for lower-carbon technologies—must be introduced.

3.2 Nuclear power

Nuclear power supplies approximately 16 percent of today's global electricity demand and, along with hydropower, accounts for the largest share of power generation from non-carbon energy sources. More than two dozen reactors are now under construction or will be refurbished over the next few years in Canada, China, several European Union countries, India, Iran, Pakistan, Russia, and South Africa. The world's existing base of nuclear capacity includes some 443 reactor units with a combined capacity of about 365 gigawatts (Figure 3.4). The great majority of these units (nearly 80 percent) are more than 15 years old.

While total nuclear electricity output is likely to grow modestly within this decade, reflecting the addition of new capacity now planned or under construction, the overall nuclear contribution is expected to plateau thereafter and even decline slightly over the next two decades as more plants retire than are added worldwide and as growth in nuclear plant output falls behind growth in overall electricity demand. As a result, the most recent IEA reference case forecast (Figure 3.5) indicates that nuclear power's share of global electricity production will fall to just 12 percent by 2030. The IEA estimate of total nuclear output for 2030 is just under 3,000 terawatt-hours, only slightly more than the 2,500 terawatt-hours produced by the industry in 2002. These projections are roughly consistent with projections released by the International Atomic Energy Agency (IAEA) in 2004 that show the nuclear contribution falling to 13–14 percent of global electricity production in 2030 under high- and low-growth assumptions.[31]

31 The IAEA's high-growth projections indicate 592 gigawatts of nuclear capacity in 2030 compared to 427 gigawatts in the IAEA's low-growth projection. As a share of overall electricity production, however, the nuclear contribution is actually slightly smaller in the high-growth case (13 percent) than in the low-growth case (14 percent). This is because overall electricity demand grows even faster than nuclear capacity in the high-growth case (IAEA, 2004).

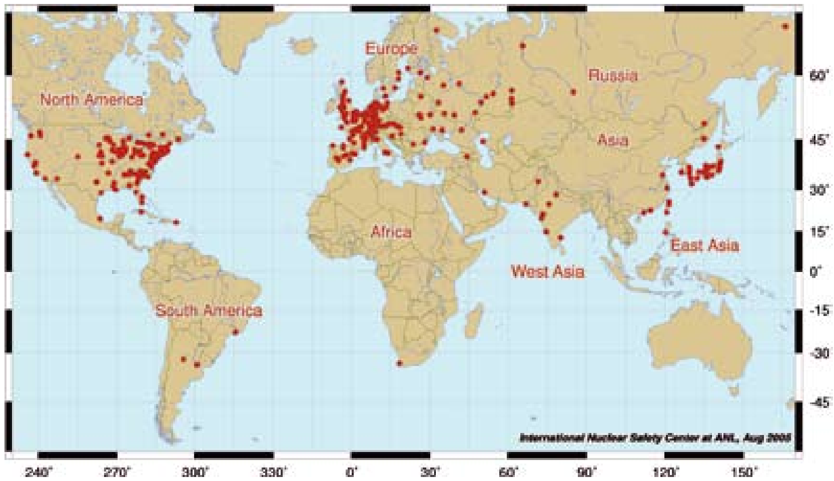

Figure 3.4 Existing and planned/proposed nuclear reactors in the world

Source: International Nuclear Safety Center, Argonne National Laboratory

Current expectations of flat or declining nuclear output reflect an assumption that high upfront capital cost[32] and other obstacles will continue to disadvantage nuclear power relative to other options for new electric-generating capacity, particularly compared to conventional, pulverized-coal power plants.

Current interest in reversing this trend and in supporting an expanded role for nuclear power is driven largely by climate change considerations and by concern that the other non-carbon options alone—including energy efficiency, renewable energy, and advanced fossil technologies with carbon sequestration—will not be adequate to reconcile burgeoning global energy demands (especially growing demand for electricity) with the need for greenhouse gas mitigation. On the one hand, nuclear technology offers important advantages: it can provide a reliable, large-scale source of baseload electric-generating capacity;[33] it does not produce emissions of greenhouse gases or conventional air pollutants; and supplies of nuclear fuel, in the form of uranium ore, are relatively abundant worldwide.[34] In addition,

32 Operating costs for nuclear plants are generally low relative to fossil-fuel power plants.
33 Conversely, a disadvantage of nuclear power plants in some contexts is that they must operate in a baseload capacity. One possibility for using nuclear power generation during off-peak hours would be to make use of another energy carrier, such as hydrogen. The production of hydrogen through electrolysis could provide one means of storing carbon-free nuclear energy at times of low demand.
34 The sustainability of uranium as long-term energy source has been much debated, with

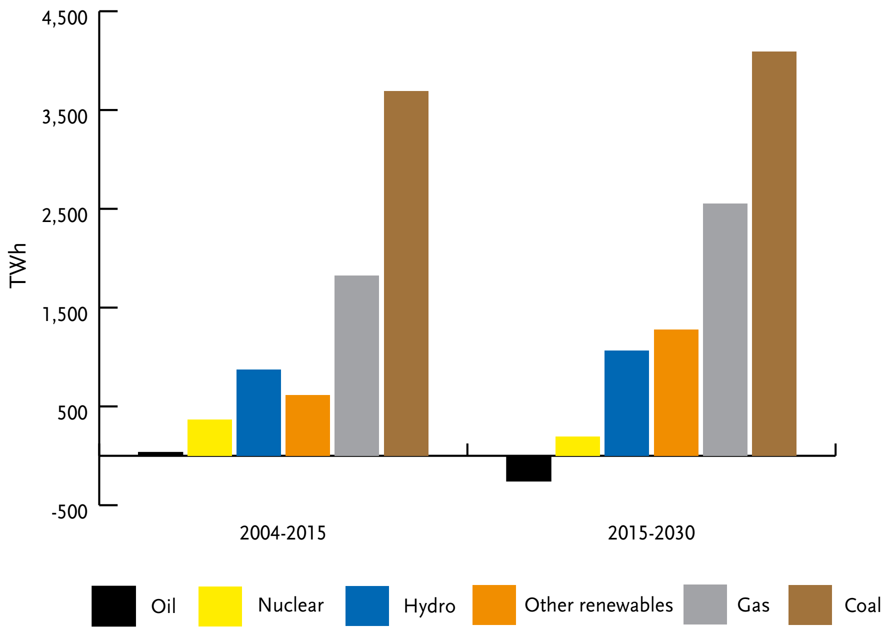

Figure 3.5 Projected world incremental electricity generation by fuel type

Note: 1 terawatt-hour (TWh) equals 3.6 petajoules.

Source: IEA, 2006

the potential exists to use nuclear power for high-temperature hydrogen production, which would enable the technology to serve a wider array of energy needs besides electricity production. Plans for 'hybrid' reactors that would co-produce hydrogen and electricity have been proposed.

Other factors that are likely to continue motivating some governments to support nuclear power include energy-security concerns, especially in light

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some arguing that limited supplies of low-cost ore will constrain nuclear power production within this century absent progress toward developing acceptable closed fuel-cycle systems. Current market conditions suggest, however, that adequacy of available uranium supplies is unlikely to be an issue for some time. For example, a MIT (2003) study concluded that the worldwide supply of uranium ore was sufficient to fuel the deployment of 1,000 new reactors in the next 50 years and to supply this new fleet of plants over a 40-year operating life. In addition, uranium prices around the world have been relatively low and stable and the geographic distribution of uranium deposits is such that the fuel itself is likely to be less susceptible to cartels, embargoes, or political instability. Should supply constraints eventually cause uranium prices to rise, this would prompt further exploration that would likely yield a substantial increase in estimated reserves; longer term, options might also emerge for extracting uranium, which is a relatively common element, from unconventional sources like sea water.

of recent volatility in world oil markets and the perception that development of an indigenous nuclear capability offers a route to technological advancement while conferring a certain 'elite' status among the world's industrialized powers. Finally, efforts to build a domestic nuclear industry can provide useful ambiguity for governments that wish to leave open the possibility of developing nuclear weapons. Associated equipment (like hot laboratories), operator training, and experience with health and safety issues are some obvious examples of the potential carry-over from nuclear power technology to nuclear weapons capability that is latent in any civilian nuclear power program.

But nuclear power also suffers from several difficult and well-known problems that are likely to continue to constrain future investments in this technology. Chief hurdles for primary investors include high upfront capital cost, siting and licensing difficulties, public opposition, and uncertainties regarding future liabilities for waste disposal and plant decommissioning. In addition to—and inextricably intertwined with—these issues, many experts agree that concerns about reactor safety, waste disposal, and nuclear weapons proliferation must be resolved if nuclear technology is to play a prominent role in the transition to a sustainable global energy mix. A further obstacle in many parts of the world relates to the need for significant amounts of capital and considerable institutional capacity and technical expertise to successfully build and safely operate nuclear power plants.

Some of these issues could be resolved by the successful development of nuclear fusion (as opposed to *fission*) technology, but this is a long-term prospect. Even if nuclear fusion ultimately proves feasible, the technology is unlikely to be available until mid-century or later.

In sum, nuclear power plants are much more complicated than fossil-fuel power plants, and the consequences of accidents are far greater. In fact, potential dependency on other countries for technological expertise or nuclear fuel may discourage some governments from developing nuclear capacity, even as a desire for technology status or energy security may motivate others in the opposite direction. Brazil's decision in the 1970s not to pursue a relationship with Germany that would have led to a major expansion of Brazil's nuclear power capability was driven by these types of considerations.

Current, near-term plans to expand nuclear-generating capacity are largely centered in Asia with India, China, and Japan leading the way in terms of numbers of new plants proposed or under construction at present. Increasingly, these countries and others are interested in developing and building their own reactor designs. Figure 3.6 shows the regional

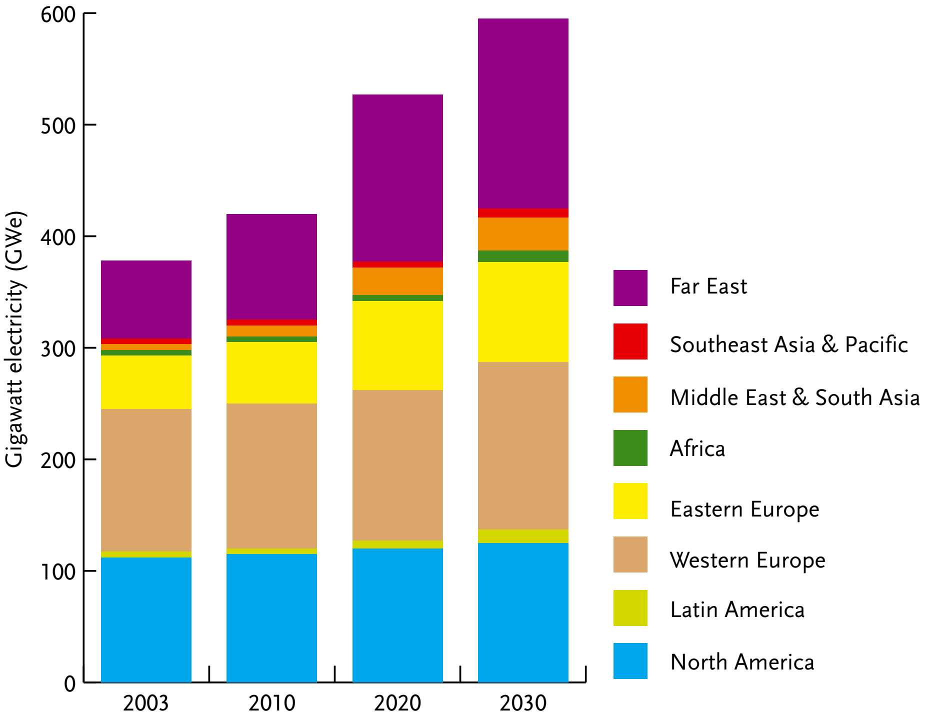

Figure 3.6 Regional distribution of global nuclear capacity in the IAEA's high projection

Source: IAEA, 2004; McDonald, 2004.

breakdown of new nuclear capacity in the 2004 IAEA high-growth projections for 2030. According to this figure, the largest increase in nuclear capacity (in terms of net gigawatts added) will occur in the Far East, while the strongest growth in percentage terms will occur in the Middle East and South Asia. Net capacity also increases, albeit less dramatically, in Eastern and Western Europe, but stays essentially flat in North America.

Most of the new plants expected to come on line in the next few years incorporate substantial modifications and improvements on existing reactor designs, including safety features that simplify cooling requirements in the event of an accident. These designs are therefore expected (though not yet demonstrated) to provide more reliable safety performance at lower overall cost.[35] Efforts are already underway to develop a third generation of

35 Most of the plants that are now under construction or have recently come on line use GEN III+ reactor designs. They are deemed passively safe because they typically rely on gravity, natural circulation, and compressed air to provide cooling of the reactor core and containment structure in the event of a severe accident. Compared to the actively safe systems used in existing reactors, these designs require fewer valves, pumps, pipes, and other components. Note that the gas-cooled pebble-bed modular reactor is classified as a GEN III+ design but is safe even in the absence of any coolant.

nuclear reactor designs that would be 'passively safe,' whereby the chance of a core meltdown would be (nearly) impossible, even in the event of a total loss of operation of the reactor control systems (Box 3.1). The fourth-generation reactors could, in addition to incorporating passive safety features, achieve further improvements in cost and performance while also reducing waste disposal requirements by minimizing fuel throughput and/or recycling spent fuel.

In 2002, ten nations and the European Union formed the Generation IV International Forum (GIF) to promote international collaboration in developing a fourth generation of nuclear plants.[36] After more than two years of study, each participating nation agreed to take the lead in exploring at least one of several different reactor types for potential deployment by 2030. The reactor types identified by the GIF as most promising include the very high temperature gas reactor, the super-critical water reactor, the lead-cooled fast reactor, the sodium-cooled fast reactor, the gas-cooled fast reactor, and the molten salt reactor. In addition, other potential reactor designs have been studied or developed in recent years, including designs for smaller, modular and even transportable types of reactors, as well as designs that are geared toward the production of hydrogen.

At this point, none of the proposed fourth-generation reactor designs have been built, though a number of countries are pursuing active research and development efforts and have adopted policies aimed at facilitating the construction of new plants. Even while many of the new designs offer important advantages over older generations of reactors—at least on paper—the industry's longer-term outlook remains uncertain. The remainder of this section provides further detail about the specific challenges that now confront nuclear power and reviews current prospects for addressing these challenges with further improvements in reactor design and nuclear technology.

Challenges facing nuclear power

Nuclear fusion remains a distant alternative to fission technologies at present. In nuclear fusion, energy is produced by the fusion of deuterium and tritium, two isotopes of hydrogen, to form helium and a neutron.

36 The United States led the formation of the GIF, which also includes the European Union, Argentina, Brazil, Canada, France, Japan, South Korea, South Africa, Switzerland, and the United Kingdom. Russia was not included due to differences over assistance to Iran s nuclear program. However Russia has initiated a separate program to address the development of advanced reactors: the IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles.

Effectively unlimited quantities of the primary fuels, deuterium and lithium (from which tritium is produced), are easily available. Due to low fuel inventory, a runaway reaction or meltdown of a fusion system is not possible. Radioactive waste from fusion decays in 100 years to activity levels similar to that from coal. The proliferation risk from fusion is minimal since any fertile materials would be easily detectable.

Box 3.1 Four generations of nuclear reactors

The first nuclear power plants to be developed, many small, are now called Generation I (GEN I) reactors. Perhaps the only GEN I reactors still in operation are six small (under 250 megawatts-electricity) gas-cooled plants in the United Kingdom. All others have been shut down.

Most reactors operating today are Generation II reactors. Designed in the late 1960s and 1970s, they are of two main types, either pressurized water reactor (PWR) or boiling water reactor (BWR). GEN II reactors have achieved very high operational reliability, mainly through continuous improvement of their operations.

Generation III reactors were designed in the 1990s, and geared to lower costs and standardized designs. They have been built in the last few years in France and Japan. More recent designs are labeled GEN III+ reactors and are likely to be constructed in the coming years. Typical examples are the advanced boiling water reactor (ABWR) in Japan, the new PWR in Korea,the evolutionary power reactor (EPR) in France, and the economic simplified boiling water reactor (ESBWR) and the AP-1000 (advanced passive) in the United States .

The GEN III+ light water reactor (LWR) are based on proven technology but with significant improvements and, in the case of the AP-1000 and ESBWR, with passive emergency cooling systems to replace the conventional power-driven systems. The 2004 World Energy Assessment specifically mentions the pebble-bed modular reactor (PBMR) as a design concept that is being revisited because of the potential for a high degree of inherent safety and the opportunity to operate on a proliferation-resistant denatured uranium/thorium fuel cycle. The PBMR is also considered a GEN III+ reactor. GEN III+ systems probably will be the type used in the next expansion of nuclear power (UNDP, UNDESA, and WEC, 2004).

None of the Generation IV 'advanced reactors' have been built and none are close to being under construction. GEN IV is widely recognized as an R&D program for reactors with advanced features well beyond the GEN III+ LWR. GEN IV reactors are being prepared for the future, starting in 2035 to 2040. Whereas previous reactor types progressed in an evolutionary manner, GEN IV reactor designs attempt to significantly shift the nature of nuclear energy, either by incorporating high-temperature, high-efficiency concepts, or by proposing solutions that significantly increase the sustainability of nuclear energy (reduced wastes; increased usage of natural resources).

Six reactor types are being studied by a group of ten countries: the very high temperature reactor, which uses gas cooling, can reach very high thermodynamic efficiency and might be able to support production of hydrogen; the supercritical water reactor, which also allows for higher efficiency and reduces the production of waste; three fast neutron reactors, cooled either by gas (gas fast reactor), lead (lead fast reactor), or sodium (sodium fast reactor), which make use of closed fuel cycles; and the molten salt reactor. The very high temperature and gas fast reactors can both use pebble-type fuel.

Future nuclear systems, such as those that are studied in the GEN IV program and the Advanced Fuel Cycle initiative are all aimed at making nuclear energy more sustainable, either by increasing system efficiency or by using closed fuel cycles where nuclear waste is either partially or totally recycled. Another objective for these systems is to reduce both capital and operational costs. Significant scientific and technical challenges must be resolved before these systems are ready for deployment:

- high temperature high fluence materials (i.e., materials not crippled by ultra-high neutron fluxes);
- fuels that can contain high quantities of minor Actinides need to be demonstrated;
- novel technologies for transporting heat and generating electricity with smaller footprints than the current steam cycles;
- separation technologies that offer high proliferation resistance and produce minimal wastes;
- more compact designs that reduce capital costs.

To achieve these ambitious objectives, a three-pronged research strategy is being implemented in the United States:

(1)The role of the basic sciences is being enhanced. Current empirical research tools need to be phased out and replaced by modern techniques.

(2) The role of simulation and modeling will become central, when current generation software—largely developed in the 1980s— is replaced by high performance tools. One can expect that certain key difficulties, for example the development of advanced fuels, can be solved more efficiently once these tools are in place

(3) The design process itself will be simplified and streamlined.

Invesitgations of possible commercial development of fusion energy include inertial fusion and various forms of magetic confinement of high-temperature plasma. Current research is focused on magnetic confinement in toroidal (doughnut-shaped) geometries and on laser-induced inertial confinement. Laboratory experiments in tokomaks—machines that produce a toroidal magnetic field for confining a plasma—have produced 10 megawatts of heat from fusion for about one second. The ITER project (ITER means 'the way' in Latin), a collaboration of China, Europe, India, Japan, Russia, South Korea and the United States, is planned to produce 500 megawatts of fusion heat for over 400 seconds. In parallel with ITER, research is planned to target higher power and continuous operation and to develop advanced materials and components that can withstand high neutron fluxes. Some ITER partners anticipate demonstration fusion power plants about 2035 and commercialization starting about 2050.

COST

While operating costs for many existing nuclear power plants are quite low, the current upfront capital cost of constructing a new plant is higher than the cost of conventional new fossil fuel-fired electricity-generating technologies.[37] Cost reductions could help to improve nuclear energy's competitiveness in terms of real, levelized cost in cents-per-kilowatt-hour, relative to other options (Table 3.3).[38] Projections of future cost for nuclear power are, of course, highly uncertain, especially in the case of advanced reactor designs that have yet to be built or operated anywhere in the world. In some countries, moreover, cost uncertainty is likely to be compounded by the potential for delays and difficulties in siting, permitting, and construction. For all of these reasons, private financial markets in many parts of the world will tend to assign a substantial risk premium to new nuclear investments for some time to come.

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37 In net present value terms, as much as 60-75 percent of the life-cycle cost of nuclear power may be front-loaded that is, upfront capital costs are much higher than long-term operating costs. Capital constraints may therefore present a significant hurdle for nuclear plant investments, especially given the relatively risk-averse nature of private financial markets and much of the electric power industry.

38 As would also be the case with many other energy technologies, it is highly misleading to simply average the performance of old and new nuclear technologies. The proper way to evaluate technology options in terms of their potential contribution to sustainable energy solutions going forward is to use characteristics typical of best-in-class performance, which might be the upper 10-15 percent of performance levels. In recent years, modern nuclear power plants have achieved capacity factors in excess of 90 percent, a significant improvement over the 75-85 percent capacity factors that were at one time more typical of the industry. This improvement in plant performance has a significant impact on the economics of nuclear power.

Table 3.3 Comparative power costs

Case	Real levelized cost (US$ cents/kW_eh)
Nuclear (light water reactor)	6.7
• Reduce construction cost by 25%	5.5
• Reduce construction time from 5 to 4 years	5.3
• Further reduce operations and management 13 million per kW_eh	5.1
• Reduce cost of capital to gas/coal	4.2
Pulverized coal	4.2
CCGT (low gas prices, $3.77 per MCF)	3.8
CCGT (moderate gas prices, $4.42 per MCF)	4.1
CCGT (high gas prices, $6.72 per MCF)	5.6

Note: Gas costs reflect real, levelized acquisition costs per thousand cubic feet (MCF) over the economic life of the project. CCGT refers to combined cycle gas turbine; kW_eh refers to kilowatt-electricity hour. Figures use 2002 US$.

Source: MIT, 2005.

