UNITED STATES AND EUROPEAN UNION SUMMIT ON
Science, Technology, Innovation, and Sustainable Economic Growth

A Report on the Deliberations of SCIENCE, ENERGY, AND SUSTAINABLE ECONOMIC GROWTH
A Workshop Convened at the Howard H. Baker Jr. Center for Public Policy, The University of Tennessee, March 30-April 1, September 19, 2011
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at the Howard H. Baker Jr. Center for Public Policy,
The University of Tennessee,
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Howard H. Baker Jr. Center for Public Policy,
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FOREWORD: Senator Howard Baker

In 1969, I was one of several fortunate American citizens who came together at a propitious moment in history and developed the concepts that, in many respects, have changed the world and altered our attitudes toward the environment.

In that year, Senator Ed Muskie from Maine, a colleague and a good friend, and I worked together in crafting the Clean Air Act of 1970. Passage of the act marked the beginning of the environmental movement in the United States. Our collaboration on environmental legislation continued with the passage of the Clean Water Act of 1972.

These two acts have endured for nearly half a century and achieved significant and continued progress in improving environmental quality in America. While many Asian and Eastern European cities suffer from unimaginable pollution, we in the United States have seen our economy, population, and energy and water use grow, and yet our air and waterways have progressively gotten cleaner. Through our Clean Air and Clean Water acts, we have been able to balance our aspirations for economic growth with our desire to protect our environment—in a sense, to achieve what has become known as sustainable economic growth. To a significant extent, the two legislative acts have endured because they are both grounded in science and technology. Indeed, years ago, members of Congress learned that serious discussions on energy or the environment must involve science and technology in fundamental ways. As we all know, energy, which in its many forms is crucial for our economic growth, often has detrimental effects on the environment. These negative impacts can be ameliorated only through science and technology, which will lead us to renewable and less-polluting energy sources.

As we move forward in setting our national priorities, our new policies must incorporate provisions that merge science, energy, environment, and economic growth.

While governments on both sides of the Atlantic agree that long-term economic health requires creation of globally competitive jobs, the way forward is not
always clear. Further, while almost everyone agrees that science, energy, and the environment are essential for sustainable economic growth, the emphasis that should be given to each and the relationships among them remain to be determined.

Increased national and international dialogue can contribute substantially to resolving these complicated issues, as can new levels of cooperation among governments and between government and the private sector.

Needless to say, I was delighted when the National Science Foundation and the Department of Energy agreed to sponsor an international dialogue on the important factors that determine sustainable economic growth in the United States and Europe. “The U.S.-E.U. Summit on Science, Technology, Innovation, and Sustainable Economic Growth” takes the form of a series of workshops and plenary sessions.

These activities are organized by the Howard Baker Center, the Woodrow Wilson International Center for Scholars, and Oak Ridge National Laboratory, in collaboration with the European Commission.

In March, The Howard Baker Center for Public Policy at the University of Tennessee convened the first of two workshops scheduled to be held in the United States as part of the Summit. The workshop, which focused on the nexus of science, energy, and sustainable economic growth, drew an international group of participants from academia, industry, and nonprofit research organizations.

The workshop presentations—and the deliberations they inspired—are summarized in this report. As such, this report represents a critical step in enhancing our understanding of the ways science, technology, and innovation affect sustainable economic growth. The report also identifies barriers to the widespread adoption and application of science and technology and examines policy options that might surmount these barriers.

Through the activities of the U.S.-E.U. Summit, we are achieving a critical step in identifying ways to enhance the impact of science on the environment, economic activity, and quality of life.
INTRODUCTION

The Howard H. Baker Jr. Center for Public Policy, the Woodrow Wilson International Center for Scholars, and Oak Ridge National Laboratory are coordinating a Summit of workshops and plenary sessions to inspire dialogue between the United States and the European Union on “Science, Technology, Innovation, and Sustainable Economic Growth.” The Summit is sponsored by the National Science Foundation and the Department of Energy, in collaboration with the European Commission.

The purpose of the U.S.-E.U. Summit is to enhance understanding of the ways in which science, technology, and innovation affect sustainable economic growth; to identify impediments to the flow of science from the “bench” to applications; and to explore policy options that might enhance the impact of science and engineering on economic activity and societal needs.

