An ISGP White Paper:

Energy Sustainability

Introduction

By the year 2050, the world's sustained energy needs are estimated to reach 25-30 terawatt-hours (TW), double today's equivalent figure (13TW) which is itself double the demand of 40 years ago. Our ability to grasp the magnitude of this issue, and its consequences, requires analyses that link credible scientific understanding and technological options with the "actionable decisions" needed to formulate and implement practical policies. Sustainable development, as reflected in economic progress, national security, and quality living standards, depends on reliable access to energy in essentially all countries. In this **White Paper**, the **Institute on Science for Global Policy** (ISGP) undertakes a preliminary examination of the issues related to ***Energy Sustainability*** by summarizing the current realities, the scientific and technological (S&T) challenges and opportunities, and some of the related domestic and international policy issues facing societies and their governments.

The ISGP Approach

Many of the most significant global challenges for 21st century societies are directly related to the profound S&T achievements of our time. Success in fostering safe, secure, and prosperous societies often reflects how well societal and governmental institutions recognize the opportunities and consequences associated with existing, emerging, and "at-the-horizon" S&T and how effectively governmental policies balance short-term challenges requiring immediate attention with the need for long-term investments in transformative research and development. Unfortunately, large gaps too often exist between S&T understanding and the governmental policies that emerge from the political processes within a society.

The ISGP seeks to significantly improve the capability of governments to effectively bridge these gaps and to help shape the relevant domestic and international policies. ISGP programs use a unique format based on multiple conferences designed to address specific aspects (e.g., nuclear, solar, wind, geothermal, biomass, etc.) of a broad S&T topic (i.e., **Energy Sustainability**) previously vetted as a priority with participating governments. While each ISGP program focuses on a specific S&T topic (e.g., energy, infectious diseases, food safety, or cyber security), the ISGP is positioned to examine several S&T topics simultaneously through parallel programs.

Each ISGP conference focuses almost exclusively on critical debates and caucuses involving highly credible, articulate scientists chosen by the ISGP and an international group of policy makers from the United States, Europe, and Asia selected by the participating governments. The ISGP selects a few (6-8) S&T experts for each conference to prepare concise, focused written documents describing their views and to participate in the critical debates led by a global group of decision makers. Emphasis remains on specific "actionable decisions" and their foreseeable consequences. Separate caucuses held during each ISGP conference provide opportunities for governmental and societal representatives to discuss next steps, both domestically and internationally.

In preparation for each conference, the ISGP staff interviews or corresponds with a wide range of globally recognized subject matter experts from academia, industry, and the non-governmental community. These discussions seek to elicit the interviewee's opinions concerning the relevant S&T realities, challenges, and options that should be considered by governments. To ensure a comprehensive understanding of these issues, the ISGP also reviews the relevant international reports, statements, and S&T publications. Taken together, these materials and information are used by the ISGP to prepare a **Strategic Roadmap** which not only summarizes all the findings, but also describes the content and structure of a series of 6-8 conferences to be convened by the ISGP on the S&T topic (e.g., energy) over a two-three-year period.

The global character of the ISGP is reflected not only through the engagement of the United States, European, and Asian governments, but also in its international network of affiliated universities. Students and professors from these affiliated institutions participate in ISGP programs and are involved in real decision-making processes occurring at each ISGP conference (fundamentally a "practical policy laboratory"). ISGP programs also seek to foster public respect for the role of S&T in policy, and obviously, to help shape strategic public policies worldwide.

Energy Sustainability

This **ISGP White Paper** has been developed to summarize the current scientific understanding and to identify some of the critical policy issues that make ***Energy Sustainabiltiy*** an appropriate topic to be examined through a comprehensive, two-three-year ISGP program. It is based on a review of some of the relevant published material and on discussions with a selected group of S&T professionals versed in energy issues through their work in academic, private sector, and non-governmental settings. While these individuals were asked for their opinions, they did not author or formally endorse this **ISGP White Paper on *Energy Sustainability,*** which remains wholly a product of the ISGP.