Obviously, a number of developments could change the relative cost picture for nuclear power. Further technology improvements, greater public acceptance and regulatory certainty, and progress in addressing the waste disposal issue would produce lower cost estimates and, perhaps more importantly, alter current perceptions of investment risk.[39] Successful development of simplified, standardized reactor designs that would expedite licensing and construction, in particular, could greatly improve the industry's prospects. Nuclear power would also be more competitive in the presence of a binding carbon constraint and/or if fossil fuel prices rise. Whether a carbon constraint would by itself produce a significant shift toward nuclear power would, of course, depend on the magnitude of the price signals and on the cost of other non- or low-carbon alternatives, including renewable energy sources, coal with carbon capture and sequestration, and highly efficient natural gas technologies. Without the presence of a carbon cap or tax on carbon and/or active government intervention in the form of risk-sharing and/or financial subsidies, most experts conclude that the private sector is unlikely to make substantial near-term investments in nuclear technology and other non-or low-carbon alternatives — especially in the context of increasingly competitive and deregulated energy markets.

39 There is considerable difference of opinion even among informed observers as to which of these concerns about nuclear power (waste management, proliferation, risk of accidents, etc.) is most significant.

An IEA analysis of nuclear economics shows that various OECD governments already subsidize the nuclear industry by providing fuel-supply services, waste disposal, fuel reprocessing, and R&D funding. Many governments also limit the liability of plant owners in the event of an accident and help with remediation. A recent case in point is the U.S. Energy Policy Act of 2005, which contains substantial subsidies and tax incentives for a new generation of nuclear power plants. Whether these incentives will prove sufficient to spur a new round of nuclear power plant construction in the United States is not yet known; in the meantime, immediate prospects for further expansion of nuclear energy capacity are likely to remain concentrated in the rapidly growing economies of Asia, notably in China and India.

plant safety and waste disposal

Accidents at Three Mile Island in 1979 and Chernobyl in 1986, as well as accidents at fuel-cycle facilities in Japan, Russia, and the United States have had a long-lasting effect on public perceptions of nuclear power and illustrate some of the safety, environmental, and health risks inherent in the use of this technology. While a completely risk-free nuclear plant design, like virtually all human endeavors, is highly unlikely, the role of nuclear energy has to be assessed in a more complete risk-benefit analysis that weighs all factors, including the environmental impacts of different energy options, their energy security risks and benefits, and the likelihood of future technology improvements.

A related challenge is training the skilled personnel needed to construct and safely operate nuclear facilities, including not only existing light water reactors but also safer GEN III reactors. The challenge of developing adequate skills and expertise is more significant in the case of GEN IV reactors, which are (a) very different from GEN III reactors,[40] (b) present more difficult safety and proliferation issues, and (c) require considerable expertise to design, construct, and operate.

In recent years, of course, the threat of terrorism has added a new and potentially more difficult dimension to long-standing concerns about the

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40 GEN IV plants are fast neutron reactors that operate with an approximately 1Mev neutron energy spectrum. As such, they are very different from GEN III reactors, which use thermal neutrons. In GEN IV reactors, the energy density is higher and cooling is much more critical. The GEN III and IIIa plants can be constructed to be very safe. In current projections of the ratio of GEN III and GEN IV plants, the ratio needed to reach steady-state burn down of long lived nuclear waste is approximately four to one. While GEN III reactors can be deployed more widely, GEN IV plants present more significant safety and proliferation issues.

safe and secure operation of nuclear facilities and the transport of nuclear materials. While the safety record of the light-water reactors that dominate the world's existing nuclear power base has generally been very good, Chernobyl remains 'a powerful symbol of how serious and long-lived the consequences of a nuclear accident can be,' however low the probability of such accidents might be (Porritt, 2006). In response to potential terrorist threats, many countries have implemented additional security measures at existing nuclear power plants; going forward, innovative reactor designs—possibly including facilities that can be built underground or have otherwise been reinforced and equipped with passive safety features to withstand outside attacks and internal sabotage—may help to alleviate public concerns about the particular vulnerabilities associated with nuclear facilities. One of the selling points of a new generation of pebble-bed reactors is that they can be built underground.

Disposing of high-level radioactive spent fuel for the millennia-scale period of time that nuclear waste could present a risk to public safety and human health is another problem that has long plagued the industry and that has yet to be fully resolved in any country with an active commercial nuclear energy program. While long-term disposal in stable geologic repositories is technically feasible, no country has yet completed and begun operating such a repository. (At present, Finland is closest to implementing this solution). Without a consensus on long-term waste storage, various interim strategies have emerged. These include storing spent fuel temporarily at power plant sites, for example using the dry cask method; or, in some countries, reprocessing or recycling the spent fuel to remove the fission products and separate the uranium and plutonium for re-use in reactor fuel. Reprocessing reduces the quantity of waste by more than an order of magnitude and has the potential of reducing the storage time by several orders of magnitude; but even after reprocessing, hundreds of years of safe storage are required. Reprocessing also raises significant proliferation concerns since it generates quantities of plutonium—the essential ingredient in nuclear weapons—that must be safeguarded to prevent theft or diversion for weapons-related purposes.

In fact, proliferation risks are a substantial concern for all current 'closed fuel-cycle' reactor designs, especially for the so-called 'breeder' reactor, which requires reprocessing of spent fuel to separate and recycle weapons-usable plutonium. An interdisciplinary study of nuclear power by MIT (2003), which analyzed the waste management implications of both once-through and closed fuel cycles, concluded that no 'convincing case can be

made on the basis of waste management considerations alone that the benefits of partitioning and transmutation will outweigh the attendant safety, environmental, and security risks and economic costs.' Other experts disagree and are more optimistic that the security, safety, and environmental concerns associated with closed fuel cycles are technically resolvable. They point out that fast neutron reactors would extend uranium supplies by 100-fold and allow for the use of thorium, while reducing the quantity of waste to be handled. Based on these advantages, they argue that concerted research efforts should be undertaken to see whether such reactors can be part of this century's energy solutions.

Given that uranium is relatively abundant and inexpensive at present and given that the waste reduction benefits of spent fuel reprocessing do not appear to outweigh the downsides in terms of proliferation risks, once-through fuel cycles are likely to remain the safer option for at least the next few decades although research that may lead to technical solutions could change that. The latest reactor designs tend to require less fuel per kilowatt-hour generated; a higher 'burn-up rate' in turn reduces the quantity of waste left to be managed at the end of the fuel cycle. This is true of newer pebble-bed designs, though it is also the case that the fuel pellets used in these designs require much higher uranium enrichment.

Meanwhile, seemingly irreducible political stresses continue to inhibit solutions to the problem of nuclear waste disposal all over the world. Half a century ago, the nuclear industry imposed on itself a standard of waste management that some experts believe has turned out to be unrealizable. The industry agreed that it would manage nuclear wastes in such a way that there would be no discernible impact on later generations for a period that was often in the range of 10,000 years. With the understanding of geology gained since, this task might have become easier. In fact it has become harder. There seems to be little prospect that the original objective can be met within this generation, though perhaps it can be met one or two generations from now.

With this realization, a consensus is beginning to emerge among experts that the objective of waste storage should shift from irretrievable storage to retrievable storage. In other words, wastes would be stored with the expectation that they will require further handling in a few decades. In the United States and elsewhere attention has recently focused on 'dry-cask' storage technology that could keep nuclear wastes thermally secure for time periods on the order of a half-century. A shift in nuclear waste-management objectives, while increasingly under discussion in expert

circles, has not however been widely proposed to the general public and would require changes in the legal framework governing waste management in the United States. The latter could present a major near-term hurdle in the United States and elsewhere.

Other countries, meanwhile, have continued to focus on spent-fuel reprocessing and long-term geological storage as primary strategies for waste management. In 2006, France, for example, adopted legislation that (a) formally declares deep geological disposal as the ‘reference solution’ for high-level and long-lived radioactive wastes, (b) sets 2015 as the target date for licensing a repository, and (c) sets 2025 as the target date for opening a long-term repository.[41] Meanwhile, some experts have suggested that if countries could reach consensus on establishing international facilities to provide spent-fuel reprocessing and uranium enrichment services in a highly secure and transparent environment, this option could be very helpful in addressing both proliferation and waste management concerns. Until this or other long-term solutions can be found, however, the waste issue is likely to continue to present a significant and perhaps intractable obstacle to the significant expansion of commercial nuclear power capacity worldwide.

Nuclear proliferation and public acceptance

The development and use of nuclear technology for commercial energy production has long generated concern that associated materials or expertise could be diverted to non-peaceful purposes. To date, no operating civilian nuclear program has been directly linked to the development of nuclear weapons, but the risk exists that commercial nuclear energy programs could be used to as ‘cover’ for illicit weapons-related activity or as a source (voluntarily or involuntarily) for the highly enriched uranium or plutonium needed to construct nuclear weapons. Both in India and North Korea, reactors nominally intended for civilian research were used to produce plutonium for weapons. Proliferation concerns apply most strongly to the uranium enrichment and spent-fuel reprocessing elements of a civilian nuclear energy program. As the American Physical Society has pointed out, ‘nuclear reactors themselves are not the primary proliferation risk; the principal concern is that countries with the intent to proliferate can

41 According to the World Nuclear Association (WNA, 2007), French law also affirms the principle of reprocessing used fuel and using recycled plutonium in mixed oxide (MOX) fuel 89 in order to reduce the quantity and toxicity of final wastes, and calls for construction of a prototype fourth-generation reactor by 2020 to test transmutation of long-lived actinides.

covertly use the associated enrichment or reprocessing plants to produce the essential material for a nuclear explosive' (APS, 2005: i).

The existing international regime for managing proliferation risks is widely viewed as inadequate and would be further stretched by a significant expansion of nuclear power to many more countries with widely varying security circumstances. Here again, it matters which technology is being deployed: the risks presented by GEN III reactors are very different and likely to be more manageable from those that would be presented by the international deployment of fast neutron systems. Given the devastating impact even a single nuclear weapon linked to a civilian nuclear energy program could have, current international safeguards will clearly need to be strengthened. Efforts to develop proliferation-resistant technologies, especially for fuel enrichment and reprocessing, also merit high priority. Increased international collaboration is needed to explore options for addressing enrichment and reprocessing needs in ways that minimize public safety and proliferation risks. In particular, it has been suggested that stronger multi-lateral arrangements—including facilities that would enrich and reprocess fuel for use by multiple countries under multinational supervision, perhaps in combination with international supply guarantees—could help to address proliferation concerns.

In some countries, public acceptance is likely to continue to present a significant challenge for nuclear power, though locating future capacity additions at existing plants may help to alleviate siting difficulties to a significant degree. Public perceptions are likely to change over time, of course, and may become significantly more accepting of nuclear energy as concern over climate change grows and as countries and communities become familiar with nuclear energy systems. However, even if the climate of opinion around nuclear energy already shows signs of shifting, it remains the case that the public is likely to be extremely unforgiving of any accident or attack involving civilian nuclear energy systems. A single incident anywhere would cast a pall over nuclear power everywhere. A substantial increase in both the number of plants operating worldwide and the amount of fuel being transported and handled for enrichment, reprocessing, or waste disposal inevitably heightens the risk that something, someday, will go wrong, even if the probability of any single event is extremely low. As a result, some experts have estimated that a further order-of-magnitude increase in reactor safety, along with substantial international progress to address current proliferation concerns, will be

required to maintain public acceptance in the face of a greatly expanded worldwide nuclear energy program. In the meantime, it seems clear that the fundamental challenges for nuclear power are as much—and perhaps more—political and social as they are technological or scientific.

In summary: Nuclear power

Based on the foregoing discussion, no certain conclusion regarding the future role of nuclear energy emerges, except that a global renaissance of commercial nuclear power is unlikely to materialize over the next few decades without substantial support from governments; effective efforts to promote international collaboration (especially to address safety, waste, and proliferation concerns); changes in public perception; and the imposition of greenhouse gas constraints that would make low- or non-carbon energy technologies more cost-competitive with their currently cheaper fossil-fuel counterparts.[42] In the case of nuclear power it is fair to say that understanding of the technology and of the potential developments that could mitigate some of the concerns reviewed above—both among the public and among policymakers—is dated. A transparent and scientifically driven re-examination of the issues surrounding nuclear power and their potential solutions is needed.

3.3 Non-biomass renewables

Renewable sources of energy—biomass, wind, solar, hydropower, geothermal, and ocean energy—have helped to meet humanity's energy needs for millennia.[43] Expanding the energy contribution from modern renewable technologies can help to advance important sustainability objectives and is widely considered desirable for several reasons:

- **Environmental and public health benefits.** In most cases, modern renewable energy technologies generate far lower (or near-zero) emissions of greenhouse gases and conventional air pollutants compared to

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42 The cost of nuclear power is dominated by the cost of design, approval, construction, and licensing. Fuel costs are a small percent of overall production costs, amortized over the life of the plant. In the United States, the utility companies that know how to operate nuclear plants efficiently (high utilization or capacity factors) are now offering training programs to other utility companies, in much the same way that major airlines offer pilot training and re-certification programs to smaller airlines. As a result, the fraction of time that U.S. nuclear power plants are producing energy has increased dramatically and is now over 90 percent.

43 The world's oceans represent a potentially vast source of energy, but current proposals to tap this resource are still in the experimental phase. Given that the potential of ocean energy remains, for now, largely speculative, this form of renewable energy does not receive further treatment here.

fossil-fuel alternatives;[44] other benefits may involve reduced water and waste-disposal requirements, as well as avoided impacts from mining and drilling.

- **Energy security benefits**. Renewable resources reduce exposure to supply shortages and price volatility in conventional-fuel markets; they also offer a means for many countries to diversify their fuel supplies and reduce dependence on non-domestic sources of energy, including dependence on imported oil.
- **Development and economic benefits**. The fact that many renewable technologies can be deployed incrementally in small-scale and stand-alone applications makes them well-suited to developing country contexts where an urgent need exists to extend access to energy services in rural areas; also, greater reliance on indigenous renewable resources can reduce transfer payments for imported energy and stimulate job creation.

As with all energy supply options, renewable energy technologies also have drawbacks, many of them related to the fact that the resource being tapped (e.g., wind or sunlight) is diffuse and typically has low power density. A first issue, obviously, is cost—in particular, cost relative to conventional resource options with and without price signals to internalize climate impacts. Without price signals, many renewable energy options remain more costly than the conventional alternatives at present (although some technologies—such as wind—are rapidly approaching or have already achieved commercial competitiveness in some settings).

The diffuse nature of many renewable resources also means that large-scale efforts to develop their energy potential typically require more land (or water) area than conventional energy development. As a result, impacts on wildlife, natural habitats, and scenic vistas can become a significant issue for some projects. In the case of large hydropower developments, additional concerns may include impacts on human settlements and the potential for offsetting methane and carbon dioxide emissions. In many cases, concerns about land or ecosystem impacts can be addressed through appropriate siting, technology modifications, or other measures;

44 The statement is not intended to imply that the impacts of renewable energy projects on greenhouse gas emissions and on the environment more generally are always unambiguously positive. In the case of hydropower, an active debate is now underway concerning the potential for significant methane and carbon dioxide emissions from large installations, particularly in tropical settings. These emissions are generated by the decomposition of submerged organic matter and may be significant.

in addition promising opportunities exist to deploy some renewable technologies in decentralized applications (e.g., rooftop solar panels).

The remainder of this section focuses on non-biomass renewable energy options. (Modern biomass technologies are discussed separately in the next section). In the near to medium term, these resources have the potential to compete with conventional fuels in four distinct markets: power generation, hot water and space heating, transportation, and rural (off-grid) energy.

Renewable resource contribution

At present, the contribution from small hydropower, wind, and other non-biomass energy resources remains relatively small, accounting for only 1.7 percent of total primary energy production on a global basis in 2005.[45] Recent years, however, have seen explosive growth in several key renewable industries. Table 3.4 shows average annual energy production and production growth rates for different modern renewable technologies for 2001–2005.[46] In average, the contribution of modern renewables to the total primary energy supply (TPES) increased by approximately 11.5 percent per year, over the period 2001–2005. Figure 3.7 shows the projected contribution of modern renewables, including biomass, to the total primary energy supply in 2010 and 2020 based on a continued growth of 11.5 percent per year.

Increasingly common in many countries, government policies—typically motivated by climate-change and energy-security concerns—have played an important role in spurring recent renewable-energy investments.[47] Currently, at least 45 countries, including 14 developing countries, have adopted various policies—often in combination—to promote renewable energy (REN21, 2006 and 2005). Chief examples include investment or production tax credits; 'feed-in' tariffs (that require utilities to pay a certain minimum amount for renewable power supplied to the grid); portfolio standards or targets (that establish a specific share of

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45 If modern biomass energy is added, this percentage increases to 3.6, and if traditional biomass energy and large hydropower are added, the percentage goes to 13.6.

46 It is important to note that recent substantial growth in installed renewable capacity worldwide has been largely driven by the introduction of aggressive policies and incentives in a handful of countries. The expansion of similar commitments to other countries would further accelerate current rates of deployment and spur additional investment in continued technology improvements.

47 Strictly from a climate-mitigation perspective, the costs of some of these policies in dollars per ton of avoided carbon dioxide may be high relative to other mitigation options. Typically, however, governments are motivated to support renewable energy for other reasons as well, including fuel diversity, energy independence, and local environmental improvement.

Table 3.4 Modern renewable energy: production and growth

Source/Technology		Production (ExaJoules) 2001	2004	2005	Growth rate (2001-2005) in % per year
Modern biomass energy	*Total*	*8.32*	*9.01*	*9.18*	*2.50*
	Bioethanol	0.40	0.67	0.73	16.36
	Biodiesel	0.04	0.07	0.13	34.27
	Electricity	1.26	1.33	1.39	2.41
	Heat	6.62	6.94	6.94	1.17
Geothermal energy	*Total*	*0.60*	*1.09*	*1.18*	*18.37*
	Electricity	0.25	0.28	0.29	3.84
	Heat	0.35	0.80	0.88	26.31
Small hydropower	*Total*	*0.79*	*1.92*	*2.08*	*27.47*
Wind electricity	*Total*	*0.73*	*1.50*	*1.86*	*26.56*
Solar energy	*Total*	*0.73*	*2.50*	*2.96*	*41.83*
	Low temp heat	0.68	2.37	2.78	41.92
	Thermal electricity	0.01	0.01	0.01	0.46
	PV grid		0.06	0.10	55.00
	PV off-grid	0.03	0.06	0.07	20.25
Marine energy	*Total*	*0.01*	*0.01*	*0.01*	*0.46*
Total non-biomass modern renewables		*2.86*	*7.02*	*8.09*	
Total modern renewables		*11.16*	*16.02*	*17.26*	*11.51*
Total primary energy supply (TPES)		*418.85*	*469.00*	*477.10*	*1.60*
Modern renewables/TPES (in percent)		*2.7*	*3.4*	*3.6*	

Sources: UNDP, UNDESA, and WEC, 2000 and 2004; REN21, 2006; and IEA, 2006.

energy or electricity supply to be provided using renewable resources);[48] and grants, loans, or other forms of direct support for research, development, demonstration, and early deployment efforts. For example, in March 2007, the member states of the European Union agreed to adopt, as a binding target, the goal of meeting 20 percent of all EU energy needs from renewable sources by 2020. China has adopted a goal of 10 percent renewable electric-generating capacity by 2010 (excluding large hydropower) and 10 percent primary energy from renewables within the same timeframe (Table 3.5).

48 Such commitments can counter the common tendency in power-system planning to favor large-scale generators.

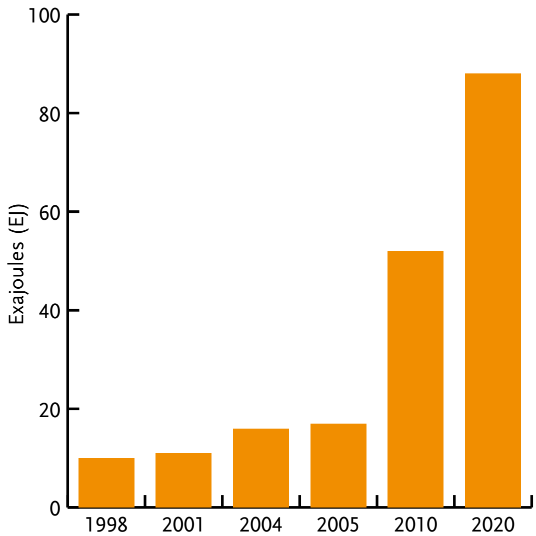

Figure 3.7 Modern renewables projections for 2010 and 2020

Note: Projections of modern renewables (including small hydro, excluding large) based on 11.5 percent growth per year, over the period 2001-2005.

Sources: UNDP, UNDESA, and WEC, 2000 and 2004; REN21, 2006; And IEA, 2006

Additional incentives or targets and other policies to promote renewable energy are increasingly also being adopted at the state and municipal level. Current research and development spending on renewable technologies by the United States and Europe now totals more than US$700 million per year; in addition, roughly half a billion dollars per year are being directed to renewable energy projects in developing countries.[49] Recent developments in the business world reflect the growing enthusiasm for renewable energy: large commercial banks have begun to 'mainstream' renewable energy investments in their lending portfolios, and several major corporations have recently made substantial investments or acquisitions in renewable energy enterprises. The 60 leading, publicly traded renewable energy companies, or divisions of companies, now have a combined market capitalization of US$25 billion and new organizations

49 Funding for developing-country projects is provided through the German Development Finance Group, the World Bank Group, the Global Environment Facility, and other donors. Data for much of the information in this chapter comes from the 2005 and 2006 REN21Global Status Reports.