The Summit began with a plenary meeting in September 2010, held at the Woodrow Wilson Center in Washington, D.C. The Summit brought together academic leaders, policymakers, scientists, and economists to discuss the impacts of investments in science and technology on the American and European economies.

Information on the initial meeting is available here: http://www.wilsoncenter.org/event/the-us-european-summit-science-technology-innovation-and-sustainable-economic-growth.
The two-year Summit also included a series of workshops focused on related issues. One such workshop convened in March 2011 at the Howard Baker Center on the University of Tennessee campus and engaged an interdisciplinary group of 14 participants from academia, industry, and nonprofit research organizations. The two-day workshop was followed by a one-day meeting in Chicago in September 2011 to review the workshop draft report and develop final recommendations.

Workshop presentations and discussions addressed the following themes: 1) the energy challenge, 2) the energy opportunity, 3) key technology and development needs, 4) translation of science and technology to economic outcomes, and 5) science, technology, and the energy challenge.

This report presents workshop deliberations and recommendations and identifies key challenges and opportunities that the current energy situation creates for both the United States and Europe. The overarching challenge is making the transition to non-carbon based sources of energy while stimulating economic growth.

The report sets out the important energy-related science and technology options as well as the policy framework necessary to speed their development and adoption. The report also includes an important discussion of the role of innovation, one of the critical links between science and economic growth. Historically, innovation has played a key role in driving economic growth, and, as the report makes clear, this same innovation process must be brought to the energy sector.
Limited fossil fuel reserves, national security issues, and climate change combine to create the Energy Challenge. The problem has many facets, but generally a few dominate the discussion: the social benefits of economic growth and improvement in quality of life, which depend on energy security and reduced reliance on petroleum, along with reduction of greenhouse gas (GHG) emissions. Achievement of these goals will require considerable changes to the existing energy system through development and implementation of more efficient and sustainable ways to produce and consume energy.

A potential major contributor to addressing the issue of energy independence is the realization that the United States and many European countries have demonstrated that they can dramatically increase their supply of low-cost natural gas with the development of techniques that fracture natural gas-containing shale to release and collect the natural gas (fracking). Similar technology is enabling a revolution in oil recovery (tight oil) from oil-bearing shale formations in the United States. It is important to note that the objectives of energy security and reduction of carbon emissions—while both desirable—need not be mutually addressed or achieved. Indeed, decarbonization is not essential for energy security and vice versa, but these objectives can have significant overlap depending on the technology path chosen. Thus, policymakers must be clear in identifying which of the objectives they seek to achieve or in articulating that they hope to achieve both simultaneously.

History teaches us that energy shortages and disruptions lead to recessions and slow economic growth. Making wholesale changes in energy sources and use patterns without disrupting the world economy presents a daunting challenge. Many point to the real costs of fossil-fuel use that are not reflected in market prices, such as external environmental costs, trade imbalances, health effects, and national-security costs. Corrective mechanisms, such as new energy taxes, that will move such unrealized costs to realized costs do not exist in the current political environment. International agreements on determining who and how to pay for global challenges, such as GHG emissions, are similarly challenging. Creation of new technologies for an emissions-dominated world requires global cooperation. Reducing GHG costs on society will be accomplished only through
government actions and, in order to work, these actions must be universally applied. There is no precedent for such control over the way energy markets function.

Since 2002, the United States has shifted attention and research toward understanding energy technologies and the related challenges. In a report titled *Basic Research Needs for a Secure Energy Future (2002)*, the Department of Energy (DOE) Office of Basic Energy Sciences explains the types of research needed for energy technologies to ensure economic prosperity and sustainability. Nine years later, similar reports elaborating on these challenges, along with new ones, continue to engage the community.\(^1\) Clearly, while we have achieved significant strides in identifying barriers to energy innovation, we have accomplished much less in terms of actually plotting a course to significantly revamp the production and use of energy.