In a two-three year comprehensive study, the ISGP would examine ***Energy Sustainability*** using the multiple conference procedures and critical debate format described above. This would involve a much larger number of interviews with subject matter experts and policy makers chosen internationally and would lead to the preparation of a **Strategic Roadmap on *Energy Sustainability*** that would be reviewed by participating governments before its implementation.

Efforts to establish strategies to meet the world's future energy needs must be predicated on an accurate understanding of the consequences of both our actions and our inactions. Identifying effective domestic and international policies connected to the "actionable decisions" that underlie sustainable solutions requires conscientious deliberation rooted in the credible S&T options. Such solutions will represent a mosaic of near-, mid-, and long-term approaches. Effective near-term policies must obtain international consensus and establish measurable, enforceable agreements affecting both domestic and international decisions. Mid-term policies are likely to be derived from evolutionary S&T developments. Long-term approaches are anticipated to become apparent only after research and development (R&D) efforts identify revolutionary S&T advances. To formulate and implement policies without informed discussion and debate of all three types of options risks highly unpredictable experimentation on the only known habitable biosphere in our Solar System.

Current Realities – Overview

The global energy requirement is growing continuously, despite the recent economic contraction. Oil, coal, and natural gas literally fuel this demand. Fossil fuels account for about 85% of current energy use, and have an even higher presence in transportation (>95%). Major infrastructure investments specialized for the use of these fuels have been made throughout the developed world and are rapidly dominating investments in developing countries.

Our continuing use of fossil fuels has significantly increased the atmospheric concentration of greenhouse gases (GHG), a phenomenon widely recognized as a cause for warming the planet's atmosphere. The primary molecular culprits are water vapor (H_20), carbon dioxide (CO_2), methane (CH_4) and ozone. Anthropogenic sources for these GHG vary: e.g., for CO_2, deforestation and burning of fossil fuels and for CH_4, livestock, farming, land use, and changes in wetlands. Ozone (O_3) is formed when sunlight reacts with hydrocarbons and nitrogen oxide formed as pollutants from the burning of fossil fuel. Ozone acts as a weak GHG in the upper atmosphere, but plays an important role in impairing the ability of plants to utilize $CO_{2,}$ (thereby "sequestering" it) in the lower atmosphere. Global scientific observations demonstrate that the increasing average air and ocean temperatures, the melting of snow and ice cover, and the rise in sea level are all directly related to the presence of GHG. It is now recognized that a major contribution to GHG concentrations can be traced to human activities, largely the use of fossil fuels.

Despite current mitigation efforts, there is broad agreement that the concentration of GHG will continue to increase throughout the next several decades. Continued warming may lead to sudden and/or irreversible consequences of dramatic proportions. How far the world progresses toward the "worst case" scenario depends critically on the level of GHG, particularly CO_2, in the atmosphere. Specific mitigation strategies must be devised to account for immediate needs, but must also reverse present trends to ensure a stable long-term environment.

Current Realities – Growth and Distribution of Demand through 2050

In the next 40 years, the world's population is predicted to rise to 9 billion. Most of that growth will occur in the developing nations, with India and China making up 37% of the total and Africa accounting for 21%. In these developing areas, individual vehicle ownership rates (per 1000 persons) are currently the lowest in the world (more than a factor of ten less than in Europe, Japan, and the United States). In 2004, transport accounted for a quarter of all global energy use, 95% of which was provided by the refined oil products associated with GHG.

Growth in the transport sector offers a social perspective on energy needs. Private vehicles often reflect economic status and freedom of choice by facilitating business ownership and both essential and non-essential travel. Citizens of developing countries aspire to standards of affluence already realized in developed countries. Access to energy is arguably now widely viewed as a fundamental human right.

Global energy sources are geographically distributed unevenly with fossil fuels concentrated in the Middle East, geothermal and hydroelectric sources available in only a few locations, and efficient generation of wind and solar energy feasible only under restricted conditions. Developing nuclear energy sources involves a wide range of financial and security issues. In addition, the infrastructure needed in each of these cases is often intimately connected to challenging, if not daunting, economic and political considerations that have historically made their use almost prohibitive.