Table 3.5 Renewable energy promotion policies and targets in selected countries

Country	Modern renewable energy targets	Policy mechanisms
Australia	9.5 terawatt-hours by 2010	Renewable portfolion standard (RPS), subsidies, tradable certificates, public financing
Brazil	3.3 gigawatts by 2006 from wind, biomass, small hydro	Feed-in tariffs, public financing
Canada	3.5%-15% of electricity in 4 provinces	Subsidies, tax credits, public financing; varies by province
China	10% of capacity by 2010 (~60 GW); 5% of primary energy by 2010, 10% of primary energy by 2020	Feed-in tariffs, subsidies, tax credits, public financing, competitive bidding
EU-25	20% of all energy by 2020	Varies by country
India	10% of new capacity between 2003-2012 (~10GW)	Subsidies, tax credits, public financing, competitive bidding
Israel	2% of electricity by 2007; 5% by 2016	Feed-in tariff
Japan	1.35% of electricity by 2010, excluding geothermal & large hydro	RPS, subsidies, tradable certificates, net metering, public financing
Korea	7% of electricity by 2010 including large hydro; 1.3 GW of grid-connected solar photovoltaic by 2011	Feed-in tariffs, subsidies, tax credits
New Zealand	30 petajoules of added capacity (including heat and transport fuels) by 2012	Subsidies, public financing
Norway	7 TWh from heat and wind by 2010	Subsidies, tax credits, tradable certificates, competitive bidding
Philippines	4.7 GW total existing capacity by 2013	Tax credits, public financing
Switzerland	3.5 TWh from electricity and heat by 2010	Feed-in tariff
Thailand	8% of total primary energy by 2011	Feed-in tariff, RPS, subsidies, net metering
USA	5%-30% of electricity in 20 states	Varies by state

Note: Data updated with new EU-targets. The table presents targets as adopted by different governments. No attempt is made to convert these targets to a single, readily-compared metric, such as electricity production, capacity, share of generation, or share of capacity. The EU decided on its target in Spring 2007; EU member states are expected to elaborate on country-specific policies and regulations.

Source: REN21, 2005.

are emerging to facilitate renewable energy investments through specialized networking, information exchange, market research, training, financing, and other assistance (REN21, 2006).

Current trends are encouraging, but most of the anticipated growth in renewable energy capacity remains concentrated in a handful (five or six) of countries. The challenge is to sustain healthy growth rates in countries

that already have ambitious renewable energy commitments and to initiate similar deployment efforts in more countries around the world. That challenge has important institutional and social dimensions, as well as technological and economic ones. Capacity building, for example, has emerged as a crucial issue for the maintenance of modern renewable energy infrastructure in the developing world. Many well-intended renewable energy projects funded by international agencies or foreign governments have failed because of a lack of attention to the concomitant need for competent technicians and managers to maintain these systems. Other factors that have contributed to a disappointing success rate for renewable energy projects in Africa include lack of suitable policies, lack of involvement by target groups, lack of commitment to maintain projects by the governments of host countries, and lack of coordination between donors.

Issues and hurdles of non-biomass options

Various issues and market hurdles apply to each of the chief non-biomass 'new' renewable energy options: wind, solar photovoltaic (PV), solar thermal, small hydropower, and geothermal. For each energy option, policymakers confront a similar set of questions:

- *Is the available technology adequate—in theory and in practice—to support growing demand?*
- *Are there aspects of the resource—such as the intermittent nature of wind and sunlight—that currently limit its role in the marketplace?*
- *Can the technology compete economically with other options in an emissions-constrained world (taking into account current subsidies for conventional and unconventional, resources as well as costs and benefits that are currently not internalized in market prices)?*
- *How can other barriers, including siting issues, market or regulatory barriers, infrastructure constraints, and other barriers be overcome?*

While the specifics of these questions vary for different technologies and resources, several general points are worth noting before proceeding to a more detailed discussion of the different options.

Resource adequacy is generally not an issue, although some parts of the world hold more promise for certain renewable technologies than others. The rate at which sunlight is absorbed by the Earth is roughly 10,000 times greater than the rate at which human beings use commercial energy of all kinds. Even when practical limitations are factored in, the remaining renewable resource base remains enormous. A recent analysis commissioned for this report suggests that if one considers only those onshore

areas that are already economic for commercially available wind turbines (i.e., areas with Class 5 or better winds) and one applies a 90 percent exclusion factor (i.e., one assumes that only 10 percent of these areas are available due to competing land uses or for other reasons), remaining wind energy potential is still theoretically sufficient to supply 100 percent of current global electricity consumption and as much as 60 percent of projected global consumption for 2025 (Greenblatt, 2005).

The challenges for renewable energy technologies, therefore, are primarily technological and economic: how to capture the energy from dispersed resources that typically have low power-density compared to fossil or nuclear fuels and deliver that energy where it is needed and when it is needed at reasonable cost. Significant cost reductions have been achieved in solar and wind technologies over the past decade, but as a means of generating electricity these options generally remain more expensive per kilowatt-hour of output than their conventional competitors. Other deployment hurdles derive from the nature of the resource itself. Wind and solar energy, because they are intermittent and not available on demand, present challenges in terms of being integrated into electricity supply grids, which must respond instantaneously to changing loads. Intermittency imposes costs on electric power systems—costs that may be substantial at foreseeable levels of wind and solar deployment.

To address this issue, large-scale improvements to transmission infrastructure, the addition of more responsive conventional generation and possibly energy storage technologies may enable wind power to supply more than 30 percent of electric generation while keeping intermittency costs below a few cents per kilowatt-hour (DeCarolis and Keith, 2005; 2006). The development of cost-effective storage options, in particular, should be a priority for future research and development since success in this area could significantly affect the cost of intermittent renewable resources and the magnitude of their contribution to long-term energy supplies. Potential storage options include added thermal capacity, pumped hydro or compressed air energy storage, and eventually hydrogen. Large hydropower has the advantage that it is not intermittent and is already quite cost-competitive, but the potential for new development in many areas is likely to be constrained by concerns about adverse impacts on natural habitats and human settlements.

Wind

With installed capacity increasing by an average of 30 percent per year since 1992, wind power is among the fastest growing renewable energy

technologies and accounts for the largest share of renewable electricity-generating capacity added in recent years. In 2006 alone, 15.2 gigawatts of new wind capacity (representing a capital investment of more than US$24 billion) was added worldwide, bringing total installed wind capacity to 59 gigawatts (GWEC, 2006). Leading countries for wind development are Germany (18.4 gigawatts total), Spain (10 gigawatts), the United States (9.1 gigawatts), India (4.4 gigawatts), and Denmark (3.1 gigawatts). This impressive progress is due in large part to continuing cost reductions (capital costs for wind energy declined more than 50 percent between 1992 and 2001) and strong government incentives in some countries (Juninger and Faaij, 2003). Over time, wind turbines have become larger and taller: the average capacity of individual turbines installed in 2004 was 1.25 megawatts, double the average size of the existing capacity base (BP, 2005).

A simple extrapolation of current trends—that is without taking into account new policy interventions—suggests that wind capacity will continue to grow robustly. The IEA (2004) *World Energy Outlook* reference case forecast for 2030 includes 328 gigawatts of global wind capacity and 929 terawatt-hours of total wind generation, a more than five-fold increase of the current capacity base. Renewable energy advocates have put forward far more aggressive scenarios for future wind deployment: the European Renewable Energy Council's Advanced International Policies Scenario, for example has wind generation increasing to 6,000 terawatt-hours by 2030 and 8,000 terawatt-hours by 2040.[50] Overall, the potential wind resource is vast though not distributed evenly around the globe. Based on available surveys, North America and a large part of the Western European coast have the most abundant resources, whereas the resource base in Asia is considerably smaller, with the possible exception of certain areas such as Inner Mongolia where the wind potential may be in excess of 200 gigawatts. Looking beyond the continental scale, wind resources in North America are concentrated in the middle of the continent, while Europe's best resources are found along the Western coast and in Russia and Siberia. Further study is needed to assess the resource base in Africa where it appears that wind resources may be concentrated in a few areas on the northern and southern edges of the continent.

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50 Assuming a roughly 30 percent capacity factor, this is roughly consistent with projections Greenblatt (2005) cites: the European Wind Energy Association (EWEA) and Greenpeace projected growth to 1,200 gigawatts by 2020 (12 percent of demand), broken down as 230 gigawatts in Europe, 250 gigawatts in the United States, 170 gigawatts in China, and 550 gigawatts in the rest of the world, with growth plateauing at 3,200 gigawatts globally in 2038. Note also that EREC s aggressive policy scenario shows photovoltaic with a slightly larger role than wind by 2040 (EWEA and Greenpeace, 2004).

Intermittency is a significant issue for wind energy: wind speeds are highly variable, and power output drops off rapidly as wind speed declines. As a result, turbines produce, on average, much less electricity than their maximum rated capacity. Typical capacity factors (the ratio of actual output to rated capacity) range from 25 percent on-shore to 40 percent off-shore depending on both wind and turbine characteristics. At current levels of penetration, wind's intermittency is generally readily manageable: grid operators can adjust output from other generators to compensate when necessary. In these situations grid operators treat wind parks much like 'negative loads' (Kelly and Weinberg, 1993; DeCarolis and Keith, 2005). Longer-term, as wind penetration expands to significantly higher levels (e.g., in excess of 20 percent of total grid capacity), the intermittency issue may become more significant and may require some combination of innovative grid management techniques, improved grid integration, dispatchable back-up resources, and cost-effective energy storage technologies.[51] Obviously, some of these options—such as back-up capacity and energy storage—would add to the marginal cost of wind power. In addition, new investments in transmission capacity and improvements in transmission technology that would allow for cost-effective transport of electricity over long distances using, for example, high-voltage direct current lines would allow for grid integration over much larger geographic areas and could play a crucial role in overcoming intermittency concerns while expanding access to remote but otherwise promising resource areas.[52]

Meanwhile, as has already been noted, options for low-cost energy storage on the scale and over the timeframes required (i.e., multiple hours or days) merit further exploration. Potential storage options for wind and other intermittent renewable resources include pumped hydroelectric storage, compressed air energy storage, and hydrogen. Pumped hydro requires

51 Many regions are either approaching or setting goals of 20 percent or higher renewable generation (Greenblatt, 2005). In current applications, where wind is generally a relatively small part of the grid, natural gas turbines often provide backup generation because of their fast ramp rates and inexpensive capital costs. In other instances, ramping coal or hydroelectric plants can be used to provide backup generation; nuclear is rarely used, due to the need to run at full output power. Complementary renewable generation (for instance, solar photovoltaic, which peaks during the day compared to wind energy which often peaks at night) or demand-side management are other options, but their use is not widespread.

52 With sufficiently low transmission costs, remote onshore wind exploited via long-distance transmission may be a strong competitor to offshore wind energy, even if the latter is located closer to demand, especially given the higher capital cost and maintenance requirements associated with offshore facilities. Indeed, even as Europe aggressively develops offshore wind parks, it is considering long-distance transmission from wind developments outside the region, such as in Morocco, Russia, and Siberia.

two reservoirs of water at different heights, whereas compressed air storage—in the two commercial projects of this type that exist to date—has entailed using a large underground cavern. Compressed air storage may also be feasible in more ubiquitous underground aquifers. While pumped hydro may be preferable when a source of elevated water storage is nearby, compressed air storage can be sited where there is suitable underground geology. It is worth noting, however, that compressed air must be heated in some way before it can be directly used in an air turbine; hence the usual assumption is that compressed air storage would be integrated with a gas turbine. Longer term, hydrogen may provide another promising storage option for intermittent renewables. When wind or solar energy is available, it could be used to produce hydrogen, which could in turn be used for a variety of applications—including for electricity production, as a primary fuel source, or in fuel cells—once appropriate distribution infrastructure and end-use technologies are developed.[53]

Longer term, other innovations have been suggested that could further improve wind's competitive position. Potential R&D frontiers include 'derating' techniques that allow turbines to operate at lower wind speeds (thereby reducing capital costs and energy storage requirements); specialized turbines and other infrastructure to access deep offshore resources; or even systems designed to capture the vast wind resources that exist in the free troposphere, several kilometers above the earth's surface.

SOLAR PHOTOVOLTAIC

Solar PV technologies use semiconductors to convert light photons directly into electricity. As with wind, installed capacity has increased rapidly over the last decade; grid-connected solar PV capacity grew on average more than 60 percent per year from 2000 to 2004. This growth started from a small base however. Total installed capacity was just 2.0 gigawatts worldwide by the end of 2004; it grew to 3.1 gigawatts by the end of 2005 (REN21, 2006) . Solar PV has long had an important niche, however, in off-grid applications providing power in areas without access to an existing electricity grid. Until recently, solar PV has been concentrated in Japan, Germany, and the United States where it is supported by various incentives and policies. Together, these countries account for over 85 percent of installed solar PV capacity in the OECD countries (BP,

53 Note that hydrogen can potentially be used as a primary fuel in dispersed applications (e.g., for heating and cooking in rural areas), even before hydrogen fuel-cell technology is successfully commercialized.

2005). Solar PV is also expected to expand rapidly in China where installed capacity—currently at approximately 100 megawatts—is set to increase to 300 megawatts in 2010 (NDRC, 2006). Increasingly, solar PV is being used in integrated applications where PV modules are incorporated in the roofs and facades of buildings and connected to the grid so that they can flow excess power back into the system.

Estimates of solar energy's future contribution vary widely and, as with all projections or forecasts, depend heavily on policy and cost assumptions. As with wind, the potential resource base is large and widely distributed around the world, though prospects are obviously better in some countries than in others. To the extent that PV modules can be integrated into the built environment, some of the siting challenges associated with other generating technologies are avoided. The main barrier to this technology in grid-connected applications remains high cost. Solar PV costs vary depending on the quality of the solar resource and module used, but they are typically higher than the cost for conventional power generation and substantially higher than current costs for wind generation.

Another significant issue, as with other renewable options like wind, is intermittency. Different economic and reliability parameters apply in non-grid applications where solar photovoltaic is often less costly than the alternatives, especially where the alternatives would require substantial grid investments.

Achieving further reductions in the cost of solar power will likely require additional technology improvements and may eventually involve novel new technologies (such as die-sensitized solar cells).[54] Near-term cost-reduction opportunities include improving cell production technology, developing thin-film technologies that reduce the amount of semiconductor material needed, designing systems that use concentrated solar light, and substituting more efficient semiconductors for silicon. In the mid- to longer-term future, ambitious proposals have been put forward to construct megawatt-scale solar PV plants in desert areas and transmit the energy by high voltage transmission lines or hydrogen pipelines.[55] Even more futuristic concepts have been suggested. Meanwhile, solar photovoltaic is likely to continue to have important near-term potential in dispersed, 'distributed generation' applications, including as an integral

54 PV installations have recently been running ahead of annual production, leading to higher prices for PV modules

55 Use of hydrogen as a carrier for solar-derived energy might be constrained in desert areas by the scarcity of water, which would be needed as a feedstock for hydrogen production.

part of building envelope design and as an alternative to other non-grid-connected options (like diesel generators) in rural areas.

SOLAR THERMAL

Solar thermal technologies can be used to provide space conditioning (both heating and cooling) in buildings, to heat water, or to produce electricity and fuels. The most promising opportunities at present are in dispersed, small-scale applications, typically to provide hot water and space heating directly to households and businesses. Solar thermal energy can be effectively captured using 'passive' architectural features such as sun-facing glazing, wall- or roof-mounted solar air collectors, double-façade wall construction, air-flow windows, thermally massive walls behind glazing, or preheating of ventilation through buried pipes. It can also be used as a direct source of light and ventilation by deploying simple devices that can concentrate and direct sunlight even deep inside a building and by exploiting pressure differences that are created between different parts of a building when the sun shines. In combination with highly efficient, end-use energy systems, as much as 50–75 percent of the total energy needs of buildings as constructed under normal practice can typically be eliminated or satisfied using passive solar means.

Active solar thermal systems can supply heat for domestic hot water in commercial and residential buildings, as well as for crop drying, industrial processes, and desalination. The main collector technologies—generally considered mature but continue to improve—include flat panels and evacuated tubes. Today, active solar thermal technology is primarily used for water heating: worldwide, an estimated 40 million households (about 2.5 percent of total households) use solar hot water systems. Major markets for this technology are in China, Europe, Israel, Turkey, and Japan, with China alone accounting for 60 percent of installed capacity worldwide.[56] Active systems to provide space heating are increasingly being deployed in a number of countries, notably in Europe. Costs for solar thermal hot water, space heating, and combined systems vary with system configuration and location. Depending on the size of panels and storage tanks, and on the building envelope, it has been estimated that 10–60 percent of combined household hot water and heating loads can be met using solar thermal energy, even at central and northern European locations.

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56 Solar water heater installations reached 62 million square-meters in China by the end of 2005. This represented only 5 percent of possible customers, however, suggesting that the potential for further expansion of solar thermal technology in China is substantial.

At present, solar thermal energy is primarily used for water heating. Technologies also exist, however, to directly use solar thermal energy for cooling and dehumidification. Cost remains a significant impediment, though cost performance can sometimes be improved by combination systems that provide both summer cooling and winter heating. Simulations of a prototype indirect-direct evaporative cooler in California indicate savings in annual cooling energy use in excess of 90 percent. Savings would be less in a more humid climate, though they can be enhanced using solar-regenerated liquid desiccants. Finally, systems that actively collect and store solar thermal energy can be designed to provide district heating and cooling to multiple buildings at once; such systems are already being demonstrated in Europe—the largest of them, in Denmark, involves 1,300 houses.

A number of technologies also exist for concentrating solar thermal energy to supply industrial process heat and to generate electricity. Typically, parabolic troughs, towers, or solar-tracking dishes are used to concentrate sunlight to a high energy density; the concentrated thermal energy is then absorbed by some material surface and used to operate a conventional power cycle (such as a Rankin engine or low-temperature steam turbine). Concentrating solar thermal electricity technologies work best in areas of high direct solar radiation and offer advantages in terms of built-in thermal energy storage.

Until recently, the market for these technologies has been stagnant with little new development since the early 1990s when a 350-megawatt facility was constructed in California using favorable tax credits. The last few years have witnessed a resurgence of interest in solar-thermal electric power generation, however, with demonstration projects now underway or proposed in Israel, Spain, and the United States and in some developing countries. The technology is also attracting significant new investments of venture capital. Longer term, the potential exists to further improve on existing methods for concentrating solar thermal power, particularly with respect to less mature dish and mirror/tower tracking technologies. Methods of producing hydrogen and other fuels (e.g., solar-assisted steam gasification of coal or other solid fuels) and other means of utilizing dilute forms of solar heat (e.g., evacuated tube collectors, solar ponds, solar chimneys, and use of ocean thermal energy) are also being investigated.

HYDROPOWER

Hydroelectricity remains the most developed renewable resource worldwide: it now accounts for most (85 percent) of renewable electricity production and is one of the lowest-cost generating technologies available. Worldwide, large hydropower capacity totaled some 772 gigawatts in 2004 and accounted for approximately 16 percent of total electricity production, which translated to 2,809 terawatt-hours out of a total 17,408 terawatt-hours in 2004 (IEA, 2006).

As with other renewable resources, the theoretical potential of hydropower is enormous, on the order of 40,000 terawatt-hours per year (World Atlas, 1998). Taking into account engineering and economic criteria, the estimated technical potential is smaller but still substantial at roughly 14,000 terawatt-hours per year (or more than 4 times current production levels). Economic potential, which takes into account societal and environmental constraints, is the most difficult to estimate since it is strongly affected by societal preferences that are inherently uncertain and difficult to predict. Assuming that, on average, 40 to 60 percent of a region's technical potential can be utilized suggests a global economic hydro-electricity potential of 7,000–9,000 terawatt-hours per year.

In Western Europe and the United States, approximately 65 percent and 76 percent, respectively, of technical hydroelectricity potential has been developed, a total that reflects societal and environmental constraints. For many developing countries, the total technical potential, based on simplified engineering and economic criteria with few environmental considerations, has not been fully measured while economic potential remains even more uncertain. Current forecasts anticipate continued growth in hydropower production, especially in the developing world where large capacity additions are planned, mostly in non-OECD Asian countries. Elsewhere, concerns about public acceptance (including concerns about the risk of dam breaks); environmental impacts (including habitat loss as well as the potential for carbon dioxide and methane emissions from large dams, especially in tropical settings); susceptibility to drought; resettlement impacts; and availability of sites are prompting a greater focus on small hydro resources. In 2000, a report issued by the World Commission on Dams identified issues concerning future dam development (for both energy and irrigation purposes) and emphasized the need for a more participatory approach to future resource management decisions (WDC, 2000).

Today, worldwide installed small hydro capacity exceeds 60 gigawatts

with most of that capacity (more than 13 gigawatts) in China.[57] Other countries with active efforts to develop small hydro resources include Australia, Canada, India, Nepal, and New Zealand. Small hydro projects are often used in autonomous (not grid-connected) applications to provide power at the village level in lieu of diesel generators or other small-scale power plants. This makes them well suited for rural populations, especially in developing countries. Worldwide, the small hydro resource base is quite large, since the technology can be applied in a wide range of streams. In addition, necessary capital investment is usually manageable, the construction cycle is short, and modern plants are highly automated and do not need permanent operational personnel. The primary barriers are therefore social and economic rather than technical. Recent R&D efforts have focused on incorporating new technology and operating methods and further minimizing impacts on fish populations and other water uses.

GEOTHERMAL

Geothermal energy lying below the earth's surface has long been mined as a source of direct heat and, within the last century, to generate electricity.[58] Geothermal electricity production is generally practical only where underground steam or water exists at temperatures greater than 100 degrees Celcius ; at lower temperatures (50–100 degrees Celcius) geothermal energy can be used for direct heat applications (e.g., greenhouse and space heating, hot water supply, absorption cooling). A different kind of application altogether involves heat pumps that effectively use the earth as a storage medium. Ground-source heat pumps take advantage of the relatively stable temperatures that exist below ground as a source of heat in the winter and as a sink for heat in the summer; they can provide heating and cooling more efficiently than conventional space-conditioning technologies or air-source heat pumps in many parts of the world.

Global geothermal electric-generating capacity is approximately 9 gigawatts, most of it concentrated in Italy, Japan, New Zealand, and the United States. The potential for further geothermal development using current technology is limited by available sites, but the available resource base could be significantly affected by improved technologies.[59] The hottest

57 There is no single, widely accepted definition for what constitutes small hydro, but a typical size threshold is on the order of 10 megawatts (capacity).

58 Geothermal energy is generally included with renewable resources despite it is not, strictly speaking, replenishable on the time scales that other renewable resources are.