**1.1 OIL DEPENDENCE**

The United States and the European Union face the common challenge of reducing their demand for imported oil. In the United States, there is growing concern over continued dependence on international supplies of oil. U.S. oil consumption has continuously increased, while domestic production has not kept pace—creating a divergence between national consumption and national production (Figure 1).\(^2\) To compensate for the divergence, the United States has relied on imported fuels, transferring $350b/year to foreign oil producers. Although this dependence has decreased somewhat in recent years due in part to enhanced techniques for recovering domestic tight oil, continued reliance on foreign oil imposes multiple risks to national security and the economy.

![Figure 1:](http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf)
The true concept of oil independence is not widely understood. Many people assume that oil independence means zero oil consumption or zero oil imports. Consequently, there is widespread belief that oil independence is an unrealistic goal and that to try to achieve it is a waste of resources; however, attaining oil independence does not mean zero consumption of oil. Instead, it means reducing oil imports to a level where oil does not influence political and/or military decisions. For example, a qualitative goal in oil independence is to reach a point where, despite all conceivable conditions in the world oil market, the cost of oil disruptions to the economy are so small that they have a minor and acceptable effect on economic, military, or foreign policies. For both the United States and the European Union, this would require a substantial reduction in imported oil. For reference, the United States consumes about 20 million barrels of oil per day but produces only about 9 million barrels per day. Additional production mostly from tight oil has the potential to grow this to about 12 million barrels per day by 2020.³

Reducing GHG emissions is a second, related challenge. Reducing fossil-fuel use is necessary to reduce atmospheric CO₂ levels. Electricity generation and transportation account for the majority of CO₂ emissions in the United States, with the share rising from 55.2 percent in 1990 to 60.4 percent in 2009.⁴

Figure 2: Indicators of Climate Change
Reaching the goals of oil independence and GHG mitigation is not the course the world is currently on. Achieving these twin goals clearly requires implementation of a number of technologies and the policies to promote their deployment. Furthermore, it is likely that dramatic, rather than incremental, improvements are needed. These improvements will be required both in the production and use technologies and revolve around a single theme: Improving the performance and lowering the cost of the high-tech materials and chemistry that underpin these new technologies. This materials and chemistry challenge will be accomplished primarily at the molecular and nanoscale level.

Stabilized CO$_2$ emissions will also require not one, but a portfolio of new technologies, as indicated by a recent study that assessed 11 potential energy technologies. According to that study, reaching a combined reduction in the U.S. petroleum balance of 11 million barrels per day (mbd) and reducing GHG emissions by 60 percent of current levels is possible only with a combination of nearly all of the technologies considered.

1.2 IMPACTS ON THE ECONOMY

Cheap and readily available energy, largely from fossil fuels, coupled with advancing technology spawned by cheap energy, has been the major driver of the economic growth that has transformed life for most of the peoples of the world since the industrial revolution. Originally, easily accessible deposits required only labor and small amounts of capital to secure. Advancing technology and innovation led to the discovery of ever larger deposits and the ability to access, produce, and deliver them to users at what, until recently, has been decreasing real costs.

The price of oil seen by consumers is made up of two parts: The first part is the resource cost of discovery, exploitation, and delivery. That cost is very low for some deposits, such as the established oil fields of the Middle East and elsewhere. As exploration and production move to less favored areas, however, such as the deep ocean and the arctic, those costs can rise. The remainder of the price paid by consumers is for the scarcity value of the fossil fuels in the ground—the “rent” that is taken in the form of payments for the right to exploit the resource.

Purchase of oil transfers not only the resource cost of extracting and delivering the oil, but also the scarcity cost to the supplying country. The resource cost is an unavoidable cost that pays for production; the scarcity cost is not used for production and is available for other uses in the country that receives it. This increase in wealth can be applied, for example, to education, health, infrastructure, commercial enterprises, or research and development.
For countries such as the United States with substantial indigenous fossil fuels, the transfer of the scarcity cost to foreign countries is not as significant as it is for much of Europe. The transfers associated with domestic production can be recycled within the economy, avoiding the transfer of wealth abroad.