An estimated 1.6 billion people in the developing world, roughly a quarter of the present global population, are not able to reliably access adequate energy. Such "energy poverty" affects not only their participation in information exchange and economic development, but also directly limits their access to food, shelter, healthy environments, and education. Rising demand for energy, fundamentally driven by population increases and expanding economic development, is likely to be exacerbated by the expected impacts of climate change and associated human mitigation. Climate changes are expected to most dramatically affect those coastal cities with high population densities already seasonally threatened by heat and storm-tracks and those persistently under-developed regions of Africa troubled by drought.

Current Realities – Energy Options

Because of the deleterious effects on Earth's atmosphere and climate, long-term reliance on fossil fuels is unwise. And yet, it is likely that fossil fuels will continue to be a major source of global energy. This reality presents a quandary of dramatic proportions and potentially catastrophic consequences. The unique geologic conditions underlying the creation of the vast amount of fossil fuels currently in use make them irreplaceable and non-renewable. In addition to their energy value, fossil fuel-derived petrochemicals are critical sources of medicines, paints, plastics, and synthetic fibers. While opinions concerning the remaining volume of these fossil fuels vary widely, reserves are generally expected to last until 2100, and perhaps beyond. The threat of depleting fossil fuels, however, pales in comparison to the negative climatic consequences inherent in their continued use as energy sources, especially with respect to the amount of carbon they introduce into the atmosphere. However, what are the options for low-carbon or carbon-neutral resources? They include biomass, hydrological (hydroelectric, wave, and tidal), solar, wind, geothermal, and nuclear power.

The energetic movement of water (i.e., hydroelectric) can be used to produce electricity in a low polluting and highly efficient (up to 80%) energy-capture process. Solar energy has the theoretical potential, based solely on insolation, to produce 120,000 TW (compare to current global demand of 13TW). While it is technically possible to harvest about 600 TW of this potential, solar energy currently is a miniscule contributor to total global energy being used. Wind energy is fundamentally also 'solar', as air movement is caused by solar temperature effects in our atmosphere. The theoretical potential for wind energy over land is only about 2TW, but off-shore collection potential is estimated to be much larger. The need to find suitable natural settings for efficient use of hydrological, solar, and wind power sources make each effective only in specific geographical regions.

Biomass, hydrological, solar, and wind solutions are "renewable" because they can be harvested and renewed within timeframes relevant to human needs. Renewable sources are sustainable, which makes them attractive, but are also intermittent, which makes them problematic as practical energy sources. Advances in storage technologies and the development of power plants relying on combined generation technologies can buffer discrepancies between production and demand. On the positive side, production may exceed demand at times, permitting excess power to be sold, or stored and released to peak periods.

The large amounts of geothermal energy available from the heat stored in Earth's crust can be used only when more advanced deep drilling methods become available. In those locations where it can be efficiently extracted, energy generated from geothermal sources is cheap and environmentally clean.

Since the generation of nuclear energy consumes radioisotopes that must be mined and extracted, it can be considered as non-renewable. While the technology for broad utilization of nuclear power is widely available, decisions concerning how to efficiently select among a variety of designs for nuclear power plants that is vital to meet the economic challenges is a matter of international debate. Much progress has been made in the development of modular, repeatable building plans, passive safety systems, and process/materials enhancements that have improved both the efficiency and acceptance of nuclear power.

While a variety of potentially useful energy sources are available, their impact on climate change through the introduction of GHG, primarily CO_2, remains an overarching issue for all of them. As we begin to understand the dramatic impacts of atmospheric CO_2 (now at levels more than twice those in the pre-Industrial Age), the urgency of mitigating CO_2 levels becomes ever clearer. Capturing the CO_2 generated during energy production is considered a temporary option. Can carbon be captured and sequestered, removing it from participating further in potentially irreversible climate changes while permitting the natural carbon cycle to stabilize? Many believe the answer is yes. Currently, injection of CO_2 in oilfields is primarily practiced for enhancing oil recovery, not for carbon sequestration. Although studies have not stringently measured leakage rates, some experts believe these are likely to be low. Will they be low enough, and can they be effectively monitored? The use of carbon sequestration technologies may be highly significant given the continued appeal and tempting accessibility of fossil fuels, but it is a ‘holding action’ that should not postpone finding and implementing long-term solutions.