59 See,further discussion of geothermal potential in chapter 7 of the World Energy Assess-

hydrothermal fields are found at the Pacific Ocean rim, in some regions of the Mediterranean, and in the Indian Ocean basin. Worldwide, more than 100 hydrothermal fields are thought to exist at rather shallow depths of 1–2 kilometers with fluid temperatures high enough to be suitable for power production. According to the IEA (2006) *World Energy Outlook* reference case, geothermal power capacity and production can be expected to grow to 25 gigawatts and 174 terawatt-hours, respectively by 2030, accounting for the roughly 9 percent of the total new renewable contribution. Technology improvements that would reduce drilling costs and enable access to geothermal resources at greater depths could substantially expand the resource base. In addition, technologies that could draw heat from dry rocks instead of relying on hot water or steam would significantly increase geothermal potential. Such technologies are not yet developed but are being explored in Europe. An existing EU research program, for example, is pursuing the use of hot dry rock geothermal energy for power production (EEIG, 2007).

The potential resource base for direct-heat applications of geothermal energy is much larger. In fact, direct-heat utilization nearly doubled from 2000 to 2005, with 13 gigawatt-thermal added over this time period and at least 13 countries using geothermal heat for the first time. Iceland leads the world in existing direct-heat capacity, supplying some 85 percent of its overall space heating needs using geothermal energy, but other countries—notably Turkey—have substantially expanded their use of this resource in recent years. About half of current global capacity is in the form of geothermal or 'ground source' heat pumps, with some 2 million units installed in over 30 countries worldwide (mostly in Europe and the United States).

In summary: Non-biomass renewable options

In the future, continued improvement in energy conversion, storage, and transmission technologies could further improve the cost-competitiveness of renewable energy options, help to address the reliability concerns that may arise at higher levels of penetration, and expand the number of sites that are suitable for renewable energy development. Ensuring that progress continues at the rate needed to support a major role for renewable energy resources within the first half of this century will require, however, that governments worldwide maintain a strong commitment to implementing policies and funding investments that will accelerate the

ment (UNDP, UNDESA, and WEC, 2000).

development and deployment of renewable technologies. Meaningful carbon constraints, especially in industrialized countries, are clearly part of the picture and will be essential in creating opportunities for new renewable alternatives to compete with the conventional technologies that currently dominate world energy markets.

3.4 Biomass

The conversion of sunlight into chemical energy supports nearly all plant and animal life on Earth. Biomass is one of humanity's oldest energy resources and, according to available estimates, still accounts for approximately 10 percent of global primary energy consumption today. Precise data do not exist, but as much as one-third of the world's population relies on fuel wood, agricultural residues, animal dung, and other domestic wastes to meet household energy needs. Such traditional uses of biomass are estimated to account for more than 90 percent of the biomass contribution to global energy supply, most of which occurs outside the formal market economy and predominately in developing countries. In these countries, traditional biomass has been estimated to account for more than 17 percent of total primary energy consumption. Modern uses of biomass to generate electricity and heat or as a source of fuels for transportation are estimated to account for less than 10 percent of total biomass energy consumption worldwide.

Because biomass is a renewable resource that can achieve low or near-zero carbon emissions (provided appropriate conversion technologies are used and feedstocks are sustainably managed), expanded reliance on biomass in modern applications is widely viewed as playing an important role in the transition to more sustainable energy systems. Biomass merits particular attention because, in the near to medium term, it offers the most promising alternatives to petroleum-based liquid fuels for the transportation sector. By contrast, biomass use in traditional applications often has negative impacts on public health and the environment and is frequently conducted in a manner that cannot be considered *sustainable* or *renewable* (in the sense that it avoids degrading or depleting the underlying resource base over time). Aggregated energy data rarely distinguish between different types of biomass uses: it is difficult to tell from available statistics, for example, what portion of the estimated biomass contribution consists of forest and agricultural waste collected manually by small communities versus large-scale production of charcoal from native forests

to supply industries and cities.[60]

In general, traditional uses of biomass, primarily for cooking in many parts of Africa, Asia, and Latin America, are quite inefficient and frequently result in the depletion of natural resources. Reliance on biomass fuels can lead to deforestation, for example, and in doing so can become a net source of greenhouse gas emissions. Moreover, in traditional applications, the quality of energy services provided using biomass resources (mostly lighting and heating) is generally poor and exacts a high price in terms of the human work necessary to collect and transport the fuel. This work can have the effect of excluding entire populations—especially girls and women—from the formal economy. And the health impacts associated with high levels of indoor air pollution typically pose a particular risk for the most vulnerable members of a community (women, children, and the elderly). Despite these drawbacks, billions of people continue to rely on dung, crop residues, and wood for the simple reason that these fuels are the most accessible and least costly energy resources available to them. Dry biomass is easily stored. Its use has cultural roots in many societies. And without it, many countries would have to increase energy imports, and many poor households would have to expend a greater share of their limited resources on purchasing other commercial forms of energy. Progress in delivering modern energy to rural areas has been slow, but significant opportunities exist to improve or displace traditional methods of using biomass energy with attendant benefits in terms of human health and conservation. Various technology options for improving combustion efficiency and reducing emissions are available at relatively modest cost: a modern cooking stove, for example, can yield efficiency improvements of 10–30 percent for a cost of US$5–10. Switching from traditional biomass to biogas, kerosene, propane (liquid petroleum gas), or even electricity can raise cooking stove efficiency substantially at a cost of US$20–60 per unit (refer back to Box 1.2 in Chapter 1).

Modern uses of biomass, however, offer a far greater array of possibilities for reducing dependence on fossil fuels, curbing greenhouse gas emissions, and promoting sustainable economic development. A range of biomass energy technologies, suitable for small- and large-scale applica-

60 The best databases available address rates of deforestation as a whole, including a large share of land-use change not related to energy consumption (FAO, 2005). Estimates of fuelwood consumption are often obtained by indirect methods that rely on other measures, such as population growth, and negative correlations with substitutes like kerosene, liquid petroleum gas, or even electricity.

tions, are available. They include gasification, combined heat and power (cogeneration) schemes, landfill gas, energy recovery from municipal solid wastes, or biofuels for the transportation sector (ethanol and biodiesel).

Recent interest in biomass energy has focused primarily on applications that produce liquid fuels for the transportation sector. Figure 3.8 outlines potential pathways to future biofuels production. Given growing concerns about global petroleum supply adequacy and the current lack of diversity in available fuel options for the transport sector, such fuels represent the highest-value use of biomass energy at present. Ultimately, the most promising biomass applications of all are likely to involve integrated systems where, for example, biomass is used as both fuel and feedstock in the co-production of liquid transportation fuels and electricity.

Of all available options, sugarcane ethanol is the most commercially successful biomass fuel in production today. Sugarcane ethanol has a positive energy balance and has benefited from supportive government policies in several countries, including Brazil that currently meets roughly 40 percent of its passenger vehicle fuel needs (one-third of its total transportation energy demand) with sugarcane ethanol (Macedo and other, 2004; Goldemberg and others, 2003). Globally, a substantial near-term opportunity exists to expand sugarcane ethanol production: almost 100 countries harvest sugarcane and state-of-art conversion technologies are available. Moreover, experience in Brazil suggests that the adverse environmental impacts associated with large-scale sugarcane ethanol production can be significantly mitigated by experience and legal enforcement of environmental regulations. Ethanol is also being produced on a commercial scale from corn in the United States, which has subsidized ethanol for a number of years and more recently adopted a federal renewable fuels mandate to promote alternatives to petroleum-based transportation fuels (USDOE, 2006; Perlack and others, 2005).

Another type of biomass-based transport fuel—biodiesel—has recently become commercially available as a result of programs in Europe and North America, but this option offers limited potential for reducing production costs and its viability is likely to continue to depend on external incentives like agricultural subsidies. In addition, adherence to fuel specifications and effective quality control are important factors for ensuring the commercial viability of biodiesel. Recent technology advances have involved efforts to diversify the biodiesel supply chain by, for example, using bioethanol instead of coal methanol as a feedstock.

Biogas energy from anaerobic digestion at landfills, sewage treatment facilities, and manure management sites, is considered a 'low-hanging

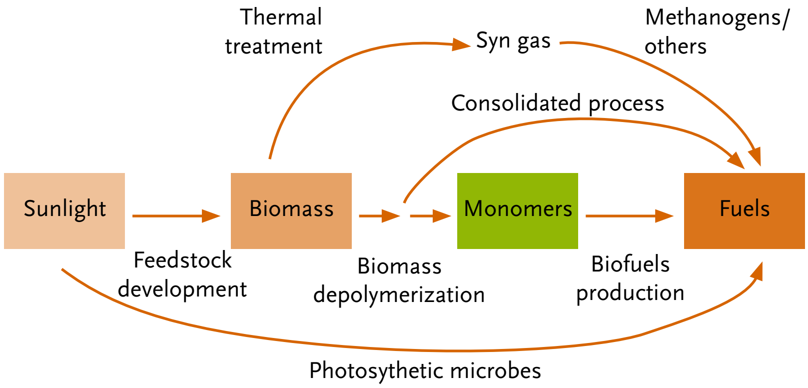

Figure 3.8 Potential pathways for biofuels production

Note: The current production of biofuels from lignocellulosic biomass feedstocks—including biomass grown for energy production and organic wastes (e.g., rice and wheat straw, wood resdidues)—proceeds through a pre-treament process that separates lignin from long-chain sugars (cellulose and hemicellulose), depolymerization into simple sugars, and finally fermentation into alcohol. Alternate pathways that are being explored include the possible consolidation of pre-treatment, depolymerization, and fermentation. An alternative pathway involves converting biomass into a synthesis gas (mixture of carbon monoxide and hydrogen), which is then converted to hydrocarbon fuel. Industrial production of biofuels via microbes, such as algae or basteria, is another possibility.

Source: Beth Burnside, Vice Chancellor for Research and Professor of Molecular and Cell Biology, University of California at Berkeley; and Steve Chu, Director of Lawrence Berkeley National Laboratory, and Professor of Physics and Molecular and Cell Biology, University of California at Berkeley.

fruit' option in the context of carbon credits available through the international Clean Development Mechanism (CDM). This form of biomass energy not only displaces fossil-fuel combustion but reduces emissions of methane, a more potent greenhouse gas than carbon dioxide.

Commercially available technologies for converting biomass to usable forms of energy vary in terms of scale, fuel quality, and cost. Large-scale technologies that are already on the market include fixed bed combustion, fluidized beds, dust combustion, biomass and coal co-firing, municipal solid wastes energy recovery as well as several types of systems for gasification, pyrolysis, etc. Many of these technologies are not yet commercially available in developing countries, however, and require financial support—as well as local capacity building—if they are to be deployed more widely.

The future of modern biomass

As with some other renewable energy options, the theoretical potential for biomass energy is enormous. Of the approximately 100,000 terawatts of solar energy flow that reach the Earth´s surface, an estimated 4,000 terawatts reach the world's 1.5 billion hectares of existing crop lands. Assuming that modern biomass technologies could achieve 1 percent energy conversion efficiency, these existing crop lands could in theory yield 40 terawatts of usable energy flow, or more than 3 times the current global primary energy supply flow of 14 terawatts. This exercise is not intended to imply that all arable land should be converted for energy-production purposes but only to illustrate that there is scope for a significant expansion of the modern biomass energy contribution, given that this contribution was estimated at only 0.17 gigawatts in 2003 (Somerville, 2005; Macedo, 2005).

There are numerous areas in developing countries where the harvesting of improved biofuel feedstocks can be substituted for the present foraging of indigenous plants. The efficient use of these biomass feedstocks for the local co-production of heat, electricity, and transportation fuel would also have a profound impact on the ability of rural populations to access modern, cleaner forms of energy. Energy solutions that can be deployed with modest capital investments will be a crucial element of an effective energy strategy. It will also be crucial—as part of any large-scale expansion of biomass energy production—to manage competing demands for food production and habitat preservation. In areas where the resource base is sufficiently abundant to support both food and energy crops, or in cases where it is feasible to make complementary use of the same feedstocks (e.g., using residues from food crops for energy production), land constraints may not emerge as a significant issue. In other areas, however, the potential for energy production to displace food production may generate concern—especially if food production serves the local population, while energy production is primarily for export.[61]

Some of the most promising opportunities for addressing these concerns and expanding the contribution of modern biomass energy involve cutting-edge advances in the biological and chemical sciences, including the development of crops designed for energy production through genetic selection or molecular engineering, specialized enzymes, and even the artificial simulation of natural biological processes such as

61 A sharp increase in corn prices, due in part to rapidly expanding demand for ethanol in the United States, caused rioting in Mexico in early 2007.

photosynthesis. Breakthroughs from new frontiers in biomass energy, in any of the several areas of current research described in Box 3.2, could have profound implications for the future of biomass energy technologies. As with other renewable resource options, the magnitude of the biomass contribution will depend on how much progress can be achieved in key areas:

- Reducing costs;
- Mitigating environmental impacts like water usage, chemicals (pesticides or fertilizers) added, biodiversity losses; and
- Minimizing pressure on scarce land resources in terms of competing requirements for food and fiber production and habitat preservation.

Solutions that simultaneously address all of these hurdles involve expanding the land available for biomass energy production; integrating biomass energy development with sustainable agricultural and forestry practices; improving crop productivity with regard to land, water, and nutrient use; and developing advanced production and conversion technologies. Biofuels produced from lignocellulose rather than starches appear more promising, both in terms of minimizing potential conflicts between food and energy production and in terms of maximizing environmental benefits (including greenhouse gas reductions) relative to fossil-fuel use.

Significant improvements have, of course, already been achieved worldwide with regard to agricultural productivity. Between 1950 and 1999, the land area used to grow cereal crops increased by 17 percent. During this same time, cereal-crop output rose by 183 percent, thanks to productivity improvements. The introduction of new strains of plant species has diversified crop cultures, allowing for efficient harvesting in different types of soils, climates, and water conditions and also achieving better yields.

The European Union and the United States are conducting intensive R&D to improve the cost competitiveness of commercial ethanol production. Current efforts are focused on promoting the efficient recovery of sugars through the hydrolysis of cellulose and hemicellulose fractions of biomass, as well as better sugar fermentation. Researchers are investigating a large number of possible process arrangements for different crops in hopes of reducing ethanol production costs by as much as one-third within five years (Macedo, 2005).

With rising oil and natural gas prices and with the new incentives generated by emerging carbon markets, landfill gas, sugarcane bagasse, biodiesel, managed forest wood, and waste-to-energy schemes are also becoming attractive options. Based on current trends in technology development,

costs for biomass energy recovery are expected to decline by up to two-thirds in 20 years, even as a broader mix of biomass-based products—including not only energy products, but also chemical feedstocks—becomes commercially viable (Macedo, 2005).

Progress in developing biomass energy alternatives, besides relieving pressure on finite fossil-fuel resources, would reduce the cost of mitigating carbon emissions. Sugarcane ethanol, for example, has a positive net energy balance of eight to one and a near-zero present carbon-mitigation cost. As a means of avoiding greenhouse gas emissions, bioethanol could soon achieve negative costs as it becomes cheaper than gasoline—even without government subsidies—in some markets. On the other hand, much of the ethanol and biodiesel commercially produced in the OECD

Box 3.2 Frontiers in biofuels production

At present, the biofuels industry is primarily based on the production of ethanol via the fermentation of sugars or starches and on the production of biodiesel derived from plant oils. The use of lignocellulosic (woody or fibrous) biomass materials—as opposed to starches or sugars—is, thought however to hold far greater potential for maximizing the efficient conversion of sunlight, water, and nutrients into biofuels. Perennial plants such as grasses or fast-growing trees appear particularly attractive for large-scale sustainable biofuel production for several reasons: (a) no tillage is required for approximately 10–15 years after first planting, (b) long-lived roots can be developed to establish symbiotic interactions with bacteria to acquire nitrogen and mineral nutrients, resulting in order-of-magnitude less nitrate runoff and soil erosion, and (c) some perennials withdraw a substantial fraction of mineral nutrients from above-ground portions of the plant before harvest. Wild-type grasses such as miscanthus have produced up to 26 dry tons per acre (sufficient to produce 2,600 gallons of ethanol per acre) on non-irrigated, non-fertilized land in the United States (Long, 2006). This is approximately five times higher than the average yield from sugarbeet or starch feedstocks such as corn (the latter in dry weight). In general, biodiesel yields from most types of feedstock—except palm oil—are smaller.

Present methods of producing ethanol from cellulosic feedstock proceed in three steps:

(a) Thermochemical pretreatment of raw biomass to make complex cellulose and hemicellulose polymers more accessible to enzymatic breakdown;
(b) Application of special enzyme cocktails that hydrolyze plant cell-wall polysaccharides into a mixture of simple sugars; and
(c) Fermentation, mediated by bacteria or yeast, to convert these sugars to ethanol

The energy-rich lignin that is separated from the cellulose and hemicellulose can then be either burned to power the biorefinery or converted to syngas and then to Fischer-Tropsch fuels.

Current methods depend on complex, energy-intensive steps where pretreatment is incompatible with enzymatic deconstruction. As a result, additional neutralization steps are necessary, adding to overall cost and reducing overall process efficiency. In future bio-refineries, depolymerization (saccharification) and fermentation processes may be consolidated into a single step using a mixture of organisms in converting biomass to ethanol. Significant improvements in reducing energy inputs, enzyme costs, and the number of processing steps are highly likely if a total systems approach to biofuels production is taken.

Applying advances from rapidly developing areas of science and technology such as synthetic biology and high throughput functional genomics holds out promise for rapidly improving feedstocks and the conversion of those feedstocks into biofuels. Possible areas of research that would increase biomass production and its conversion into fuel are listed in Table 3.6. Cellulosic materials such as rice and wheat straw, corn stover, and other crop and forest residues can serve as sources of cellulosic feedstock.

The development of photosynthetic microbes that produce lipids or hydrocarbons also has great potential for biofuels production. While plant production of useable biomass is unlikely to exceed an overall solar conversion efficiency of 1–2 percent, algae can convert solar power at efficiencies in excess of 10 percent. A combination of anaerobic and aerobic microbial processes can be separately optimized so that a fuel precursor can be produced in an anaerobic environment and the final product in an aerobic setting. Efficient algae cultivation that would take full advantage of the high quantum efficiency of these micro-organisms would, however, require capital intensive infrastructure.

Table 3.6 Research pathways to improved cellulosic biofuels production

Objective	***Current status***	***Scientific questions***	***Technologies to be used***
Feedstock development			
Develop high yield, low maintenance, sustainable energy crops.	Most biomass feedstocks are unimproved plants. Modern breeding and molecular engineering methods should be able to greatly improve biomass yield, disease and drought resistance, and other desired traits.	*Which genes control the various aspects of polysaccharide composition and synthesis? Can useful modifications to cell- wall composition be made by modifying the activities of these genes?*	High-throughput functional genomics to identify functions of all carbohydrate-active proteins in representative plant species. Genes that confer drought resistance can be identified. Engineer plants to contain the nitrogen fixation genes to accept nitrogen-fixing symbionts.
Engineer crops to facilitate the breakdown of ligno-cellulose into simple sugars	The presence of large amounts of lignin greatly impedes the hydrolysis of polysaccharides. Removal of lignin requires energy intensive and harsh pretreatments such as steam explosion or hydrolysis with hot acid	Lignin is needed to confer structural integrity to plants. *Can the ratio and composition of various lignins be altered to produce robust plants that can easily be broken down so that most of the polysaccharides can be accessible to hydrolysis?*	Altering the ratios of guiacyl and syringyl lignin has been shown to greatly improve hydrolysis efficiency. Modification of existing lignins for improved plant deconstruction (e.g., lignin designed with cleavable linkages) should be possible.
Deconstruction			
Develop highly efficient feedstock pretreatment methods.	Current pretreatment methods, such as steam explosion, hot acid hydrolysis, thermo hydrolysis, are expensive and energy intensive.	*Are there less harsh pretreatment processes that can increase the surface area binding sites for enzymatic depolymerization and are more compatible with the enzymes or microbes to be used?*	Employ high throughput, micro-system testing of pretreatment combinations with lignin-modified transgenic plants. Use modeling of different physical and chemical processes to optimize the pretreatment method.
Identify more efficient enzymes for depolymerization.	The efficiency and cost of the enzymes is a major cost in the production of cellulose-based ethanol.	*Can we significantly improve the enzymatic activity with decreased product inhibition?*	Employ more systematic, high throughput searches for better enzymes. Improve newly discovered enzymes with mutagenesis and directed evolution methods.
Develop microbial communities for ligno-cellulose degradation.	Microbial communities and their role in biomass decomposition is poorly understood.	*Can self-sustaining microbial communities be used in lignocellulose deconstruction?*	There exist many unexplored microbial communities that can be screened for compost degradation, metagenomic sequencing, characterization, and cultivation. These microbial communities can serve as a new source of lignocellulolytic enzymes

TABLE CONTINUES ON NEXT PAGE

continued table 3.6

Fuels synthesis			
Improve ethanol production.	Existing microorganisms are incompatible with current pretreaments.	*Can we develop fermentation organisms that can tolerate low pH or other processing conditions?*	Use genomics, metagenomics and synthetic biology to engineer tolerance to treatment conditions not found in nature.
	Current organisms are not compatible with high levels (greater than 15%) of ethanol production.	*Can we understand and improve an organism's tolerance to the fuels it produces?*	Apply systems and synthetic biology to engineer tolerance. Develop continuous fuel extraction methods to limit fuel concentration in the fermenting medium
Develop microorganisms to produce improved transportation fuels.	Ethanol production via fermentation is based on a 5,000-year old technology.	Butanol and heavier hydrocarbon (diesel-like) fuels have higher energy density and efficiency, and do not absorb or mix in water. *Can organisms be developed to produce these more desirable transportation fuels?*	A challenge of synthetic biology to create micro-organisms that can efficiently produce a heavier hydrocarbon transportation fuel that will self-separate from its aqueous environment.

countries at present has carbon mitigation costs in the range between US$60–400 per ton of carbon dioxide equivalent if upstream energy and chemical inputs are accounted for. Fertilizer use to grow biomass feedstocks, for example, can produce emissions of nitrous oxide, an extremely potent greenhouse gas—thereby offsetting some of the climate benefits associated with avoided petroleum use. Similarly, converting biomass to liquid fuels requires energy and—depending on the conversion efficiency of the process and the energy sources used—can also produce significant offsetting emissions. Improving the performance of biomass fuels from a climate mitigation perspective therefore depends on reducing these inputs.