The European Union and the United States currently face other societal challenges, including caring for an aging population, devising sustainable methods for producing food, improving water quality and supply, and developing smart transport systems that reduce congestion. Rather than pursue a piecemeal approach to addressing these challenges, the challenge for the European Union and the United States is to tackle them—along with climate change and security issues—while creating new business opportunities.
Options for radical transformation in energy use in the short to intermediate timeframes are limited. Societies’ dependence on fossil resources developed because the resources could be exploited at low cost and the energy obtained was significantly greater than the energy expended in production. There are no current alternatives that match fossil fuels on these economic and energy-return criteria. Non-fossil energy sources are limited to those provided by the sun, such as solar, wind, and biomass; nuclear, both fission and fusion; those derived from gravity, such as tides; and those derived from the earth, such as geothermal.

Barriers are present to harnessing any of these options. For example, solar power has issues with conversion efficiencies and storage technologies. The recent earthquake and tsunami in Japan have resurrected concerns over the long-term safety of nuclear power. Further, there is little agreement on the best approach to disposing of nuclear wastes (current options include deep on-site burial, vitrification, and the controversial Yucca Mountain nuclear waste repository). A recent MIT study group recommended intermediate rather than long-term storage of nuclear waste.\(^6\) This approach has the advantage of allowing the waste to be reprocessed to increase the useful amount of nuclear fuel.

Biomass is a thinly distributed resource that is constrained by photosynthetic efficiencies and competition with food crops; in addition, it is limited in many places by seasons.

**ALTERNATIVE TECHNOLOGIES AND THEIR DEVELOPMENT NEEDS**

A portfolio of energy technologies/methods is essential if U.S. and European economies are to reach the combined goals of sustainability and security. (See a comprehensive review of technologies in US Department of Energy, *Quadrennial Technology Review* [2011], http://energy.gov/quadrennial-technology-review). The well-known GHG-abatement cost curve prepared by McKinsey and Company shows the costs of reducing emissions beyond “business as usual,” through use of current or near-term technologies (Figure 3). The
height of each bar indicates the cost of abatement, while the width represents the emissions reduction that each technology/process creates. For example, reducing GHG emissions by 26 gigatons of CO$_2$/yr would require all of the technologies up to the circle labeled 26 (i.e., marginal cost of emissions would reach 40 Euros per ton CO$_2$ equivalent). Interestingly, some of the measures pay for themselves, including increases in fuel efficiency in automobiles, increased insulation in buildings, and more efficient water heating. Reaching the emissions targets put forth by the United States and the European Union will require not only energy efficiency measures (the lower cost portion of the curve), but also renewable technologies (e.g., higher cost wind and solar).

![Figure 3: Abatement Cost Curve](http://www.epa.gov/oar/caaac/coaltech/2007_05_mckinsey.pdf)

Individually, alternative technologies and their required breakthroughs can be assessed based on three sustainability criteria: First, the technology must last a long time. In the 1900s, oil was used without regard for its finite supply. Today as coal use increases, its finite supply must ultimately be considered. The second criterion is that the technology does no harm. These criteria often have compensating positive and negative features. Electricity from nuclear fission is desirable in the sense that it emits no CO$_2$, but, without policy changes, management of spent fuel remains a liability. Nuclear fusion has high potential, but it is a long-term target. Five or six years ago, first-generation biofuels, such as corn ethanol, were thought to offer a solution for nearly carbon-
neutral transportation, but some analysts argue that biofuels from corn have about the same carbon footprint as gasoline produced from petroleum. Third, the technology must precipitate no change so that, once used, it leaves the world in the same or at least no worse physical and chemical state than before.

A recent article by Crabtree and Sarrao (2009) assessed a number of alternative technologies in terms of these three criteria and also identified the breakthroughs needed for the technologies to be successful. Their findings are represented in the table below.