Scientific Challenges and Opportunities – Biomass

Sources of biomass can be fuel crops, plant residues and waste, or livestock and municipal wastes. Biofuels derive from recently living biological matter, in contrast to fossil fuels which represent ancient, buried, and geochemically processed bio-matter. Energy from modern biofuels is most commonly produced by harvesting crops high in sugar (sugar beet, sugar cane), starch (corn), structural lignocellulose (wood, switchgrass), or oil (soybean, palm, algae). These products may need to be processed or refined before combustion. In addition to crop growth, chemical and microbial processes produce both biofuels and biogases using waste source material.

Manipulation of microbial processes, and genetic engineering, hold substantial promise in this area. Some species of microalgae directly produce desirable bio-oils. For example, algal colonies of *Botryococcus braunii* secrete oil (3%), gasoline (65%), diesel (18%), and kerosene (15%). Algae use CO_2 as a nutrient, acting as a carbon “sink”, and can grow on the organic nutrients in biowaste, processing it and purifying it for release into the environment. Intriguing pilot tests are being conducted in preparation for growing farms of such microalgae at high densities. These microalgae are contained in huge semiporous selective membrane bags tethered off-shore and fed with partially treated municipal sewage in order to derive bioenergy directly from sunlight while concentrating their bioproducts for harvesting as fuels. Microbes conditioned the Earth for larger life forms billions of years ago, and are still able to repeat the process.

Scientific Challenges and Opportunities – Solar

Solar energy systems must be efficient (in energy capture and conversion), low cost (to manufacture and install), and reliable (maintenance and life-cycle). Single-crystal silicon photovoltaic (PV) cells, first produced in 1954 at Bell Labs, still dominate the market. The second generation of PV cells reduced cost through the use of thin films, based on various materials, without dramatically changing their capture/conversion efficiencies. Tremendous effort is now being invested in the development of third generation modified and alternate materials that optimize electron capture from the energy inherent in every incident photon.

The first theoretical thermodynamic limit for PV efficiency (32%), calculated in 1961, assumed that uncaptured, highly energetic photons dissipate their energy through heat. If this is not assumed, and these photons can be captured using new materials and technologies, theoretical efficiencies could soar beyond 65%. Reported efficiencies of research grade multijunction concentrator PV cells have risen steadily, from 16% in 1983 to almost 40% in 2005 although even the best commercial prototypes typically lag behind in efficiency.

The key to revolutionary advances and ‘ultra-high’ efficiencies lies in novel materials, and the ability to manipulate and combine components at atomic scales. Photoelectrochemical cells built with nanostructures have shown good efficiencies in electrical power generation (~15%) and hydrogen production (>10%). Currently, costs preclude their commercialization although they remain attractive options since they combine energy conversion and storage.

In addition to improvements in materials, structural designs optimizing photon capture are being developed. These include large surface area modules producing lightweight, strong, flexible installations, solar concentrators using inexpensive optics to focus and collect incident light onto small cells, and fiberoptics to funnel incident light into tunnels designed to more efficiently absorb the potentially reactive photons. At least some of these approaches may hold the key to cheap, plentiful energy conversion direct from sunlight.

Scientific Challenges and Opportunities – Nuclear

Research on the fuel cycle aimed at maximizing energy recovery from today's Generation II plants centers on optimizing both the pelletized fuel and its interaction with the tubes containing the fuel pellets, the "cladding". Higher burnup rates can extend the lifespan of reactor cores by ~20%, improve operational control (and therefore safety), and may produce efficiencies for recycled mixed-oxide fuels comparable to those for uranium-oxide fuel.

Generation III and III+ plants, such as Canada's Advanced CANDU 6 Reactor (slated for operations in 2016) and the European Pressurized Reactor design (plants under construction in Finland and France), represent today's maturation of the field, incorporating increased efficiencies, standardization of designs (for lower maintenance costs), and increased operational safety. Generation IV plants (in development) will continue the advance of nuclear technology, using recycled fuel in high burnup processes with economic life-cycle costs and further attention to obviating the risks of resulting final waste. These reactors are not expected to enter commercial construction before 2030, with the exception of the Next Generation Nuclear Plant in the United States, linked to a hydrogen production facility, which could be completed by 2021.

