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.