Toward that objective, significant R&D efforts are now being focused on the development of commercially viable methods for producing ethanol from cellulosic feedstocks, which could substantially reduce costs and enhance associated greenhouse gas reductions. Interest is also growing in the development of integrated systems that would allow for the co-production of energy feedstocks with other agricultural outputs as a means of achieving significant cost savings and environmental benefits. For example, biodiesel production may make sense only if it uses seeds that are non-edible (by both humans and animals) as a feedstock or if it can be coupled with the cultivation of animal food.

Other potentially promising examples of integrated systems involve gasification processes that could allow for the co-production of multiple valuable outputs, including electricity, liquid transportation fuels, and chemicals. Gasification technology can be used with multiple feedstocks, including energy crops, animal waste, and a wide range of organic materials, as well as coal and other carbonaceous fuels. In general, the process involves producing a synthesis gas (composed primarily of carbon monoxide and hydrogen) from any carbon- and hydrogen-containing material; the synthesis gas can then be used to drive highly efficient turbines and as a feedstock for manufacturing a variety of synthetic chemicals or fuels. Small-scale gasification technology may eventually emerge as a promising option for improving energy access in isolated regions. Meanwhile, the most important use of locally available biomass residues may be in combination with modern combustion technologies as a replacement for diesel oil, which is now commonly used in old and inefficient diesel engines. Potential technologies for directly converting biomass for these purposes include thermal-chemical and catalysis processes.

Today's biotechnology industry is beginning to look beyond established production processes to more advanced options such as ethanol hydrolysis and fermentation, biodiesel enzymes, higher carbon fixation in roots, and improved oil recovery (Somerville, 2005). Advances in genetic engineering have already allowed for the development of disease-resistant strains and for crops that are viable in environments (such as degraded lands) that were previously considered unsuitable for cultivation, as well as for crops with reduced requirements in terms of chemical inputs and water. New cutting-edge technologies under development include lignocellullosic bioprocessing techniques that would allow for the co-production of fuels and chemicals in 'bio-refineries' and genetic modifications to biomass feedstocks to facilitate the application of process technologies that could achieve 70–90 percent energy conversion efficiencies (Box 3.2).

In summary: Biomass

The biomass industry is market driven and will pursue productivity improvements accordingly. Private actors will also want to remove trading barriers—both tariff-related and technical—to the wider use of their products. More sophisticated markets, public pressure, international agreements, and tighter environmental controls are forcing biofuels producers to develop socially and environmentally sound practices that reduce water

and chemical requirements, preserve ecosystems, reduce greenhouse gas and conventional pollutant emissions, and generate high-quality jobs. Nevertheless, subsidies and other incentives may be necessary to advance biomass technologies in the early stages. Such subsidies should be progressively removed as biomass-energy industries move up the learning curve. Brazil's successful effort to develop sugarcane ethanol as an alternative transportation fuel, which is today fully competitive with gasoline in international markets, provides a useful paradigm in this regard.

At the same time, enthusiam for biomass alternatives to petroleum-based transportation fuels must be tempered: government inducements and mandates to promote energy independence should not overly distort market forces that moderate the competition between biofuels, food production, and other land-uses—nor should they jump ahead of the technology needed to achieve large-scale biofuels production in an environmentally sustainable and economically sensible manner.

3.5 Summary points

The world is not about to run out of energy: coal reserves alone would be adequate to support hundreds of years of consumption at current rates, while the theoretical potential of renewable resources is virtually limitless. The constraints we face are fundamentally environmental and economic: can we come up with new energy supplies that do not incur unacceptable climate or other risks, at a price, in the quantity, and in the timeframe needed to meet growing global demand?

- **Without some unforeseeable, fundamental energy-technology breakthrough, no single energy supply option provides a 'silver bullet' solution for the world's energy woes.** The path to sustainability will surely involve—along with a heavy emphasis on energy efficiency and demand-side options—a diverse portfolio of supply resources. This does not mean that all supply options should be pursued with equal vigor. The world's resources are finite and choices will need to be made. Scientists can make a unique contribution in the selection of R&D priorities, which should be based on economics, scalability, technological promise, and other factors.
- **Future choices regarding final energy carriers—such as electricity or hydrogen—will have important implications for the mix of primary energy sources used to meet global energy needs**.
- **At present, global and regional supply-security and price concerns are most relevant for conventional oil and, to a lesser extent, natural gas.** Given the finite nature of conventional oil reserves in particular, and the

uneven geographical distribution of these resources, oil- and gas-related energy-security concerns will continue to be a high priority for many governments over the next several decades. Assuring access to natural gas will be a significant issue given the importance of natural gas as a 'bridge' fuel in the transition to a less carbon-intensive portfolio of energy resources. Meanwhile, to address oil security concerns it will be vital to develop alternatives to conventional oil, especially in the transport sector, that are compatible with other sustainability objectives. At the same time, it is worth pointing out that governments have been known to guess wrong. Poorly designed incentives and mandates can produce significant unintended consequences and undesirable market distortions.

- **Given ample global supplies and relatively low cost, coal is likely to be an important part of the energy picture for some time to come.** Therefore great urgency must be given to developing and commercializing technologies—such as carbon capture and sequestration—that would allow for the continued use of coal in a manner that does not pose unacceptable environmental risks.
- **Nuclear technology could make an important contribution to future low-carbon energy supplies**, but significant new investments in nuclear power are unlikely without substantial government support; more effective international collaboration on safety, waste, and proliferation concerns; changes in public perception; and the imposition of greenhouse gas constraints that would make low- or non-carbon technologies more cost-competitive with conventional fossil technologies. A transparent and scientifically driven re-examination of the issues surrounding nuclear power and their potential solutions is needed.
- **Earth's untapped renewable energy potential is enormous and widely distributed in industrialized and developing countries alike.** In many settings, exploiting this potential offers unique opportunities to advance both environmental and economic development objectives. Dramatic cost declines, strong growth in many renewable energy industries, and new policy commitments are promising. For example, the European Union has recently adopted the target of meeting 20 percent of overall energy needs by 2020 using renewable resources. Nevertheless, significant technological and market hurdles remain and must be overcome for renewable energy to play a significantly larger role in the world's energy mix.

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4. The role of government and the contribution of science and technology

The current structure of market incentives and regulatory conditions in much of the world will not, by itself, produce sustainable outcomes or socially optimal investment decisions. Alternatives to today's dominant technologies may exist, but there is no certainty that they will be deployed on the scale and in the timeframe necessary to avoid some of the most troubling consequences of the world's current energy trajectory.

The energy picture will surely change—but, without policy intervention and technological innovation, not necessarily for the better. If the aim is to simultaneously address climate-change risks, improve energy security, and expand access to modern energy services for the world's poor—while at the same time improving environmental quality and protecting public health—governments will need to act now and technology will need to improve.

This chapter discusses the role of government and the contribution of science and technology (S&T) in initiating and sustaining a broad-based transformation of the world's energy systems. Certainly, government—with its ability to influence markets, technology, and behavior through policies and regulations—has a critical role to play. Judicious policy interventions, far from interfering with the proper functioning of markets, may be necessary to address pervasive market failures and to ensure that private incentives align with societal imperatives to produce economically and environmentally sustainable outcomes. Experience has shown that purely free market economies seldom deal adequately with macroeconomic or international problems (such as water and air pollution or open sea fishing) that exhibit 'tragedy of the commons' characteristics. At the same time, the process of technological innovation to develop new energy options for the next generation and beyond must also accelerate. Public and private sector investments in energy research, development, and demonstration (RD&D) have been inadequate to the world's energy challenges for some time now and this will have to change as soon as possible.

At the same time, a more widespread deployment of existing technologies should be pushed by governments even earlier.

At their best, government policy and technology RD&D interact in complementary and mutually reinforcing ways. Well-designed policies and regulations can generate a market *pull* for technologies that are already developed and close to commercialization. At the same time, concerted public and private investments in energy RD&D can *push* the process of innovation, expanding the menu of technology options that will be available in the future. Related policies—with respect to educating the public, issuing patents, and developing human capital by nurturing a new generation of professionals and scientist with energy expertise—also have a critical role to play. Several recent reports argue that the combination of pull and push mechanisms is likely to be more effective than either approach alone (NCEP, 2004; CBO, 2006).

This chapter also reviews, in general terms, some of the policy levers available to government for advancing sustainable energy objectives, as well as the role of science and technology and some near-term RD&D priorities. At the outset, it is worth remembering that while interest in reducing greenhouse gas emissions per se is relatively new, the history of energy policy and of energy RD&D around the world is rich with experience. Many nations have, at one time or other, sought to advance indigenous fuel sources, reduce conventional energy-related pollutant emissions, develop new technology options, or make energy more widely available. A wide variety of strategies to advance these and other energy-related objectives have been employed, with varying degrees of success. On the one hand, bad energy planning and poorly designed price controls and subsidies, at a rate of more than US$200 billion per year, have distorted markets, produced unintended consequences, and in some cases led to artificial shortages (UNDP, UNDESA, and WEC, 2004). Similarly, the fact that large sums of public money have been expended on technology programs that have yielded, at best, disappointing results points to the need for improved management of future research & development (R&D) efforts, which should be subjected to continual expert cost/benefit analysis, and to the importance of pursuing the end-goal of shifting technology investments to the private sector.

On the other hand, the record of accomplishment is also impressive. Rural electrification programs have given hundreds of millions more people access to modern energy services. Many countries have successfully nurtured new energy industries, and environmental laws and standards

have prompted the development of radically cleaner and more efficient technologies. Around the world, the amount of energy used and pollution generated to produce a dollar of wealth has declined steadily, even as quality of life and access to energy amenities has improved for large segments (though by no means all) of the world's population.

4.1 Policy options

Governments have many options for advancing a sustainable energy agenda. Table 4.1 provides a basic taxonomy of policy approaches, along with numerous specific examples: it is intended to suggest the breadth and variety of strategies that are available and is by no means exhaustive. Importantly, most of the policy options noted in the table could be applied to promote solutions on both the supply and the end-use side of the energy equation. Within the broad category of 'carrots' are policies that rely on positive incentives to stimulate desired activities or technologies; examples include grants, loan guarantees, subsidies, or information and technical assistance programs. Efforts to raise public awareness, provide training (especially to energy professionals), and educate building designers and architects can also help to advance a sustainable energy agenda. Public infrastructure investments, while they do not exactly constitute an incentive, are included here because such investments can help overcome economic or technical obstacles that would otherwise impede the adoption of new technologies. For example, efficient, long-distance electricity transmission systems can open new markets for renewable energy resources while sophisticated metering networks could help homeowners and businesses manage their energy consumption more efficiently.

Policies that create positive incentives tend to be politically popular (or at least relatively uncontroversial) but usually require government to expend revenues, often with uncertain results. Like nearly all policy options, they impose opportunity costs on society (in the sense that the money spent could be put to other uses). But because those costs are diffuse and borne by taxpayers, they are often, in a political sense, hidden. The effectiveness of voluntary, incentive-based or information-based programs depends on the scale of the resources that are brought to bear and on how efficiently those resources are deployed: targeting social spending so that it achieves maximum public benefits at lowest cost is often a significant challenge. Subsidies, for example, can be quite effective in accelerating the adoption of certain technologies. But subsidies can also be inefficient (to the extent that they benefit households or industries that do not need them) and difficult to remove, unless an eventual phase-out is part of the policy from the

Table 4.1 Policy options for promoting a transition to a sustainable energy future

Incentives: 'Carrots'			
Financial incentives • tax credits • subsidies • grants, other direct funding • loan guarantees • procurement policies • feed-in tariffs		**Non-financial incentives** • publicly-funded RD&D • infrastructure investments • education/information/labeling • technical assistance • award/recognition programs • grid access	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
• Potentially useful to advance 'cutting-edge' technologies. • Often politically popular. • Can be targeted to overcome particular market obstacles or promote specific technologies.	• Require government to spend money. • Spending may be politically influenced and not always cost-effective (e.g., subsidies continue even when no longer needed). • Results are difficult to predict. They tend to be biased toward well-understood options.	• Provide means to address other market failures/ barriers. • Usually politically popular. • May have a variety of spillover benefits. • Can help address competitiveness concerns.	• Difficult to target RD&D, infrastructure investments. • Institutional and technical capacity required to develop and deliver programs. • Benefits/impacts may be limited, especially without complementary financial incentives.
Disincentives: 'Sticks'			
Market-based policies • energy or emissions taxes • emissions cap-and-trade programs		**Prescriptive regulations** • emissions standards • efficiency standards • portfolio standards	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
• Can be applied economy-wide. • Markets deliver least costly reductions. • Individual firms, consumers retain choice, flexibility. • Generate revenues that can be used for other purposes. • Consistent price signals yield economically rational outcomes across all covered sectors. • Can be designed to meet specific objectives in terms of cost, emissions reductions, etc.	• May generate strong political opposition because they raise prices. • Energy-price impacts on poor households will be a concern (though should note that revenues generated by policy can be used to address this issue). • May raise concerns about impacts on domestic industry in terms of jobs and competitiveness in world markets. • Price signals may be inadequate to overcome other market failures or stimulate new technologies.	• Effective where price signals alone would not elicit all cost-effective responses (e.g., car, building, appliance markets). • Policy outcomes are relatively certain (though costs may not be). • Many manufacturers, industries already subject to some regulation. • Costs are less evident, potentially reducing political opposition. • No action needed on part of consumer.	• Usually do not encourage or reward better than minimal compliance. • Require technical and institutional capacity to develop, enforce standards. • Different policies needed for different sectors. • Defining cost-effectiveness is uncertain and often contentious, especially if regulators have to project future tech development. • Less flexible and (potentially) more costly than market-based approaches. • Policies need to be updated over time.

outset. Also, subsidies that are too large discourage innovation to lower costs and can freeze development

One issue that has not been solved is how to more closely couple capital investments in energy-efficient commercial and residential building budgets with savings that would be accrued in operation and maintenance costs. In industrialized countries, additional investments are seldom made unless the pay-back time is less than one to two years; and in developing countries, the initial cost dominates virtually all investment decisions. If the payback time on energy efficiency investments were extended to 6–10 years, the building industry would be transformed. Regulations such as energy-efficient building codes are a partial solution; access to low-cost capital targeted for energy-efficiency investments in both new construction and in building retrofits is also needed.

Governments also have the option of deploying policy 'sticks' to compel changes in technology and behavior. This category of approaches can achieve desired results more expeditiously and more efficiently (that is, at lower net social cost), and typically does not involve large outlays from the public treasury. Some options, like fuel taxes, actually generate revenues. Removing subsidies to conventional energy sources or ensuring that energy prices reflect external costs and benefits can also produce effective results by shifting the market incentives for different technologies. (The failure to include externalities in market prices by itself often constitutes a form of subsidy for entrenched technologies.) Not surprisingly, however, policies that are perceived as raising prices are also more likely to confront organized political resistance from affected interests and to give rise to concerns about the potential for regressive impacts on poor households and for adverse effects on industry competitiveness. Many of these concerns can be ameliorated by careful policy design, but it will also be critically important to educate the public and foster greater awareness of the energy-sustainability challenge so as to build political support for difficult policy choices.

Policymakers should also recognize that energy markets are extremely volatile, and hence quite sensitive to supply disruptions and/or manipulation. A significant number of energy technology investments initiated during the spike in oil prices that began in the mid-1970s were wiped out when the cost of oil dropped to US$20 per barrel in 1980s and remained at that level for most of the 1990s (Figure 4.1). The private sector is less likely to make long-term investments in new energy technologies if there is a real possibility that the price of oil will again decline from current

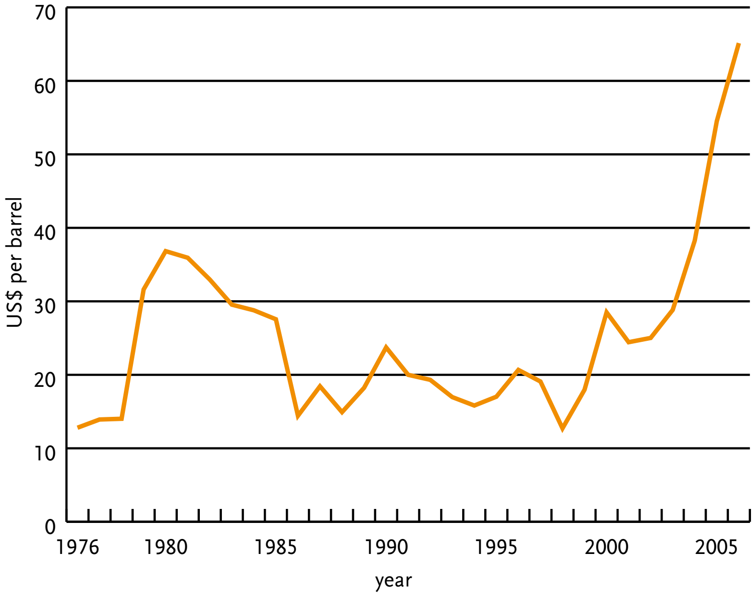

Figure 4.1 The development of crude oil prices over the last three decades

Note: Shown are nominal (not inflation-adjusted) spot prices for Brent crude.

Source: Platts, 2007.

levels of US$60–70 per barrel to below US$30 per barrel. Indeed, existing stakeholders in a given industry have sometimes sought to protect their economic interests against a threatening new technology by dropping the price of their product before the infant competition can advance too far down the learning curve.

Science and technology policies are not individually identified as distinct options in Table 4.1, though nearly all of the examples listed could be used to directly or indirectly spur the development and deployment of more sustainable energy technologies. Clearly, public support for research and development (included under policy 'carrots' in Table 4.1) is among the most important tools available to government for influencing future energy developments. Because of its importance and complementarity with other policy options, however, publicly funded research and development (R&D) is included with a broader discussion of the role of science and technology in the second half of this chapter.

4.2 Policy choices in context

The best mix of strategies for promoting sustainable energy objectives will vary depending on a given country's policy priorities; its financial, institu-

tional, and technical capacities; its political and regulatory traditions and market structure; and other factors. For many wealthy, industrialized countries, the chief objective will be to maximize cost-effective, energy-efficiency improvements; accelerate the adoption of low- and non-carbon technologies; and address energy-security concerns (especially related to dependence on oil and natural gas and nuclear non-proliferation). Policies well-suited to advancing these objectives are likely to include standards, environmental regulations, and market-based programs (such as a carbon tax or emissions-trading program.

The situation for developing countries, by contrast, is likely to be complicated by additional imperatives and constraints. To the extent that some sectors of the economy and segments of the population consume energy in much the same way as in industrialized countries, developing countries may share similar objectives—and confront similar opportunities—in terms of addressing energy-related environmental externalities and energy-security concerns. For this reason, policies aimed at promoting alternative fuels, low-carbon technologies, or improved efficiency are needed as urgently in developing countries as in industrialized countries.

In these situations, pricing or other policies can be used to promote investments in energy efficiency and alternative technologies. Where price signals are used to discourage consumption and/or produce more sustainable technology choices, it may be necessary to ameliorate potentially regressive impacts on lower-income households; this can often be accomplished using a variety of policy mechanisms. At the same time, other policies—such as appliance and equipment standards—can help to ensure that, as developing economies industrialize, they 'leapfrog' to cleaner, more efficient technologies. Countries that are rapidly expanding their stock of buildings, infrastructure, and capital assets have a unique opportunity to 'build in' improved energy performance at lower cost and with greater long-term benefits than would be possible if energy and environmental liabilities are addressed only as an afterthought.

The list of available policy options is long and lends itself to virtually endless variations, as indicated in Table 4.1. Most of these options have strengths and disadvantages. And it is unlikely that a single policy will achieve all desired objectives. A policy designed to create a consistent, economy-wide price signals for reducing greenhouse gas emissions (such as a carbon tax or cap-and-trade program) may not be sufficient to ensure that all cost-effective efficiency opportunities are captured or to overcome barriers to entry for new technologies. Complementary policies (such as

vehicle and appliance efficiency standards) may be appropriate. Subsidies or tax credits used to stimulate innovation should be invoked with built-in 'sunset' clauses.

Often, thoughtful policy design can overcome some of the drawbacks of a particular approach, producing hybrid strategies that combine the best features from multiple options. A portfolio standard can be used to require that a specific percentage of electricity production is derived from renewable or non-carbon resources while still allowing the market to sort out what mix of those resources would meet that requirement most cost-effectively. Similarly, innovative mechanisms such as a 'reverse auction'—in which providers of clean energy bid for a share of some available limited-term incentive pool based on the minimum subsidy required to successfully compete in the market—can help to maximize the benefits achieved using scarce public resources. In addition, trading or averaging can be used to implement an efficiency standard while incorporating some of the flexibility and cost-reduction benefits associated with market-based programs.

Individual countries will, of course, need to evaluate their options and their priorities and decide on a mix of approaches that suit their specific circumstances. Even as different countries pursue different approaches, however, it is likely that significant benefits can be achieved by maximizing coordination and information-sharing, where feasible. For example, manufacturers that sell products all over the world may benefit from harmonized efficiency or emissions standards while certain economic sectors, such as marine shipping and aviation, may be most effectively regulated at an international level. Similarly, the ability to trade well-defined and reliably-documented emission-reduction credits across national boundaries could allow for significant cost reductions in reducing global greenhouse gas emissions while providing an important mechanism for facilitating technology transfer to poorer nations.

An important related question arises: *how can companies be encouraged in rich countries to share advanced technologies—both end-use and supply technologies—with developing countries?* Businesses are not charities and requiring them to share intellectual property at below 'market value' will discourage investment in the development of new technologies. On the other hand, without subsidizing the cost, superior technology alternatives may go unused in such countries as China and India. It would therefore be useful to explore options for providing low-cost access to intellectual property related to sustainable energy technologies and practices. For example, it

might be possible to devise a mechanism for compensating intellectual-property holders from an international fund established by wealthier countries.