The commercial reality of thermonuclear fusion is being studied at the International Thermonuclear Experimental Reactor (ITER) currently under construction in France. An international team (seven countries) is evaluating the potential for magnetic confinement fusion to make the transition from research in plasma physics to commercial production of electricity. Construction of ITER is expected to be complete in 2017, to be followed by a commissioning phase, a shakedown phase, and operations with deuterium before final full power is achieved with an equal mixture of deuterium and tritium. Optimistically, by using relatively common isotopes of water, ITER could provide essentially limitless energy without substantial amounts of waste material.

Scientific Challenges and Opportunities – Carbon Sequestration

CO_2 can be trapped under low permeability (non-porous) geologic formations as a supercritical fluid. Pilot sites in use inject about 1 million tons of CO_2 annually, a tiny fraction of the 10 billion tons that may need to be sequestered annually by 2050. In addition to utilizing oil and gas fields, CO_2 could be injected into deep alkaline settings, where reaction of dissolved bicarbonates would form insoluble (precipitated solids) chemically stable carbonates. Deep sea floor sediments are another proposed storage site where CO_2 would become entrained in the sediment as a dense liquid or solid hydrate and not dissolved in ocean waters. The options of stable sedimentary geologic settings, on land, and sea floor sediments offer alternative solutions that could provide appropriate sequestration choices in various regions of the globe.

A primary scientific question about sequestration is whether the CO_2 will be reliably contained over timescales that positively impact the restoration of balance to the global carbon cycle. In addition to addressing this question based on current technologies and observations of pilot operations, discussion should engage researchers whose expertise extends to paleoclimate and the record of extreme climatic fluctuations over geologic time periods. Reviewing cause and effect in periods when the Earth entered, and escaped, glaciations reaching equatorial regions can inform our understanding of planetary cooling, GHG warming, and the uncontrolled global experiment in which we are currently engaged.

Policy Issues

The increasingly urgent societal issues to be addressed when considering energy sustainability are two-fold. First, governments seek to provide security and prosperity for their citizens. Second, they must ensure sustainability for the planet. Striving to achieve the former without succeeding at the latter will be a short-lived gain.

Fulfilling the world's energy requirements is a task of global proportions. Actionable decisions require policies based on clear understanding of the broad scope of S&T issues, and international cooperation. Solutions are likely to contain a mixture of near-term, implementable and measurable actions, mid-term plans using evolutionary advances based on current S&T understanding, and investments needed to develop transformational S&T discoveries.

Policy Areas of S&T Consensus

Surprisingly, recent decades have seen a dramatic reduction in both public and private funding of energy related S&T research. The 2007 figures for spending in the European Union show public and private funding of research on low-carbon energy sources totaled €3.2 billion, of which about 28% was invested in research on nuclear energy. In the U.S., the fraction of research and development monies targeted at this sector decreased from a high of 10% (post 1970's oil embargo) to today's 2%. Private investment is estimated to have dropped 75%. In 2005, total private funding for energy research, at $1 billion, was less than the research and development budget of a single large biotechnology company, Amgen ($2.5 billion).

Renewable energy sources are notoriously intermittent. Some energy consumers (e.g. manufacturing and heavy industry) require highly dependable power. Some consumers (e.g. data centers) require reliably high quality power. Key to enabling the robust utilization of solar and wind energies are modern, even post-modern, electricity storage and distribution networks. The next generation distribution network for electricity is the Smartgrid, in which detailed information on demand and use is part of vast intelligent feedback loops. This requires physical infrastructure (construction), software development, and sensor deployment (in homes, offices, communities and embedded in circuitry and consumer products). The Smartgrid will allow consumers, of all demand sizes, to select their power's type, amount, and source. It will allow "consumers" on the grid to be also "producers". Excess energy derived from renewable sources at the point of use can be fed into the grid as a "credit" and community resource. Individuals can recoup their investment by selling power in their peak production periods. Local storage technologies (c.f. hydrogen, below) may also allow them to reserve energy and release it in peak pricing periods.