### Sustainability Profile

<table>
<thead>
<tr>
<th>Technology</th>
<th>Lasts a Long Time</th>
<th>Does No Harm</th>
<th>Leaves No Change</th>
<th>Breakthroughs Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Electricity</td>
<td>😊</td>
<td>😊</td>
<td>😊</td>
<td>Lower-cost, higher-efficiency photovoltaics; third-generation materials and nanostructures; electricity storage</td>
</tr>
<tr>
<td>Carbon Sequestration</td>
<td>😞 (emissions)</td>
<td>😞 (sequestration)</td>
<td>😞</td>
<td>Chemical reactivity with rocks in extreme environments; migration through porous rocks; geologic monitoring and predictive modeling; leakage routes to atmosphere</td>
</tr>
<tr>
<td>Nuclear Electricity</td>
<td>😞 (emissions)</td>
<td>😞 (spent fuel)</td>
<td>😞</td>
<td>Materials for extreme environments; high-temperature, high-radiation flux, high-corrosivity; geologic monitoring and modeling</td>
</tr>
<tr>
<td>Cellulosic biofuel/solar chemical fuel</td>
<td>😊</td>
<td>😊</td>
<td>😊</td>
<td>Cellulosic breakdown to sugar or fuel</td>
</tr>
<tr>
<td>Oil sands and shale, coal to liquid</td>
<td>😞</td>
<td>😞</td>
<td>😞</td>
<td>Chemistry of carbon dioxide to fuel</td>
</tr>
<tr>
<td>Electrify transportation</td>
<td>😊</td>
<td>😊</td>
<td>😊</td>
<td>X2-5 higher density in batteries; catalysts, membranes and electrodes in fuel cells</td>
</tr>
</tbody>
</table>

While these technologies have promise, none has reached economic parity with incumbent energy technologies. Significant scientific and engineering innovation is required to bring these technologies to the brink of competitiveness.

Fossil resources remain dominant because the cost and energy return from using fossil fuels is better than any currently available alternatives. Recent advances in recovery of shale gas greatly reduced the cost and increased the supply of natural gas, which could have major impact on domestic energy supply and energy security. Given the low cost of shale gas, it can be expected to affect the economic attractiveness of alternative sources of energy. Alternatives gain market share as cost structures change—incumbent technologies can become cost prohibitive or alternative technologies can experience dramatic improvements. Such advances frequently are the outcome of basic science, which uses the emerging understanding of nanoscale phenomena to reduce size and material cost while enhancing efficiency.

Caution must be exercised, however, in comparing energy opportunities to recent technology revolutions in electronics or telecommunications. In the latter technologies, basic science enabled a reduction in scale that led to million-fold increases in performance over three or four decades. Such scaling does not apply to the performance of energy technologies; the absolute limits on Carnot and other efficiencies of energy conversion to electricity or transportation fuel cap the potential performance gains in energy technology, while the miniaturization that produced such dramatic advances in processing speed and cost of semiconductor electronics has nanoscale limits that are far from the conventional size scales that were in use in the 1970s. The gains in alternative energy will come from higher efficiency and lower cost due to basic understanding and application of nanoscale materials and chemistry, with potential for factors of five or 10 improvement, depending on the technology, boosting the alternatives to parity or better, compared to traditional fossil energy sources.

2.2 ENERGY STORAGE

High-profile approaches to electricity generation, such as wind and solar, suffer because electricity generated from these sources is variable or intermittent. Energy storage is frequently cited as necessary for these technologies to realize their full potential. Energy storage can affect both electricity generation and transportation. The electrification of vehicles serves as one way to significantly reduce carbon emissions from transportation (provided the electricity source is low carbon), but better batteries are clearly needed. Storage of energy is essential for large-scale deployment of variable renewable sources. Today, most experts do not foresee increasing the energy density of batteries by more than an order of magnitude.
While energy density is an important parameter, it is not the only market need. Longer lifetime, higher charging rate, and lower cost systems could increase adoption even at current energy densities.

### HIGH-TECH MATERIALS AND CHEMISTRY

The role of materials in alternative energy technologies is fundamentally different from their role in fossil-fuel technologies. In fossil-fuel technologies, the important component is the fuel, a commodity valued for its high energy density and low cost. The first step in the fossil energy production chain is combustion, where the fuel is destroyed and converted to heat, which is then further converted to mechanical energy by the engine of a car or by a turbine driving an electrical generator. In alternative energy technologies, the input is not a fuel but an underutilized energy flow such as sunlight, water, or wind, some of which is then directly converted to useful energy. The alternative energy chain eliminates the combustion step associated with fossil energy, often the step that is least efficient and most damaging to the environment. The important materials in alternative energy chains are not fuels that are destroyed by combustion, but complex high-tech functional materials that convert, for example, sunlight to electricity at ambient temperature. These materials are designed, often at the nanoscale, to perform complex physical and chemical energy conversions that may require a sequence of electronic and molecular transformations. They are made to be durable, performing for decades after which they can be recycled to begin life anew in the next generation of alternative energy technologies.