4.3 The importance of market signals

Although few specific policy recommendations can be ventured at an international level, certain policies are likely to have widespread applicability. Efficiency standards and building codes have been implemented cost-effectively in many industrialized countries. The knowledge gained there can be emulated and improved upon to help moderate energy demand growth in rapidly industrializing economies. Subsidies that distort energy markets, particularly when they do so in ways that favor increased fossil-fuel consumption, should be reduced and reformed; instead energy prices should reflect, to the maximum extent feasible, environmental and other externalities.

The point is critical: without market incentives to prompt different behaviors and investment decisions, policies that focus solely or primarily on voluntary reductions in greenhouse gas emissions and technology R&D are unlikely to promote change on a scale commensurate with the environmental challenge at hand. Opinions vary as to the level of price signals that are warranted, but many experts believe that a price on the order of US$100–150 per ton of carbon equivalent emissions (in other widely used units, US$27–41 per ton of carbon dioxide equivalent emissions) may be necessary to overcome current cost differentials for many low- and non-carbon technologies and to stimulate the large-scale changes that will be required to eventually stabilize atmospheric concentrations of greenhouse gases. The two policy options that are most frequently proposed to address climate concerns are energy or carbon taxes and cap-and-trade programs; important features of each approach are discussed in Box 4.1.

It is important here to emphasize, however, that establishing in every market that there eventually will be an emissions price—in the range of US$100–150 per avoided metric ton of carbon equivalent (US$27–41 per ton of carbon dioxide equivalent)—is more important than establishing exactly the number of years in which such a transition will occur. For many countries, pragmatic considerations are likely to argue for a phased and multi-pronged approach, wherein an initial carbon price signal is gradually increased over time and complemented by other policies to address remaining market barriers and accelerate the commercialization of more efficient, lower-carbon technologies. Complementary policies, such as

appliance and building standards and air pollution control requirements, can likewise be introduced slowly but inexorably. By making resistance from entrenched stakeholders begin to appear futile, this approach can effectively stimulate innovation and reduce transition costs. In sum, given that the world's energy infrastructure includes many long-lived, capital-intensive assets, it would be extremely expensive and probably infeasible to

Box 4.1 Reducing emissions: Taxes vs. cap-and-trade programs

Carbon taxes and cap-and-trade programs are the two market-based regulatory options most often advanced for limiting greenhouse gas emissions. Both options are well-suited to situations where there are a large number and variety of emissions sources that must be regulated and where the opportunities for mitigation are similarly diverse and characterized by a wide range of costs. Indeed, the salient argument in favor of either approach is precisely that they rely on market forces to produce emissions reductions at the lowest marginal cost and without relying on policymakers to identify the optimal set of technology pathways.

The carbon tax recommended by neoclassical theory is one that accurately reflects the environmental damage or 'externality ' associated with each ton of emissions and that therefore produces the socially optimal level of emissions. That is, society as a whole will spend only as much to reduce emissions as those reductions are worth in terms of avoided damages. A carbon tax would have the effect of raising prices on fossil fuels in proportion to their carbon content and—assuming properly functioning markets—should stimulate users of fossil fuels to reduce their consumption wherever it is cheaper to do so than to pay tax.[a] The cost of a tax policy is transparent and known in advance. What is not known in advance is how much emissions abatement will occur in response since this depends on the cost and magnitude of mitigation opportunities available throughout the economy. Another noteworthy feature of a carbon tax is that it generates revenues for the government that could be used for other socially productive purposes.

Monetizing the environmental damages associated with carbon emissions is a necessary, albeit difficult, first step. Even where this is done, however, there is abundant evidence to suggest that markets will respond only imperfectly to a carbon price signal. For reasons discussed in Chapter 3, cost-effective energy-efficiency opportunities are routinely overlooked by large corporations and individual consumers alike, and new technologies often face barriers to entry that are not strictly a function of cost. Carbon or energy taxes have proved politically unpalatable in some countries—notably the United States—though they have been accepted more readily elsewhere.

A carbon cap-and-trade system functions, in many ways, like a tax. The recent experience of the European Union, which has created a market for carbon with values in the realm of US$100 per ton through a cap-and-trade-type program for large industrial emitters of carbon dioxide, provides a useful, real-world example of how this approach can work in practice. In principle, the mechanism is simple: government requires that each ton of emissions be accompanied by a permit and then constrains the quantity of permits available to emitters. As with a tax, this approach effectively raises the price of fossil fuels and—provided permits can be freely traded—stimulates the lowest cost emissions reductions. In addition, some cap-and-trade programs provide for 'offset credits ' to stimulate mitigation activities in sectors not covered by the cap. Companies will use permits only when the cost of doing so is lower than the cost of avoiding emissions. Like a tax, a cap-and-trade program can generate revenues if government chooses to auction permits, although past programs of this type have typically allocated most permits for free to regulated entities.[b]

The key difference between the two approaches is that, under a tax, costs are known but final emissions are not. By contrast, under a cap-and-trade program, final emissions are known (assuming requirements are enforced, they are determined by the cap) and costs are uncertain. In theory, a tax could be adjusted to achieve a desired emissions goal. Similarly, it is possible to design a cap-and-trade system that improves price certainty by building in a 'safety valve '—essentially a promise that government will sell additional permits and allow emissions to rise above the cap if the market price of permits exceeds a certain threshold. The latter approach may be attractive in situations where political considerations favor a cap-and-trade approach but there are also significant concerns about cost and competitiveness.

[a] Additional provisions might be necessary under a tax-based system to recognize emissions avoided by carbon capture and sequestration. A tax rebate, for example, might be used to accommodate this form of mitigation.

[b] Giving permits for free to regulated entities may seem to 'mask ' the cost impacts of a cap-and-trade program, but in practice both policies will raise energy prices and generate revenues. In a cap-and-trade program with a free allocation those revenues simply go to the recipients of permits, rather than to the public treasury.

transform that infrastructure overnight. But for precisely the same reason, policies that allow for continued expansion of carbon-intensive energy systems are also unwise and—as climate-related policies are introduced—will also prove costly. Thus, the process of initiating change must begin soon.

4.4 The role of science and technology

Over the past 150 years, progress in science and technology has been a key driver of human and societal development, vastly expanding the horizons of human potential and enabling radical transformations in the quality of life enjoyed by millions of people. The harnessing of modern sources of energy counts among the major accomplishments of past scientific and technological progress. And expanding access to modern forms of energy is itself essential to create the conditions for further progress. All available forecasts point to continued rapid growth in global demand for energy to fuel economic growth and meet the needs of a still-expanding world population. In this context, few questions are more urgent than *how can science and technology can be enlisted to meet the challenge of long-term energy sustainability?*

As a starting point for exploring that question, it is useful to distinguish between several generally accepted phases of technological evolution, beginning with basic scientific research and followed by development and demonstration, RD&D. When all goes well, RD&D is followed by a 'third D'—the deployment phase— wherein demonstrated technologies cross the threshold to commercial viability and gain acceptance in the marketplace. Typically, government's role is most pronounced in the early *research* and *development* phases of this progression while the private sector plays a larger role in the *demonstration* and *deployment* phases. Nevertheless, government can also make an important contribution in the demonstration and early deployment phases, for example, by funding demonstration projects, providing financial incentives to overcome early deployment hurdles, and helping to create a market for new technologies through purchasing and other policies.

The remainder of this section focuses on the pre-deployment phases when issues of science and technology are most central. Nevertheless it is worth emphasizing that the deployment/commercialization step is crucial, and that it generates much information and insight that can benefit the R&D focused on in the early steps, in a process of refinement and adoption that is fundamentally iterative. Many demonstrated technologies encoun-

ter significant market hurdles as they approach the deployment phase; for some—hybrid vehicles, hydrogen as a transport fuel, solar energy, coal-based integrated gasification combined cycle (IGCC), and fuel cells— cost rather than technological feasibility becomes the central issue. Established private-sector stakeholders can be expected to resist, or even actively undermine, the deployment of new technologies, thus necessitating additional policy interventions.

Most of the energy technologies that are now in some phase of the RD&D process have something in common: either by themselves or in combination with each other, they hold significant promise for reducing carbon dioxide emissions (Table 4.2). New technology that promotes end-use efficiency (in buildings and appliances, vehicles, and processes) probably offers the most cost-effective opportunities, relative to technology on the supply side. Within the large set of supply options noted in Table 4.2, the use of biofuels in the transport sector may offer the most leverage, at least within the next ten to twenty years, while—in a somewhat longer timeframe—carbon capture and storage may play a major role. But these changes will occur within the next several decades only if decisive, initial action is undertaken at a global level within the next five to ten years. Further RD&D in third-and fourth-generation nuclear reactors can help diversify the world's future low-carbon energy portfolio, but only if solid, enforceable worldwide agreements can be reached on non-proliferation and on the disposal/storage of spent nuclear fuel. Further RD&D attention should also be focused on improving the efficiency and reducing the cost of energy conversion and storage technologies, including fuel cells, conventional batteries, and compressed air.

It should be emphasized that Table 4.2 lists only some of the promising RD&D opportunities that exist on the end-use side of the energy equation. With further technology investments, significant advances could be achieved in the efficiency of key energy-using devices, such as vehicles, appliances, and equipment, as well as in larger energy systems, such as cities, transportation systems, industrial processes, and whole buildings. The requisite technologies are still in a basic research phase in some promising areas, including:

- efficiently extracting useful energy from the lignocellulosic part of biomass,
- increasing biomass yields by boosting photosynthetic water and nutrient efficiencies through genetic engineering,
- applying nanotechnology and/or using new materials to improve the energy conversion efficiency of photovoltaic devices, and
- developing solid-state storage options for hydrogen.

Table 4.2 Energy R&D opportunities

Technologies	R&D	Demonstration
Transport sector		
Hybrid vehicle	Yellow	
Hydrogen fuel cell vehicle	Yellow	
Fuel – ethanol (cellulosic)	Orange	Orange
Fuel – Hydrogen	Orange	Orange
Industry sector		
Materials production process	Orange	Orange
Materials/product efficiency	Yellow	Orange
Feedstock substitution	Orange	Orange
Carbon dioxide capture and storage	Orange	Orange
Buildings and appliances sector		
Heating and cooling technologies	Yellow	
Building energy management systems	Yellow	Yellow
Lighting systems	Yellow	Yellow
Reduce stand-by losses		Yellow
Building envelope measures	Yellow	Yellow
Solar heating and cooling		Yellow
Power generation sector		
Biomass	Yellow	Yellow
Geothermal	Yellow	Yellow
Wind (onshore and offshore)		Yellow
Solar photovoltaics	Orange	Orange
Concentrating solar power	Yellow	Orange
Ocean energy	Orange	Orange
Advanced steam cycles (coal)		Yellow
Integrated gasification combined cycle (coal)	Yellow	Orange
Fuel cells	Orange	Orange
Carbon capture and storage + Advanced steam cycle with flue-gas separation (coal)	Yellow	Orange
Carbon capture and storage + Advanced steam cycle with oxyfueling (coal)	Orange	Orange
Carbon capture and storage + Integrated gasification combined cycle (coal)	Orange	Orange
Carbon capture and storage + Chemical absorption flue-gas separation (natural gas)	Yellow	Orange
Nuclear – Generation II and III	Yellow	Yellow
Nuclear – Generation IV	Orange	Orange

Orange: indicate significant opportunities and needs.

Yellow: Indicate that the technology under scrutiny would benefit from further R&D and/or demonstration.

Source: IEA, 2006.

Other technologies require more applied research or further development, including scale-up to a working, experimental laboratory model. The transition to demonstration, which is the prerequisite for eventual deployment, is critical and often gets insufficient attention from those who are or have been engaged in funding the R&D phase.

In sum, the world's S&T community has a central role to play in enabling the transition to sustainable energy systems. At least two conditions however must be met:

- Funding (both public and private) for energy RD&D must be sufficient.
- RD&D efforts must be effectively targeted and internationally coordinated to address both the supply and demand sides of the energy equation.

With regard to the first condition, it should be noted that global average public and private expenditures on energy R&D have declined over the last two decades, with a tendency to level off over the last decade, whereas total average public expenditures on all forms of R&D increased over the same time period (Kammen and Nemet, 2005; Nature, 2006). Figure 4.2 shows total public energy R&D expenditures by IEA member countries, and compares them to the global price of oil (in U.S. dollar per barrel) over the period 1974–2004. In 2005, total R&D expenditures (on the same purchasing power parity basis and adjusted for inflation to the value of the U.S. dollar in the year 2000) amounted to US$726 billion for OECD countries and US$155 billion for non-OECD countries. Governments' shares in these expenditures were 30 percent and 40 percent, respectively; hence total public R&D expenditures amounted to US$280 billion (OECD, 2006a). At approximately US$9 billion,[62] the share of these expenditures specifically directed to energy technologies accounts for a mere 3.2 percent of all public R&D funding.

The development of a diverse portfolio of sustainable energy technologies will require a sizeable boost—on the order of a doubling—in worldwide public investments in energy R&D. Such an increase in energy R&D funding should occur within the next five years and will most likely need to be sustained for at least several decades, if not longer. At the same time, governments must promote the expansion of private-sector investments in long-term energy R&D. Industry can bring crucial expertise and insights to the RD&D process (especially since deployment usually occurs through the private sector), as well as resources greater than those available to governments once the deployment stage has been reached. Government

62 This number excludes expenditures for basic research but includes funding of demonstration projects.

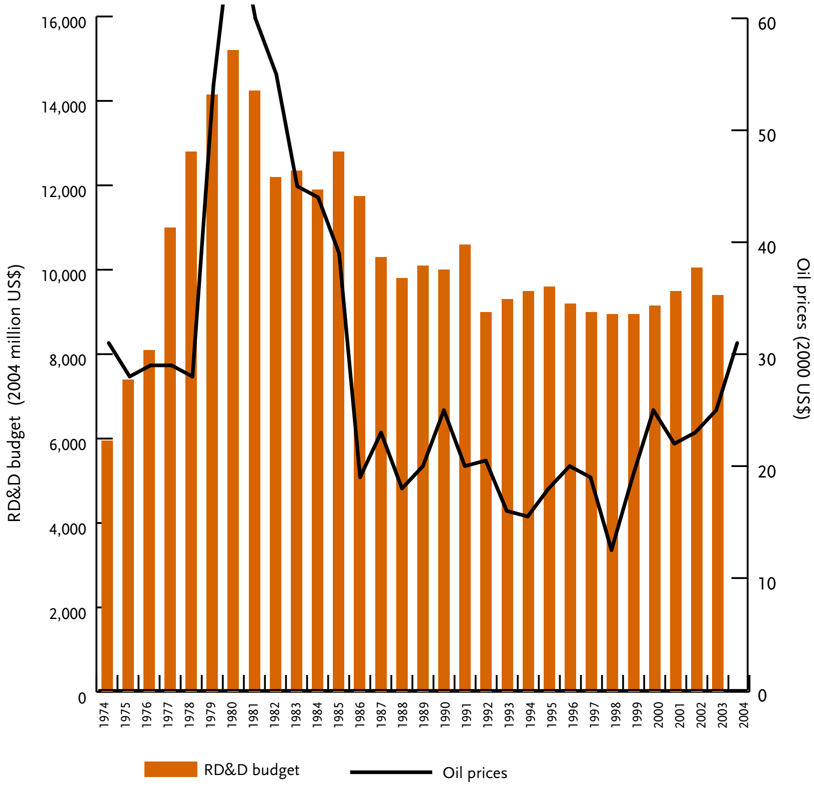

Figure 4.2 Public energy R&D expenditures in IEA countries and real oil price 1974–2004

Note: Total R&D budget includes conservation, fossil fuels, nuclear fussion, nuclear fission, renewable energy, power and storage technologies, amd other technology and research.

*Source*s: IEA, 2005; and OECD, 2006b

policies—such as a cap-and-trade program for limiting emissions or a carbon tax—would be hugely instrumental in creating incentives for the private sector to increase its RD&D investments. Thus, for example, a policy designed to expand the contribution from new renewable, carbon-neutral energy sources will force 'traditional' energy companies to rethink their future product portfolio and marketing strategies.

Continued policy uncertainty makes it difficult for energy companies to develop mid- and long-term business strategies. During the often protracted period required to formulate a comprehensive new policy, governments can reduce this uncertainty by adopting legislation that awards early action in the right direction while penalizing further activities that are counterproductive to achieving sustainability objectives.

Increased public funding for energy RD&D can come from a variety of sources. In many industrialized and large developing countries, much could be accomplished by refocusing or redirecting funds that are already in the national budget.[63] Additional funds could be obtained by rationalizing existing subsidy programs and/or by raising new revenues through energy consumption or pollution taxes (usually of the excise type) or by auctioning permits-to-emit under an emissions trading program.

Success depends, of course, not only on funding but on well-managed programs. Given that the scale of the challenge is likely to continue to exceed the public resources made available to address it, energy RD&D efforts around the world must be thoughtfully focused and aimed at answering concrete questions and solving defined problems. Energy RD&D should also be coordinated internationally and conducted in a framework of collaboration—both between countries and between the public and private sectors—to avoid unnecessary duplication and inefficient use of funds. International efforts to promote coordination and collaboration should thoroughly involve developing countries, not least to help them leapfrog to more advanced energy technologies and systems. Implicitly, this requires concerted efforts to facilitate technology transfer. The scientific community can play a moderating role in the often thorny debate about how best to accomplish this; developing countries, in turn, should create the right conditions for technology transfer.

The stakes are very high. Bringing the combined energies and expertise of the world's S&T community to bear on finding solutions is essential and will likely demand new international institutions or mechanisms to better leverage and harmonize global efforts.

4.5 The role of policy and technology in a developing country context

More than 2 billion people in developing countries lack access to either (or both) clean cooking and heating fuels and electricity. It is estimated that roughly 1.5 million people die each year due to respiratory illness and carbon-monoxide poisoning caused by indoor air pollution associated with the use of solid fuels such as twigs, dung, and brown coal for cooking. Access to modern energy services would also have a profound impact on other critical aspects of human development and quality of life for the

63 A public energy RD&D investment of US$20 billion per year would amount to an annual contribution of approximately US$27 per person in the United States and the European Union combined.

world's poorest citizens, including access to clean drinking water, irrigation, pollution-free indoor lighting, education, and communications.

Few priorities are therefore more important—both to the governments of developing countries and in terms of fulfilling international commitments to broadly held development goals—than expanding access to modern energy services and ensuring that developing nations have the energy infrastructure needed to sustain economic growth and raise living standards for their poorest citizens. Here policy and technology clearly have critical roles to play, especially in helping developing nations transition directly to cleaner and more efficient energy options. Just as it has been possible for many countries to go directly to cellular phones without having to lay telephone cables, it is becoming possible for many rural areas to be electrified using mini-grids or completely distributed systems without having to wait for expensive grid extensions. Technology innovation can also produce promising synergies for developing country applications. For example, efforts to develop liquid transport fuels from lignocellulosic biomass have driven research on enzymes and new, self-sustaining, microbial approaches that could eventually improve the performance of low-cost biogas digesters useful in rural areas of tropical developing countries. Moreover, development of such enzymes can be pursued not only in industrialized countries but in leading developing country laboratories as well.

Successfully transferring technology innovations from the prosperous to the poor presents its own, often formidable, challenges. The rural areas of many developing countries are littered with the remnants of energy demonstration projects that have failed—creating veritable technology graveyards. This is not the place to apportion blame or to list causes for these failures. Suffice it to say that researchers working on the development of sustainable energy technologies must avoid the tendency to understate costs, or belittle potential practical problems with the technologies they promote. Instead it will be critical to build on successes and learn from experience with past development projects. This, in turn, requires independent assessment or tracking of project performance with subsequent dissemination of results. Developing countries themselves must not be viewed as bystanders in this process. Though assistance from industrialized countries—especially in the form of financial resources but also to facilitate the sharing of intellectual property and technical expertise—is critical, developing countries must assume responsibility for effective technology transfer and poverty alleviation if the needs of the poor are to be met.

Human and institutional capacity building is also a critical issue in many developing country contexts. Research has shown that technology transfer is more successful and innovation is more likely to occur when host institutions have the requisite technical and managerial skills to manage new energy systems. Without those skills, new technologies often fail to deliver expected services. Capacity building is needed within the companies that produce, market, install, and maintain sustainable energy technologies and within the communities that will manage and operate those technologies. The latter need can be met by establishing regional institutes to provide training in basic technology management skills. Such institutes could also help to provide independent assessments of alternative technologies and policy choices, and explore strategies for overcoming barriers inhibiting the large-scale implementation of sustainable energy technologies.

Yet another issue is financing. In the recent past, governments usually relied on cross-subsidies (charging higher prices to one set of customers to reduce costs for another set of customers) to extend electricity or telecommunications services to remote areas. More recently cross-subsidies have fallen out of favor, in part because there is a limit to how much one class of consumers can be charged to bring service to another class of customers (especially when some high-use energy customers have the option to switch to other power sources or to off-grid generators). Many governments, however, continue to directly subsidize electricity sales to farmers, often because it is easier than providing direct income support. Often, electricity charges are flat, un-metered, and decoupled from actual consumption. This can produce a number of undesirable outcomes: when pumping costs are low, for example, farmers tend to over-use or inefficiently use water. Because of limits to cross-subsidization between customer classes and the growing financial burden of direct subsidies, new approaches will be needed to further grid expansions to rural areas in a number of developing countries.

More broadly, subsidies can be an effective mechanism for overcoming deployment hurdles for new technologies or to advance other societal goals. When subsidies are used to support already entrenched or unsustainable technologies, however, they produce a number of undesirable effects. Some of the generic problems with conventional-energy subsidies—which remain in widespread use around the world—are discussed in more detail in Box 4.2.

Given the resource constraints faced by many developing countries, there is an urgent need for greater international support for sustainable

Box 4.2 Energy subsidies

Although subsidies on fossil fuels have been declining over the last decade or so, they are pervasive and remain widely used around the world. On a global basis, fossil-fuel subsidies still amount to several hundreds of billions of U.S. dollars in industrialized and (to a lesser extent) developing countries (Table 4.3).

While cumulative funds expended on energy subsidies are often less than the revenues collected through taxes on other fossil fuels, such as petrol (gasoline), subsidies for established sources of energy lead to at least the following two problems:

• The common feature of all subsidies is that they distort market signals and influence consumer and producer behavior.