Smartgrid access will be, like entertainment, e-mail, data, and telephone services, accessible via the internet on today's ubiquitous personal communication devices. How will reaching into the data service 'ether' to snatch a cup of energy change the face of economies, and individual interaction with, and access to, the energy marketplace? Might it open unprecedented opportunities for the energy disenfranchised? Many of the "energy poor" using simple biofuels for subsistence needs and live in regions where solar energy is abundant—even in excess. Can advances in solar technology combined with Smartgrid distribution enable these areas to take gradual steps, including microfinancing and community-scaled projects, to eventually emerge as literal powerhouses?

Evolutionary S&T Achievements

Various estimates put the energy loss along the pathway from generation to use at 37-61%. Most is wasted as heat. Highly efficient design solutions are cheaper to implement during initial construction than to retrofit. Governments can insist on full-cycle, lifetime project costing, require energy-conscious design, and place cost levies on excess energy consumption as on GHG production.

Addressing efficiency is an important aspect of planning for a sustainable energy future, and has two significant optimistic perspectives. First, most of the offices, homes, transit systems, roads, vehicles, appliances, computers, etc. that will be in use in the coming decades, requiring power, are not yet in existence. Second, incorporating best-practice solutions is far more effective, in life-cycle cost and performance, than retrofits. Policies can address energy efficiency of project construction and product manufacturing through financial incentives, permit standards, and international trade agreements. The value of intellectual capital (technical expertise, training, services, and information) is an evident benefit of supporting skilled, intelligent design strategies and a comparably talented workforce. Investing in improving efficiency has the potential to provide all of these benefits. However, the single most dramatic impact in reducing reliance on fossil fuels, and thereby decreasing carbon emissions, will be achieved by electrification of transportation.

Some suggest investment in hydrogen storage and fuel cell research is one key. The enormous gap between present state-of-the-art capabilities and comparative energy costs must be narrowed for hydrogen technologies to become competitive and, therefore, the bases for practical solutions. The putative hydrogen economy would involve dramatic changes in networked infrastructure, but could provide clean and flexible solutions. Hydrogen could link electricity to transportation demands, replacing fossil fuels, and could act as a storage medium for the intermittent power generation of renewable sources.

While transportation continues to primarily utilize fossil fuels, and coal remains a substantial source of electricity, policy considerations based on the S&T of carbon sequestration to mitigate atmospheric GHG are timely. The world is expected to continue to rely on this plentiful and (currently) cheap resource, compatible with present infrastructures, particularly the five countries that hold 75% of the world's coal reserves (the United States, Russia, China, India, and Australia). It is important to remember that coal produces more CO_2 per unit consumed than any other fossil fuel.

Design considerations are extremely significant in this discussion. Conventional coal-fired power plants can be fitted with carbon capture facilities, but these modifications are substantial and costly. Policies can encourage construction of modern coal gasification plants with incorporated sequestration technologies. Co-locating new or retrofitted facilities with sequestration sites is essential, as transporting captured CO_2 is technically difficult and expensive.

International dialogue is essential in evaluating large-scale carbon sequestration sites. Basic agreement on emission measurement standards from pre- to post-sequestration scenarios is necessary. Suitable sequestration sites will not necessarily be directly accessible to all nations and therefore, shared use across borders can be expected to become a policy issue. Thus, sequestration facilities must be managed with transparency through international agreements.

Today's pilot experiments in carbon sequestration largely result from efforts to maximize extraction of oil reserves. In contrast, there is substantial experience with managing nuclear power generation. These two evolutionary approaches, however, are similar when considering the impact of operational failures and public perceptions of safety. Both, also, present significant S&T development challenges.

Advanced materials research and high performance modeling (with real-world verification) continue to contribute to improvements in optimizing nuclear plant operations, power generation efficiencies, production, use, and re-use of nuclear fuel, ease of maintenance/re-processing, and waste minimization/disposal. In fuel reprocessing research, complex chemistries are being explored to recover unexpended uranium and plutonium by using specific selective strategies. Waste stream minimization and improvements in packaging radioactive fission products in glass matrices (vitrification) are also important target areas for both research and regulation.