High-tech materials and chemistry are simultaneously the driving force and the bottleneck of alternative energy technologies. While they perform high function, they do so at low efficiency. The best commercially available solar cells are about 20-percent efficient, well below their theoretical limit and well below the efficiency of combined cycle gas turbines, which generate electricity at about 60-percent efficiency. In the research laboratory, multi-junction solar cells operate with over 40-percent efficiency, illustrating the potential for improvement typical of alternative energy technologies. Innovations driven by basic science and engineering are needed to close this performance gap and bring alternative energy technologies to economically competitive levels.

### BIOFUELS

Biomass and its derivative fuels are significant components of the energy supply in many countries. Globally, the majority of biomass use takes place in undeveloped or developing countries, where it is harvested and used, often in inefficient household stoves, without regard for replacement. In developed countries, biomass
Combustion provides energy at a larger rate than all other renewable energy sources. The opportunity for growth of biomass energy is in conversion to transportation fuels, already well advanced in Brazil based on sugar cane fermentation to ethanol and with significant potential there and in temperate climates based on cellulosic conversion to ethanol and other hydrocarbons.

Many tout the possibility of algae to revolutionize energy production. Biofuels are disproportionately targeted at transportation fuels. The ability for these fuels to provide “green” options within the existing infrastructure is a large part of their appeal. Cellulosic ethanol has been a focus of much research, but has yet to reach commercialization. Recent trends have moved past alcohol fuels in search of drop-in replacement fuels. Production of hydrocarbon fuels from biomass is certainly possible. Photosynthetic efficiency and limited growing seasons in much of the world ultimately limit the potential for biofuels. Limited arable land and water resources also cloud biofuels’ future.

Current biofuels production is dominated by sugarcane in Brazil and corn in the United States. In both geographies, improving the efficiency of production is desirable. The structural advantages due to use of a tropical, perennial crop gives Brazil advantages that cannot be duplicated in temperate climates. In both temperate and tropical climates, improvements in the crops have made impacts. A Brazilian research center has developed 100 strains of sugarcane and uses satellite sensing to determine locations of optimal soil conditions. Brazil’s biofuels production is viewed as a success, but several aspects that led to this success should not be overlooked.

Even with the established ethanol production capability and crop practices, government intervention was required to spur industrial development. Unlike many parts of the world, land was available and was not shifted from other productive use. Water was not a limiting resource, and technology for implementation for transportation was readily available. It should also be noted that, while ethanol production satisfies a large fraction of the demand for liquid fuels in Brazil, liquid fuel consumption in Brazil is very small—only a few percent of the liquid fuel consumption in the United States.

By contrast, the United States faces barriers to widespread production and use of biofuels. Ethanol from corn has likely reached its maximum capacity and requires significant water and fossil-fuel inputs. Current technology for conversion of woody biomass to transportation fuels is inadequate. Technologies for drop-in replacement fuels by pyrolysis are undergoing testing, and energy-efficient conversion of plant sugars to high-octane gasoline has been demonstrated. These conversion routes seek to transcend the limitations of cellulosic ethanol, better utilizing refinery capacity and providing true drop-in hydrocarbon fuels. Use of woody biomass for power is commercially practiced, but is not economically viable for widespread use,
except in some developing countries. Use of agricultural wastes and purpose-grown energy crops are still in the future. Fuel from algae is similarly in its infancy, and successful cultivation of algae for fuels is not yet certain.

2.5 NUCLEAR
Given all the constraints and national objectives on climate change and oil independence, nuclear energy is an attractive option for carbon-free base-load electricity in the future energy mix. One prospect lies in construction of advanced light-water reactors for large-scale power production and small modular nuclear reactors for smaller developing electricity markets around the world, which would lower capital investment and risk in developed countries.