• Subsidies for conventional fuel often have the effect of further tilting the playing field against energy efficiency and cleaner sources.

Subsidies are addictive, and those who benefit from them do not easily acquiesce in their cessation without some other inducement. Commitments to eliminate or reduce subsidies may be adopted but they are notoriously difficult to implement for politicians who have to renew their mandates periodically. Moreover, as noted earlier in this chapter, failure to include environmental, energy security, and other externalities in market prices itself constitutes a form of subsidy that is common to conventional fuels in many countries. (Another example of this form of subsidy is the Price-Anderson Act in the United States, which indemnifies the nuclear industry against liability claims arising from accidents at civilian nuclear power plants).

Direct fuel subsidies rarely go to the most needy, as in the case of many current subsidies for diesel and kerosene. Governments should seek to eliminate or phase out subsidies that no longer serve the public interest. Conventional sources of energy, in particular, should at least be sold at the cost of production and ideally at a cost that also reflects associated environmental and other externalities. Where unsubsidized prices would impose excessive burdens on the poor, these burdens should be cushioned with direct income supports. Again, such recommendations are easy to make, but harder to implement. Since they lack reliable implementation mechanisms to transfer resources to the truly needy, many governments prefer to mask transfer payments by using subsidies over which they have some control. There is an urgent need for experimentation in such transfer mechanisms. This is a challenge both for the research community and for the NGO community.

In most countries, subsidies on some fuels, taxes on other fuels, and some public support for renewables co-exist in varying degrees. It is well known that 'incentives ' are required to motivate the private sector to invest in providing services to the often remote and underdeveloped areas where the poor reside. Wherever absolute poverty prevails, there is a long history of applying intelligently designed subsidies, which are targeted, simple, competitive, and time-limited. This can often be accomplished, at least in part, by shifting current subsidies for fossil fuel use to sustainable energy systems.

Table 4.3 Cost of energy subsidies by source, 1995-1998 (US$ billion/year)

	US$ billion per year		
	OECD countries	Non-OECD countries	Total
Coal	30	23	53
Oil	19	33	52
Gas	8	38	46
All fossil fuels	***57***	***94***	***151***
Electricity	[a]	48	48
Nuclear	16	unknown	16
Renewable and end-use	9	unknown	9
Non-payments and bailout[b]	0	20	20
Total	82	162	244
Per capita (US$)	88	35	44

[a] Subsidies for electricity in OECD countries are included in fossil fuel subsidies, by energy source.

[b] Subsidies from non-payments and bail out operations are not included in data by energy source.

Source: UNDP, UNDESA, and WEC, 2004.

Box 4.3 The Grameen experience with photovoltaics

The Grameen Bank of Bangladesh (Grameen Shakti), a micro-lending agency set up a non-profit subsidiary in 1996 to administer loans for photovoltaic solar home systems to serve those without access to electricity. Initially, Grameen Shakti found many obstacles—long distances, poor transport infrastructure, periodically flooded and impassable roads, low literacy rates, lack of technical skills, transactions based on barters—that contributed to high transaction costs and difficulty in building consumer confidence in their product.

In 1998, a Global Environment Facility grant through International Finance Corporation's Small and Medium Enterprises Program enabled Grameen Shakti to offer improved credit terms to its customers and install thousands of systems. They also found that after a critical mass of installations in an area (around 100 systems), building consumer confidence and demand became less time consuming.

Grameen Shakti now expects to be able to draw additional financing for scale-up activities from commercial banks.

For more information on Grameen Bank, go to www.gshakti.org.

energy projects. As the Policy Report at the World Summit on Sustainable Development concluded, 'The scale and magnitude of tasks involved in progressing towards the objective and goals of energy for sustainable development are so enormous that, in addition to national efforts, international, regional, and sub-regional co-operation are of critical importance' (WSSD, 2002). There is also an urgent need to ensure that future efforts in this direction are well-designed, thoughtfully implemented, and focused on technologies that are appropriate to the situation in which they are being deployed.[64]

Realistically, industrialized countries will have to provide much of the investment needed to move new energy technologies up the learning curve and bring down their marginal costs, in parallel with their phased deployment, before those technologies can be used in developing countries. Meanwhile, substantial opportunities exist to facilitate the transfer of sustainable technologies that are already cost-effective, especially in more remote and currently underserved areas, using innovative program designs and financing mechanisms. An example of one such successful program, involving the dissemination of small solar photovoltaic home systems in Bangladesh, is described in Box 4.3.

4.6 Summary points

Governments around the world must act now to initiate a transition to sustainable energy systems.

- **Though specific policy choices must take into account each country's unique circumstances, efforts to introduce a market signal for reducing carbon emissions, promote investments in improved energy efficiency, and reduce or eliminate distorting subsidies (especially for fossil fuel consumption), must be broadly undertaken.**
- **Science and technology have an indispensable role to play in improving the sustainable energy options that are available today and in developing new options for tomorrow.** Given the scale and urgency of the challenge at hand, public and private-sector investments in energy technology RD&D must be substantially increased (to at least a doubling of current levels, if not more) and consistently maintained over the next several decades. Putting necessary efforts into R&D does not provide an accept-

64 Many policy options are potentially relevant in developing country contexts: the Global Network on Energy for Sustainable Development, for example, has published analyses of strategies for reforming the electric power sector and enhancing access to energy services (www.gnesd.org).

able reason to postpone strong action now to make use of already existing technologies and to correct existing distortions in the energy market place.

- **Extending access to modern forms of energy for billions of the world's poorest citizens is necessary to meet basic human needs (clean cooking fuels and clean water) and to achieve broader development goals (night-time lighting, communication, economic opportunity)**. More broadly, advancing sustainability objectives in developing countries will require policies and technologies that reflect the particular needs and opportunities of those countries, along with an increased commitment on the part of the S&T community to develop and help deploy effective technology for the rural and urban poor.
- **Concerns about affordability, especially in developing countries, should be addressed by developing mechanisms that subsidize consumption only up to a threshold level adequate to serve basic needs.**

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5. The case for immediate action

Scientific evidence is overwhelming that current energy trends are unsustainable. Immediate action is required to effect change in the timeframe needed to address significant ecological, human health and development, and energy security needs. Aggressive changes in policy are thus needed to accelerate the deployment of superior technologies. With a combination of such policies at the local, national, and international level, it should be possible—both technically and economically—to elevate the living conditions of most of humanity, while simultaneously addressing the risks posed by climate change and other forms of energy-related environmental degradation and reducing the geopolitical tensions and economic vulnerabilities generated by existing patterns of dependence on predominantly fossil-fuel resources.

This chapter presents nine major conclusions reached by the Study Panel, along with actionable recommendations. These conclusions and recommendations have been formulated within a holistic approach to the transition toward a sustainable energy future. This implies that not a single one of them can be successfully pursued without proper attention to the others. Prioritization of the recommendations is thus intrinsically difficult. Nonetheless, the Study Panel believes that, given the dire prospect of climate change, the following three recommendations should be acted upon *without delay and simultaneously*:

- Concerted efforts should be mounted to improve energy efficiency and reduce the carbon intensity of the world economy, including the worldwide introduction of price signals for carbon emissions, with consideration of different economic and energy systems in individual countries.
- Technologies should be developed and deployed for capturing and sequestering carbon from fossil fuels, particularly coal.
- Development and deployment of renewable energy technologies should be accelerated in an environmentally responsible way.

Taking into account the three urgent recommendations above, another recommendation stands out by itself as a moral and social imperative and should be pursued with all means available:

- The poorest people on this planet should be supplied with basic, modern energy services.

Achieving a sustainable energy future requires the participation of all. But there is a division of labor in implementing the various recommendations of this report. The Study Panel has identified the following principal 'actors' that must take responsibility for achieving results:

- Multi-national organizations (e.g., United Nations, World Bank, Regional Development Banks, etc.)
- Governments (national, regional, and local)
- Science and technology (S&T) community (academia)
- Private sector (businesses, industry, foundations)
- Nongovernmental organizations (NGOs)
- Media
- General public

Conclusions, recommendations, actions

Based on the key points developed in this report, the Study Panel offers these conclusions with recommendations and respective actions by the principal actors.

Conclusion 1

Meeting the basic energy needs of the poorest people on this planet is a moral and social imperative that can and must be pursued in concert with sustainability objectives.

Today an estimated 2.4 billion people use coal, charcoal, firewood, agricultural residues, or dung as their primary cooking fuel. Roughly 1.6 billion people worldwide live without electricity. Vast numbers of people, especially women and girls, are deprived of economic and educational opportunities without access to affordable, basic labor-saving devices or adequate lighting, added to the time each day spent gathering fuel and water. The indoor air pollution caused by traditional cooking fuels exposes millions of families to substantial health risks. Providing modern forms of energy to the world's poor could generate multiple benefits, easing the day-to-day struggle to secure basic means of survival; reducing substantial pollution-related health risks; freeing up scarce capital and human resources; facilitating the delivery of essential services, including basic medical care; and mitigating local environmental degradation. Receiving increased international attention, these linkages were a major focus of the 2002 World

Summit for Sustainable Development in Johannesburg, which recognized the importance of expanded access to reliable and affordable energy services as a prerequisite for achieving the United Nation's Millennium Development Goals.

Recommendations

- Place priority on rapidly achieving much greater access of the world's poor to clean, affordable, high-quality fuels and electricity. The challenge of expanding access to modern forms of energy revolves primarily around issues of social equity and distribution—the fundamental problem is not one of inadequate global resources, unacceptable environmental damage, or unavailable technologies. Addressing the basic energy needs of the world's poor is clearly central to the larger goal of sustainable development and must be a top priority for the international community if some dent is to be made in reducing current inequities.
- Formulate policy at all levels, from global to village scale, with greater awareness of the substantial inequalities in access to energy services that now exist, not only between countries but between populations within the same country and even between households within the same town or village. In many developing countries, a small elite uses energy in much the same way as in the industrialized world, while most of the rest of the population relies on traditional, often poor-quality and highly polluting forms of energy. In other developing countries, energy consumption by a growing middle class is contributing significantly to global energy demand growth and is substantially raising national per capita consumption rates, despite little change in the consumption patterns of the very poor. The reality that billions of people suffer from limited access to electricity and clean cooking fuels must not be lost in per capita statistics.

Needed actions

- Given the international dimension of the problem, multinational organizations like the United Nations and the World Bank should take the initiative to draw up a plan for eliminating the energy poverty of the world's poor. As a first step, governments and NGOs can assist by supplying data on the extent of the problem in their countries.
- The private sector and the S&T community can help promote the transfer of appropriate technologies. The private sector can, in addition, help by making appropriate investments.
- The media should make the general public aware of the enormity of the problem.

Conclusion 2

Concerted efforts must be made to improve energy efficiency and reduce the carbon intensity of the world economy.

Economic competitiveness, energy security, and environmental considerations all argue for pursuing cost-effective end-use efficiency opportunities. Such opportunities may be found throughout industry, transportation, and the built environment. To maximize efficiency gains and minimize costs, improvements should be incorporated in a holistic manner and from the ground up wherever possible, especially where long-lived infrastructure is involved. At the same time it will be important to avoid underestimating the difficulty of achieving nominal energy efficiency gains, as frequently happens when analyses assume that reduced energy use is an end in itself rather than an objective regularly traded against other desired attributes.

Recommendations

- Promote the enhanced dissemination of technology improvement and innovation between industrialized and developing countries. It will be especially important for all nations to work together to ensure that developing countries adopt cleaner and more efficient technologies as they industrialize.
- Align economic incentives—especially for durable capital investments—with long-run sustainability objectives and cost considerations. Incentives for regulated energy service providers should be structured to encourage co-investment in cost-effective efficiency improvements and profits should be de-linked from energy sales.
- Adopt policies aimed at accelerating the worldwide rate of decline in the carbon intensity of the global economy, where carbon intensity is measured as carbon dioxide equivalent emissions divided by gross world product, a crude measure of global well-being. Specifically, the Study Panel recommends immediate policy action to introduce meaningful price signals for avoided greenhouse gas emissions. Less important than the initial prices is that clear expectations be established concerning a predictable escalation of those prices over time. Merely holding carbon dioxide emissions constant over the next several decades implies that the carbon intensity of the world economy needs to decline at roughly the

same rate as gross world product grows. Achieving the absolute *reductions* in global emissions needed to stabilize atmospheric concentrations of greenhouse gases will require the worldwide rate of decline in carbon intensity to begin outpacing worldwide economic growth.
- Enlist cities as a major driving force for the rapid implementation of practical steps to improve energy efficiency.
- Inform consumers about the energy-use characteristics of products through labeling and implement mandatory minimum efficiency standards for appliances and equipment. Standards should be regularly updated and must be effectively enforced.

Needed actions

- Governments, in a dialogue with the private sector and the S&T community, should develop and implement (further) policies and regulations aimed at achieving greater energy efficiency and lower energy intensity for a great variety of processes, services, and products.
- The general public must be made aware, by governments, the media, and NGOs, of the meaning and necessity of such policies and regulations.
- The S&T community should step up its efforts to research and develop new, low-energy technologies.
- Governments, united in intergovernmental organizations, should agree on realistic price signals for carbon emissions, recognizing that the economies and energy systems of different countries will result in different individual strategies and trajectories, and make these price signals key components of further actions on reducing the carbon emissions.
- The private sector and the general public should insist that governments issue clear carbon price signals.

Conclusion 3

Technologies for capturing and sequestering carbon from fossil fuels, particularly coal, can play a major role in the cost-effective management of global carbon dioxide emissions.

As the world's most abundant fossil fuel resource, coal will continue to play a large role in the world's energy mix. It is also the most carbon-intensive conventional fuel in use today, generating almost twice as much carbon dioxide per unit of energy supplied than natural gas. Today, new coal-fired power plants—most of which can be expected to last more than half a century—are being constructed at an unprecedented rate. Moreover, the carbon contribution from coal could expand further if nations with large coal reserves like the United States, China, and India turn to coal to address energy security concerns and develop alternatives to petroleum.

Recommendations

- Accelerate the development and deployment of advanced coal technologies. Without policy interventions the vast majority of the coal-fired power plants constructed in the next two decades will be 'conventional' pulverized coal plants. Present technologies for capturing carbon dioxide emissions from pulverized coal plants on a retrofit basis are expensive and energy-intensive. Where new coal plants without capture must be constructed, the most efficient technologies should be used. In addition, priority should be given to minimize the costs of future retrofits for carbon capture by developing at least some elements of carbon capture technology at every new plant. Active efforts to develop such technologies for different types of base plants are currently underway and should be encouraged by promoting the construction of full-scale plants that utilize the latest technology advances.
- Aggressively pursue efforts to commercialize carbon capture and storage. Moving forward with full-scale demonstration projects is critical, as is continued study and experimentation to reduce costs, improve reliability, and address concerns about leakage, public safety, and other issues. For capture and sequestration to be widely implemented it will be necessary to develop regulations and to introduce price signals for carbon emissions. Based on current cost estimates, the Study Panel

believes price signals on the order of US$100–150 per avoided metric ton of carbon equivalent (US$27–41 per ton of carbon dioxide equivalent) will be required to induce the widespread adoption of carbon capture and storage. Price signals at this level would also give impetus to the accelerated deployment of biomass and other renewable energy technologies.

- Explore potential retrofit technologies for post-combustion carbon capture suitable for the large and rapidly growing population of existing pulverized coal plants. In the near-term, efficiency improvements and advanced pollution control technologies should be applied to existing coal plants as a means of mitigating their immediate climate change and public health impacts.
- Pursue carbon capture and storage with systems that co-fire coal and biomass. This technology combination provides an opportunity to achieve net negative greenhouse gas emissions—effectively removing carbon dioxide from the atmosphere.

Needed actions

- The private sector and the S&T community should join forces to further investigate the possibilities for carbon capture and sequestration and develop adequate technologies for demonstration.
- Governments should facilitate the development of these technologies by making available funds and opportunities (such as test sites).
- The general public needs to be thoroughly informed about the advantages of carbon sequestration and about the relative manageability of associated risks. The media can assist with this.

Conclusion 4

Competition for oil and natural gas supplies has the potential to become a source of growing geopolitical tension and economic vulnerability for many nations in the decades ahead.

In many developing countries, expenditures for energy imports also divert scarce resources from other urgent public health, education, and infrastructure development needs. The transport sector accounts for just 25 percent of primary energy consumption worldwide, but the lack of fuel diversity in this sector makes transport fuels especially valuable.

Recommendations

- Introduce policies and regulations that promote reduced energy consumption in the transport sector by (a) improving the energy efficiency of automobiles and other modes of transport and (b) improving the efficiency of transport systems (e.g., through investments in mass transit, better land-use and city planning, etc.).
- Develop alternatives to petroleum to meet the energy needs of the transport sector, including biomass fuels, plug-in hybrids, and compressed natural gas, as well as—in the longer run—advanced alternatives such as hydrogen fuel cells.
- Implement policies to ensure that the development of petroleum alternatives is pursued in a manner that is compatible with other sustainability objectives. Current methods for liquefying coal and extracting oil from unconventional sources like tar sands and shale oil generate substantially higher levels of carbon dioxide and other pollutant emissions compared to conventional petroleum consumption. Even with carbon capture and sequestration, a liquid fuel derived from coal will at best produce emissions of carbon dioxide roughly equivalent to those of conventional petroleum at the point of combustion. If carbon emissions from the conversion process are not captured and stored, total fuel-cycle emissions for this energy pathway as much as double. The conversion of natural gas to liquids is less carbon-intensive than coal to liquids, but biomass remains the only near-term feedstock that has the potential to be truly carbon-neutral and sustainable on a long-term basis. In all cases, full fuel-cycle impacts depend critically on the feedstock being used and on the specific extraction or conversion methods being employed.

Needed actions

- Governments should introduce (further) policies and regulations aimed at reducing energy consumption and developing petroleum alternatives for use in the transport sector.
- The private sector and the S&T community should continue developing technologies adequate to that end.
- The general public's awareness of sustainability issues related to transportation energy use should be significantly increased. Again, the media can play an important role in this effort.

Conclusion 5

As a low-carbon resource, nuclear power can continue to make a significant contribution to the world's energy portfolio in the future, but only if major concerns related to capital cost, safety, and weapons proliferation are addressed.

Nuclear power plants generate no carbon dioxide or conventional air pollutant emissions during operation, use a relatively abundant fuel feed-stock, and involve orders-of-magnitude smaller mass flows, relative to fossil fuels. Nuclear's potential, however, is currently limited by concerns related to cost, waste management, proliferation risks, and plant safety (including concerns about vulnerability to acts of terrorism and concerns about the impact of neutron damage on plant materials in the case of life extensions). A sustained role for nuclear power will require addressing these hurdles.

Recommendations

- Replace the current fleet of aging reactors with plants that incorporate improved intrinsic (passive) safety features.
- Address cost issues by pursuing the development of standardized reactor designs.
- Understand the impact of long-term aging on nuclear reactor systems (e.g., neutron damage to materials) and provide for the safe and economic decommissioning of existing plants.
- Develop safe, retrievable waste management solutions based on dry cask storage as longer term disposal options are explored. While long-term disposal in stable geological repositories is technically feasible, finding socially acceptable pathways to implementing this solution remains a significant challenge.
- Address the risk that civilian nuclear materials and knowledge will be diverted to weapons applications through continued research on proliferation-resistant uranium enrichment and fuel-recycling capability and on safe, fast neutron reactors that can burn down waste generated from thermal neutron reactors and through efforts to remedy shortcomings in existing international frameworks and governance mechanisms.
- Undertake a transparent and objective re-examination of the issues surrounding nuclear power and their potential solutions. The results of such a re-examination should be used to educate the public and policy-makers.

Needed actions

- Given the controversy over the future of nuclear power worldwide, the United Nations should commission—as soon as possible—a transparent and objective re-examination of the issues that surround nuclear power and their potential solutions. It is essential that the general public be informed about the outcome of this re-examination.
- The private sector and the S&T community should continue research and development efforts targeted at improving reactor safety and developing safe waste management solutions.
- Governments should facilitate the replacement of the current fleet of aging reactors with modern, safer plants. Governments and intergovernmental organizations should enhance their efforts to remedy shortcomings in existing international frameworks and governance mechanisms.

Conclusion 6

Renewable energy in its many forms offers immense opportunities for technological progress and innovation.

Over the next 30–60 years sustained efforts must be directed toward realizing these opportunities as part of a comprehensive strategy that supports a diversity of resource options over the next century. The fundamental challenge for most renewable options involves cost-effectively tapping inherently diffuse and in some cases intermittent resources. Sustained, long-term support—in various forms—is needed to overcome these hurdles. Renewable energy development can provide important benefits in underdeveloped and developing countries because oil, gas, and other fuels are hard cash commodities.

Recommendations

- Implement policies—including policies that generate price signals for avoided carbon emissions—to ensure that the environmental benefits of renewable resources relative to non-renewable resources will be systematically recognized in the marketplace.
- Provide subsidies and other forms of public support for the early deployment of new renewable technologies. Subsidies should be targeted to promising but not-yet-commercial technologies and decline gradually over time.
- Explore alternate policy mechanisms to nurture renewable energy technologies, such as renewable portfolio standards (which set specific goals for renewable energy deployment) and 'reverse auctions' (in which renewable energy developers bid for a share of limited public funds on the basis of the minimum subsidy they require on a per kilowatt-hour basis).
- Invest in research and development on more transformational technologies, such as new classes of solar cells that can be made with thin-film, continuous fabrication processes. (See also biofuels recommendations under conclusion 7.)
- Conduct sustained research to assess and mitigate any negative environmental impacts associated with the large-scale deployment of renewable energy technologies. Although these technologies offer many environmental benefits, they may also pose new environmental risks as a result of their low power density and the consequently large land area required for large-scale deployment.

Needed actions

- Governments should substantially facilitate the use—in an environmentally sustainable way—of renewable energy resources through adequate policies and subsidies. A major policy step in this direction would include implementing clear price signals for avoided greenhouse gas emissions.
- Governments should also promote research and development in renewable energy technologies by supplying significantly more public funding.
- The private sector, aided by government subsidies, should seek entrepreneurial opportunities in the growing renewable energy market.
- The science and technology community should devote more attention to overcoming the cost and technology barriers that currently limit the contribution of renewable energy sources.
- NGOs can assist in promoting the use of renewable energy sources in developing countries.
- The media can play an essential role in heightening the general public's awareness of issues related to renewable energy.