If the number of nuclear plants in operation were to expand by a factor of three by 2050, and if they displaced coal-fired plants, the production and emission of 2 billion tons of carbon annually could be averted. The impediments to such actions are many including high capital costs, long development timelines, and both real and perceived concerns about waste management, safe operations, and nuclear arms proliferation. The controversial setting of a price on carbon emission added to the use of fossil fuels can be expected to critically impact the economic viability of both nuclear power and carbon sequestration.

Revolutionary Scientific Understanding and Technological Ingenuity

The Sun delivers more energy to the Earth than can be feasibly captured, but even theoretical capture would outshine requirements by many powers of ten. Why, then, is solar energy (independent of photosynthesis) currently providing only a tiny fraction of global energy needs? Until now, fossil fuels have been cheap and accessible. Large scale economic and political disruption has accompanied the world's reliance on this commodity, although carbon generation itself has until recently carried no economic fee or social stigma. In addition to the research and development investment solar technologies require, economic and social incentives may be needed to affect widespread public adoption. These issues are avenues for international policy discussions.

Nanotechnology is revolutionizing research on photovoltaic and photoelectric cells and on ideal thermoelectric materials to produce electricity from heat. This and other specific areas of advanced materials research are promising and are supported by both national and private entities. However, is the scale of this support comparable to the scale of the need? This question must be asked about each and every potential energy generation, storage, and distribution solution, but most particularly it is relevant to investing in the research and development of the S&T underlying revolutionary solutions.

Biofuels are used today, as they have been for millennia, for residential heating and cooking by the roughly 25% of the world's population who are energy-poor, and "off-the-grid." Open burning of these fuels in homes where cooking and living spaces are contingent results in concentrating air pollutants and particulates to levels that create serious health risks. The dissemination of improved kilns and cooking stoves could improve these health conditions for a very large number of people while providing a bridge to more efficient and safer energy sources.

Modern biofuel research is a broad and interdisciplinary arena. Some advances will be gradual and evolutionary, others will be revolutionary discoveries. Genetic engineering, itself a revolutionary capability, is an important enabling technology. Biofuels could loosen the grip of fossil fuels on transportation, in addition to supplanting them in traditional heating and cooking. Besides revolutions in S&T, this change would require further revolutions in the politics, economics, taxation, and regulation of distribution networks and vehicle manufacture and marketing.

Planning for production and distribution of biofuels has several provisos. If the land use decreases current carbon sinks (wetlands, forests), it will worsen global warming scenarios. If it decreases food production, it worsens food security. Producing and using biofuels may also negatively affect water resources and GHG emissions out of proportion to their ability to contribute to energy needs. All these considerations cross national boundaries. Stringently derived international accounting standards must be developed and applied that address the impact of specific biofuels on food sustainability, GHG impacts, soil stability, and water consumption and the maintenance of biodiversity.

Conclusion

This **ISGP White Paper** attempts to assess and characterize some of the significant S&T options and policy issues that surround ***Energy Sustainability***. The urgent need to identify "actionable decisions" that lead to practical policies is apparent. The realities are potentially dire, the challenges significant, and while the S&T opportunities are encouraging, almost all require further maturation and an expansion of our physical and societal infrastructure.

Overall, potential solutions contain elements of near-, mid-, and long-term planning based on integrated domestic and global policies. The most attractive near-term options capitalize on currently accessible S&T approaches that require support by consensus. Mid-term options need to harness evolutionary progress, largely involving S&T research and development often already underway. In the foreseeable future, these mid-term options are likely to have the largest impact on optimizing the world's ability to meet its domestic and global energy needs. Long-term options can be realized only from investments in R&D that challenge the existing S&T understanding and fundamentally change the technological opportunities available to transform our access to sufficient, environmentally safe energy resources. Policy decisions need to consider how to integrate all three types of options into a globally supported direction since no single S&T approach can be expected to be sufficient to meet the scale of the recognized challenges associated with ***Energy Sustainability***.

A comprehensive ISGP study of ***Energy Sustainability*** would examine the topic in detail, develop a Strategic Roadmap from extensive interviews and a through review of the literature, and utilize the ISGP's unique format of critical debates and caucuses extending over a two-three year series of interviews and international conferences to help shape domestic and international policies.