Modular reactors with factory fabrication could significantly decrease capital costs and construction times. In the United States, spent nuclear fuel is not recycled. This is a policy decision, not a science-based decision. The decision not to recycle spent nuclear fuel originated during the Cold War and was intended to provide protection against potential nuclear proliferation. This is in contrast to the spent-fuel recycle and mixed oxide used in France. The recent Fukushima Daiichi tragedy in Japan focused much attention on issues associated with assuring the proper design basis for extreme natural events and associated accident management.

Currently there are over 434 existing nuclear reactor units worldwide.\textsuperscript{11} Consideration should be given to refurbishing these plants as appropriate for power upgrades and extended life while ensuring safety. It is also essential that the regulatory cost burden of building new nuclear reactors be reduced. It is not profitable to shut these existing plants down if building a new one takes too long or is not cost competitive.\textsuperscript{12} In addition, new fuel cycles, research on new reactor designs, and waste management technologies, including research and development and policy issues associated with them, should be considered.\textsuperscript{13} Current reactors need to have active safety systems and operator actions to provide long-term cooling to remove nuclear decay heat and maintain safety. The next generation of advanced light-water reactors (e.g., Westinghouse’s AP1000 or GE’s ESBWR) use passive features to assure long-term cooling for days without the need for external power or operator actions.

Finally, research and development of the Generation IV advanced small modular reactors are focused on providing long-term cooling to remove decay heat for weeks or more without the need for active systems or operator actions. These walk-away safe designs are modular light-water reactors (e.g., NuScale and Babcock and Wilcox designs), the gas-cooled thermal reactor designs (e.g., AREVA pebble-bed design), and the sodium-cooled fast reactors (e.g., GE’s PRISM Integral Fast reactor).
2.6 NATURAL GAS

Technological advances, including the development of the hydraulic fracturing (fracking) process in shale deposits, have brought large quantities of natural gas to market over the past decade, leading to the lowest inflation-adjusted prices for this clean burning fuel since before the energy crises of the 1970s. Moreover, the extent of the potential reserves in the United States suggest that ample supplies of gas will be available for a substantial period at current or even increased consumption rates.\textsuperscript{14}

Questions remain. Concerns have been raised about the potential for pollution of groundwater from the fracking process, especially unless “best-practice” production technology is strictly enforced. In addition, the short history of production from shale deposits leaves uncertainty about whether the ultimate recovery will meet current expectations.

The encouraging future for direct use of natural gas in the near and intermediate terms in the United States is not assured in other parts of the world, especially Western Europe. For one thing, the insecurity of supply—an issue that is trivial in the United States as related to the potential for geopolitical manipulation—is certainly a factor in Europe. Dominant supplies arrive in Europe through a limited number of pipelines from the East. Unlike the case of petroleum, the market for gas is more closely coupled between suppliers and consumers for a fuel that is difficult to store.

2.7 VARIABLE ENERGY SOURCES

An important consideration on the use of renewable resources such as wind and solar is the variability in energy supply. Another consideration for solar energy is the relatively high cost per kWh for today’s photovoltaics compared to conventional energy sources. To address this cost differential, the government of Germany has created a market for solar energy to increase leading-edge manufacturing and ultimately decrease the cost of solar energy. Installed capacity and actual power generation for solar and wind energy differ significantly.

Consider the case of Spain, which, by 2008, had installed a considerable wind capacity of 15.58 GW. Energy supplied from wind ranged anywhere from less than 1-percent of supply (minimum occurred on 5/3/2008) to 43-percent of demand (maximum occurred on 11/24/2008).\textsuperscript{15} On those days for which wind does not make up a large portion of supply, Spain needs to rely on other sources such as natural gas (e.g., natural gas and wind are complements.) At low penetration, the issue of backup for variable solar and wind generation is manageable through use of conventional reserve, some of which is already in place. At high penetration (above 20-30 percent), the cost of building gas or other conventional reserves becomes significant, effectively duplicating the installed capacity of
the renewable resource. At these penetrations, large-scale electricity storage becomes a priority that the United States and European Union are only now beginning to explore.\textsuperscript{16}