Conclusion 7

Biofuels hold great promise for simultaneously addressing climate-change and energy-security concerns.

Improvements in agriculture will allow for food production adequate to support a predicted peak world population on the order of 9 billion people with excess capacity for growing energy crops. Maximizing the potential contribution of biofuels requires commercializing methods for producing fuels from lignocellulosic feedstocks (including agricultural residues and wastes), which have the potential to generate five to ten times more fuel than processes that use starches from feedstocks like sugar cane and corn. Recent advances in molecular and systems biology show great promise in developing improved feedstocks and much less energy-intensive means of converting plant material into liquid fuel. In addition, intrinsically more efficient conversion of sunlight, water, and nutrients into chemical energy may be possible with microbes.

Recommendations

- Conduct intensive research into the production of biofuels based on lignocellulose conversion.
- Invest in research and development on direct microbial production of butanol or other forms of biofuels that may be superior to ethanol.
- Implement strict regulations to insure that the cultivation of biofuels feedstocks accords with sustainable agricultural practices and promotes biodiversity, habitat protection, and other land management objectives.
- Develop advanced bio-refineries that use biomass feedstocks to self-generate power and extract higher-value co-products. Such refineries have the potential to maximize economic and environmental gains from the use of biomass resources.
- Develop improved biofuels feedstocks through genetic selection and/or molecular engineering, including drought resistant and self-fertilizing plants that require minimal tillage and fertilizer or chemical inputs.
- Mount a concerted effort to collect and analyze data on current uses of biomass by type and technology (both direct and for conversion to other fuels), including traditional uses of biomass.
- Conduct sustained research to assess and mitigate any adverse environmental or ecosystem impacts associated with the large-scale cultivation

of biomass energy feedstocks, including impacts related to competition with other land uses (including uses for habitat preservation and food production), water needs, etc.

Needed actions

- The S&T community and the private sector should greatly augment their research and development (and deployment) efforts toward more efficient, environmentally sustainable technologies and processes for the production of modern biofuels.
- Governments can help by stepping up public research and development funding and by adapting existing subsidy and fiscal policies so as to favor the use of biofuels over that of fossil fuels, especially in the transport sector.
- Governments should pay appropriate attention to promoting sustainable means of biofuels production and to avoiding conflicts between biofuel production and food production.

Conclusion 8

The development of cost-effective energy storage technologies, new energy carriers, and improved transmission infrastructure could substantially reduce costs and expand the contribution from a variety of energy supply options.

Such technology improvements and infrastructure investments are particularly important to tap the full potential of intermittent renewable resources, especially in cases where some of the most abundant and cost-effective resource opportunities exist far from load centers. Improved storage technologies, new energy carriers, and enhanced transmission and distribution infrastructure will also facilitate the delivery of modern energy services to the world's poor—especially in rural areas.

Recommendations

- Continue long-term research and development into potential new energy carriers for the future, such as hydrogen. Hydrogen can be directly combusted or used to power a fuel cell and has a variety of potential applications—including as an energy source for generating electricity or in other stationary applications and as an alternative to petroleum fuels for aviation and road transport. Cost and infrastructure constraints, however, are likely to delay widespread commercial viability until mid-century or later.
- Develop improved energy storage technologies, either physical (e.g. compressed air or elevated water storage) or chemical (e.g. batteries, hydrogen, or hydrocarbon fuel produced from the reduction of carbon dioxide), that could significantly improve the market prospects of intermittent renewable resources such as wind and solar power.
- Pursue continued improvements and cost reductions in technologies for transmitting electricity over long distances. High voltage, direct-current transmission lines, in particular, could be decisive in making remote areas accessible for renewable energy development, improving grid reliability, and maximizing the contribution from a variety of low-carbon electricity sources. In addition, it will be important to improve overall grid management and performance through the development and application of advanced or 'smart' grid technologies that could greatly enhance the responsiveness and reliability of electricity transmission and distribution networks.

Needed actions

- The S&T community, together with the private sector, should have focus on research and development in this area
- Governments can assist by increasing public funding for research and development and by facilitating needed infrastructure investments.

Conclusion 9

The science and technology community—together with the general public—has a critical role to play in advancing sustainable energy solutions and must be effectively engaged.

As noted repeatedly in the foregoing recommendations, the energy challenges of this century and beyond demand sustained progress in developing, demonstrating, and deploying new and improved energy technologies. These advances will need to come from the S&T community, motivated and supported by appropriate policies, incentives, and market drivers.

Recommendations

- Provide increased funding for public investments in sustainable energy research and development, along with incentives and market signals to promote increased private-sector investments.
- Effect greater coordination of technology efforts internationally, along with efforts to focus universities and research institutions on the sustainability challenge.
- Conduct rigorous analysis and scenario development to identify possible combinations of energy resources and end-use and supply technologies that have the potential to simultaneously address the multiple sustainability challenges linked to energy.
- Stimulate efforts to identify and assess specific changes in institutions, regulations, market incentives, and policy that would most effectively advance sustainable energy solutions.
- Create an increased focus on specifically energy-relevant awareness, education, and training across all professional fields with a role to play in the sustainable energy transition.
- Initiate concerted efforts to inform and educate the public about important aspects of the sustainable energy challenge, such as the connection between current patterns of energy production and use and critical environmental and security risks.
- Begin enhanced data collection efforts to support better decisionmaking in important policy areas that are currently characterized by a lack of reliable information (large cities in many developing countries, for example, lack the basic data needed to plan effectively for transportation needs).

Needed actions

- The S&T community must strive for better international coordination of energy research and development efforts, partly in collaboration with the private sector. It should seek to articulate a focused, collaborative agenda aimed at addressing key obstacles to a sustainable energy future.
- Governments (and inter-governmental organizations) must make more public funding available to not only boost the existing contribution from the S&T community but also to attract more scientists and engineers to working on sustainable energy problems.
- The why and how of energy research and development should be made transparent to the general public to build support for the significant and sustained investments that will be needed to address long-term sustainability needs.
- The S&T community itself, inter-governmental organizations, governments, NGOs, the media and—to a lesser extent—the private sector, should be actively engaged in educating the public about the need for these investments.

Lighting the way

While the current energy outlook is very sobering, the Study Panel believes that there are sustainable solutions to the energy problem. Aggressive support of energy science and technology must be coupled with incentives that accelerate the concurrent development and deployment of innovative solutions that can transform the entire landscape of energy demand and supply. Opportunities to substitute superior supply-side and end-use technologies exist throughout the world's energy systems, but current investment flows generally do not reflect these opportunities.

Science and engineering provide guiding principles for the sustainability agenda. Science provides the basis for a rational discourse about tradeoffs and risks, for selecting research and development priorities, and for identifying new opportunities—openness is one of its dominant values. Engineering, through the relentless optimization of the most promising technologies, can deliver solutions—learning by doing is among its dominant values. Better results will be achieved if many avenues are explored in parallel, if outcomes are evaluated with actual performance measures, if results are reported widely and fully, and if strategies are open to revision and adaptation.

Long-term energy research and development is thus an essential component of the pursuit of sustainability. Significant progress can be achieved with existing technology but the scale of the long-term challenge will demand new solutions. The research community must have the means to pursue promising technology pathways that are already in view and some that may still be over the horizon.

The transition to sustainable energy systems also requires that market incentives be aligned with sustainability objectives. In particular, robust price signals for avoided carbon emissions are critical to spur the development and deployment of low-carbon energy technologies. Such price signals can be phased in gradually, but expectations about how they will change over time must be established in advance and communicated clearly so that businesses can plan with confidence and optimize their long-term capital investments.

Critical to the success of all the tasks ahead are the abilities of individuals and institutions to effect changes in energy resources and usage. Capacity building, both in terms of investments in individual expertise and institutional effectiveness, must become an urgent priority of all principal actors: multi-national organizations, governments, corporations, educational institutions, non-profit organizations, and the media. Above all, the general public must be provided with sound information about the choices ahead and the actions required for achieving a sustainable energy future.

Annex A. Study panel biographies

Co-Chairs

Steven CHU is Director of the Lawrence Berkeley National Laboratory, Professor of Physics, Molecular and Cell Biology, University of California, Berkeley. Previously, he was at Stanford and Bell Laboratories. His research includes tests of fundamental physics, the development of methods to laser cool and trap atoms, polymer physics, and single molecule biology. He has numerous awards, including the 1997 Nobel Prize in Physics. He is a member of the National Academy of Sciences, the American Philosophical Society, the American Academy of Arts and Sciences, the Academia Sinica, and a foreign member of the Chinese Academy of Sciences and the Korean Academy of Science and Engineering. At Stanford, he helped start Bio-X, a multi-disciplinary initiative linking the physical and biological sciences with engineering and medicine. He serves on the Boards of the Hewlett Foundation, the University of Rochester, NVIDIA and the Scientific Board of the Moore Foundation, Helicos and NABsys. He has served on a number of other committees, including the Augustine Committee that produced 'Rising Above the Gathering Storm,' the Advisory Committee to the Directors of the NIH and the National Nuclear Security Agency, the Executive Committee of the NAS Board on Physics and Astronomy. He received AB and BS degrees in mathematics and physics from the University of Rochester, a PhD in physics from UC Berkeley, and ten honorary degrees.

José GOLDEMBERG earned his PhD in Physical Sciences in 1954 from the University de São Paulo of which he became Full Professor and Rector. Member of the Brazilian Academy of Sciences, he has served as the President of Brazilian Association for the Advancement of Science and President of the Energy Company of the State of São Paulo (CESP). Between 1990 and 1992, he was Secretary of State for Science and Technology and Minister of State for Education of the Federal Government of Brazil. Over the years, he did research and taught at the University of Illinois, Stanford University of Paris (Orsay), and Princeton University. From 1998-2000, he served as Chairman of the World Energy Assessment. More recently, between 2002 and 2006, he was Secretary for the Environment of the State of São Paulo. He has authored many technical papers and books on Nuclear Physics, Sustainable Development and Energy.

Panelists

Shem ARUNGU OLENDE has a background in electrical engineering. From 1968 to 1971, at the University of Nairobi, he conducted research on (electrical) power systems, their (mathematical) analysis, planning, design and operation. During the years 1969 and 1970, he was a Visiting Scholar at the Department of Economics, MIT, engaged in research on the application of mathematical programming techniques to large systems; he also did research at the LTV Aerospace Corporation on spacecraft guidance systems. From 1971 to 2000 he was an expert on energy at the United Nations, New York, where he provided advice on the development and use of energy resources (fossil fuels, renewable, and nuclear). He supervised the preparation of major studies in energy, including renewable sources; electricity; and the environment. He also assisted in the organization of major meetings and conferences on energy and the environment at the UN. Furthermore, he provided technical inputs into intergovernmental committees, commissions, and councils of the UN. Currently, he is the Secretary-General of the African Academy of Sciences. He is also the Chairman and CEO of QUECONSULT Ltd, which provides professional consultancy services in Engineering, Energy and Sustainable Development, Environment, Economic Development, Science and Technology, and Software Development to the U.N., UNDP, the African Development Bank, UNESCO, and the World Bank.

Ged DAVIS has a background in economics and engineering from London and Stanford universities. He joined the Royal Dutch/Shell in 1972 and stayed with that company for 30 years. During his time at Shell, he held positions predominantly in scenario planning, strategy and finance, including Head of Planning (Europe), Head of Energy (Group Planning), Head of Group Investor Relations, Head of Scenario Processes and Applications, Head of the Socio-Politics and Technology Team (Group Planning), and lastly as the company's Vice-President for Global Business Environment and Head of the Scenarios Team. For the last three years, he has been Managing Director of the World Economic Forum, responsible for global research, scenario projects, and the design of the annual Forum meeting at Davos. During the late 1990s, he served as Director of the World Business Council for Sustainable Development's Global Scenarios and as Facilitator and Lead Author of the IPCC's Emission Scenarios. Currently, he is Co-President of the Global Energy Assessment with the International Institute for Applied Systems Analysis (IIASA); a Director of Low Carbon Accelerator Limited; a Governor of the International Development Research Centre in Ottawa; and a Member of the INDEX Design Awards Jury.

Mohamed EL-ASHRY was educated and trained as a geologist. He pursued a successful scientific career for many years. During the 1990s, he served as the Chief Environmental Adviser to the President and as the Director of the Environment Department at the World Bank, as Senior Vice President of the World Resources Institute (WRI), as Senior Environmental Adviser to UNDP, as Special Adviser to the Secretary General of the 1992 U.N. Conference on Environment and Development (UNCED), and as a member of the World Water Commission and the International Task Force on Global Public Goods. He joined the Global Environment Facility (GEF) in its pilot phase in 1991 as Chairman, and led the GEF as CEO and Chairman from 1994 to 2003. He is a member of the Academy of Sciences for the Developing World (TWAS) and the African Academy of Sciences.

Thomas B. JOHANSSON is a nuclear physicist by training. He is a Professor of energy systems analysis and Director of the International Institute for Industrial Environmental Economics (IIIEE) at Lund University, Lund, Sweden. He previously served as Director of UNDP's Energy and Atmosphere Programme, and as a Member of the Editorial Board of the World Energy Assessment. He has published widely in the area of energy for sustainable development. Currently, he is Co-Chair of the Steering Committee of the Global Network on Energy for Sustainable Development (GNESD), Co-Chair of the Executive Committee of the Global Energy Assessment, and Chairman of the Board of the International Energy Initiative (IEI).

David KEITH (Canada) holds the Canada Research Chair in Energy and the Environment at the University of Calgary. He is Professor, Department of Chemical and Petroleum Engineering and Department of Economics, University of Calgary; and Adjunct Professor, Department of Engineering and Public Policy, Carnegie Mellon University. He is the Director of ISEEE Energy and Environmental Systems Group. His technical and policy work addresses the capture and storage of carbon dioxide, the economics and climatic impacts of large-scale wind power, the use of hydrogen as a transportation fuel, and the technology and implications of geoengineering. He serves on Canada's Capture and Storage Task Force. He has served as a member of Canada's *Panel on Sustainable Energy Technology* and on committees of the U. S. National Academy of Sciences. As an undergraduate, he took first prize in Canada's national physics prize exam. As a graduate student, he won MIT's biennial departmental prize for excellence in experimental physics, and was named environmental scientist of the year by Canadian Geographic in 2006.

LI Jinghai was trained as a chemical engineer. From 1987 to 1990, he conducted research at the City University of New York and the Swiss Federal Institute of Technology. From 1990 onwards, he continued his scientific career at the Institute of Process Engineering (IPE) of the Chinese Academy of Sciences as a professor, and from the mid-1990s onwards took the lead, first as vice director then as director, of the IPE. In 2004, he was appointed as Vice President of the Chinese Academy of Sciences. He served as Chairman of the Expert Committee on Energy under the 863 Program in China from 2001-2006, and as President of the Chinese Society of Particulogy from 2002 to present. He serves several international journals as editor or advisory member.

Nebosja NAKICENOVIC is Professor of Energy Economics at the Vienna University of Technology (TU Wien), Leader of the Energy and Technology Programs at the International Institute for Applied Systems Analysis (IIASA), and Director of the Global Energy Assessment (GEA). He is Associate Editor of the *International Journal on Technological Forecasting and Social Change;* Editor of *International Journal on Climate Policy*; Member of Editorial Board of the *International Journal of Energy Sector Management*; a Coordinating Lead Author of the Intergovernmental Panel of Climate Change (IPCC), Fourth Assessment Report; Coordinating Lead Author of the Millennium Ecosystem Assessment; and Director of Global Energy Assessment. He holds bachelor's and master's degrees in economics and computer science from Princeton University and the University of Vienna, where he also completed his PhD. He also holds an Honoris Causa PhD degree in engineering from the Russian Academy of Sciences.

R.K. PACHAURI has been the Chief Executive of The Energy and Resources Institute (TERI) since 1981, designated initially as Director and since April 2001 as Director-General. In April 2002 he was elected as Chairman of the Intergovernmental Panel on Climate Change (IPCC), which was established by the World Meteorological Organization and the United Nations Environment Programme in 1988. He has a PhD in Industrial Engineering and a PhD in Economics. He has taught on the faculty of Yale University, West Virginia University, North Carolina State University and the Administrative Staff College of India in Hyderabad. He has been active in several international forums dealing with climate change and its policy dimensions. He was awarded the *Padma Bhushan* in 2001 by the President of India and was bestowed the *Officier De La Légion D'Honneur* by the Government of France in 2006.

Majid SHAFIE-POUR was trained in mechanical engineering in the U.K., with specializations in the application of alternative sources of energy for heavy-duty engines, and in environmental and air pollution engineering. He spent the early part of his academic career in various faculty positions at universities in the U.

K (Bath and Brunel) and at the University of Tehran. He is a member of the Board of the Faculty of Environment of the University of Tehran. He is a former member of the Governing Council of the Iranian Department of the Environment since 1998. He has served as an Executive Director in a number of World Bank-sponsored projects on environmental issues in Iran, and advised on or headed numerous national, regional, and city projects on air pollution, climate change, waste recycling & composting, and general environmental management. He represented his country as Head of the Iranian Delegation to the UNFCCC (COP8) in 2002 and was a National Consultant of the UNDP/UNEP/Department of the Environment of Iran International Project on Climate Change in Iran. He is a member of the National Committee on Sustainable Development of Iran and is currently Professor of Environmental Engineering (Energy, Air Pollution and Climate Change) Faculty of Environment at the University of Tehran.

Evald SHPILRAIN was trained as thermal and power engineer and as a thermophysicist. He spent a long career as a Professor in some of Russia's most prominent universities and research institutes, and has published over 350 articles in scientific journals and 12 monographs. In recent times, he has been the Head of the Department of Energy and Energy Technology at the Institute for High Temperatures (IVTAN) of the Russian Academy of Sciences, Chairman of the Scientific Council for Non-traditional, Renewable Sources of Energy, Russian Academy of Sciences, Executive Director of the Moscow International Energy Club & Representative of Russia in the IEA Implementing Agreement 'SolarPACES.' Currently he is Chairman, Scientific Committee for New and Renewable Sources of Energy, State Committee for Science and Technology, Russian Academy of Sciences (RAS); and Advisor for RAS.

Robert SOCOLOW, Professor of Mechanical and Aerospace Engineering at Princeton University, teaches in both the School of Engineering and Applied Science and the Woodrow Wilson School of Public and International Affairs. With ecologist, Stephen Pacala, Socolow leads the University's Carbon Mitigation Initiative. His research focuses on technology and policy for fossil fuels under climate constraints. He was awarded the 2003 Leo Szilard Lectureship Award by the American Physical Society: 'For leadership in establishing energy and environmental problems as legitimate research fields for physicists, and for demonstrating that these broadly defined problems can be addressed with the highest scientific standards.' He earned a BA in 1959 (summa cum laude) and PhD in theoretical high energy physics in 1964 from Harvard University.

Kenji YAMAJI is Professor of Electrical Engineering, School of Engineering at the University of Tokyo. He is a member of Science Council of Japan, Vice-Chair of the Council of the International Institute for Applied Systems Analysis (IIASA), and Chairman of the Green Power Certification Council of Japan. During the earlier part of his career, he has been extensively involved in the research and analysis of energy systems, mainly at the Central Research Institute of Electric Power Industry (CRIEPI) in Japan. He is serving on many advisory bodies on energy and environmental policy for the Japanese Government. During the mid-1990s, he served as Director of the Technical Program Committee of Tokyo Congress for the World Energy Council (WEC).

Luguang YAN was trained as an electrical engineer at the Moscow Power Institute (Russia). His research has dealt with the development of special electrical equipment and on the development of new technologies in electrical engineering. Main areas include high-pulse power, fusion electrical engineering, superconducting electrical engineering, magneto-hydrodynamic power, renewable energy, and magnetic levitated train. He is a Research Professor and Chairman of the Scientific Committee of the Institute of Electrical Engineering of the Chinese Academy of Sciences, Honorary President of Ningbo University, Deputy Head of Technological Sciences and Vice Chairman of the Energy Research Council of the Chinese Academy of Sciences, President of the Chinese Solar Energy Society, Vice-President of the China Electro-technical Society and of the China Energy Research Society.

Annex B. Acronyms and abbreviations

BTU	British thermal unit
CCGT	Combined cycle gas turbine
EJ	Exajoule
EU	European Union
GDP	Gross domestic product
GIF	Generation IV International Forum
GJ	Gigajoule
HID	Human Development Index
HVAC	Heating, ventilation, and air conditioning
IAC	InterAcademy Council
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
kWh	Kilowatt-hour
Mtoe	Million ton oil equivalent
MWe	Megawatt electricity
NGO	Nongovernmental organization
OECD	Organization for Economic Coordination and Development
PJ	Petajoule
PPP	Purchasing power parity
PV	Photovoltaic
R&D	Research and development
RD&D	Research, development, and demonstration
S&T	Science and technology
TPES	Total primary energy supply
TWh	Terawatt-hour

Annex C. Common energy unit conversion factors and unit prefixes

Common Energy Unit Conversion Factors

To:	Terajoule (TJ)	Gigacalorie (Gcal)	Megaton oil (equiv) (Mtoe)	Million British thermal units (Mbtu)	Gigawatt-hour (GWh)
From:	**Multiply by:**				
TJ	1	238.8	2.388×10^{-5}	947.8	0.2778
Mtoe	4.1868×10^{4}	10^{7}	1	3.968×10^{7}	11,630
Mbtu	1.0551×10^{-3}	0.252	2.52×10^{-8}	1	2.931×10^{-4}
GWh	3.6	860	8.6×10^{-5}	3,412	1

Source: IEA figures. Additional conversion figures available at http://www.iea.org/stat.htm

Unit Prefixes

k kilo (10^{3})
M mega (10^{6})
G giga (10^{9})
T tera (10^{12})
P peta (10^{15})
E exa (10^{18})

Annex D. List of boxes, figures, and tables

Boxes

Figures

Tables