\section*{2.8 CARBON CAPTURE AND SEQUESTRATION (CCS)}

Achieving safe and cost effective CCS would permit decarbonization, even with continued use of fossil fuels. A recent study\textsuperscript{17} determined that inclusion of CCS is essential in the portfolio of technologies needed to reach the dual goals of climate-change mitigation and reduced dependence on foreign sources of oil. It was determined that even if the goals were relaxed from a 60-percent to a 50-percent reduction in GHG emissions and from 11mmbd to 8mmbd reduction in imported oil, the probability of meeting these goals without CCS is only 1 percent. CCS is politically popular, but people are divided on the feasibility of its implementation, both in terms of technical feasibility and public acceptance.

There are four fundamental issues associated with CCS: First, CCS works in pilot projects, but it is unclear whether it will work at the enormous scale that is required for effectiveness. Second, it is unclear what will happen to saline aquifers as massive quantities of supercritical CO\textsubscript{2} are injected into them. Third, credible sequestration of carbon requires geological formations that would provide for such storage, but these formations aren’t available in many countries. For example, the Netherlands can store CO\textsubscript{2}, but Bavaria cannot. Therefore, CCS is a possibility only if a country is geographically proximate to an appropriate geological formation. Last, the long time frames associated with CCS imply that significant reduction of GHG emissions from fossil fuels, if achievable, are at least two decades away.

\section*{2.9 THE GRID}

Population growth and consumer technology have increased electricity demand, straining the aging grid infrastructure. Most of the electric grids in the United States, the European Union, and the world were constructed in the post-World War II era, before the emergence of several contemporary issues, including the need for high-quality digital power, long-distance transmission of renewable electricity, storage of electricity to mitigate the variability of renewable generation, and two-way communication between utility and customer to manage demand. The existing grid was designed for delivery of power a few tens of miles from rural generation stations to urban demand centers and for regulation by local government.
In the United States, requirements for clean digital power, the variability of renewable generation, and the location of abundant solar resources (in the Southwest) and wind resources (at mid-continent) far from population centers on the east and west coasts have rapidly and permanently changed the requirements for an effective electricity grid. The U.S. patchwork grid must be modernized to provide higher quality and greater reliability, facilitate long-distance transmission, and incorporate the intelligence necessary for measuring and directing power flows to targeted areas. The European Union also recognizes this as a priority\textsuperscript{18} and is proposing the long-distance transmission of North Africa’s abundant solar energy to Europe (Desertec, www.desertec.org/), a challenge of comparable scale to that faced by the United States.

Modernizing the U.S. electric grid is a massive political and technological undertaking that will take decades to achieve. In addition to the technology challenges noted above, the layered regulatory structure of the U.S. grid—with federal, state, and local regulators often claiming jurisdiction over the same grid functions—must be streamlined. The complex and interconnected regulatory system supports the status quo and promotes local control. The grid’s Balkanized regulatory structure, rather than technological challenge, is the major impediment to innovation. Even many standard technologies, such as long-distance high-voltage DC transmission, which is more efficient than AC transmission, are blocked by regulatory issues. And emergent technologies, such as superconductivity-based offshore wind turbines and magnetic energy storage, face even greater challenges to reach the market. To enter the modern energy era, the grid needs a holistic vision that drives the fundamental technological and regulatory revisions that are critical to providing an effective electrical energy carrier that embraces new technology, promotes economic growth, and enhances quality of life.\textsuperscript{19}
BARRIERS TO ENERGY R&D

3.1 HIGH CAPITAL COSTS, UNPREDICTABILITY, AND LONG TIMEFRAMES

Energy-related R&D tends to be the current focus of governmental R&D investment, but R&D is not an end in itself. Indeed, society does not benefit from R&D alone but rather from the translation of R&D into the products and processes that society desires and needs. Likewise, a company benefits only if deployment of such products and processes is profitable; profitability allows the company to make additional investments in R&D. For example, companies can invest in carbon sequestration, but the odds of this investment being profitable are very low. As a result, few companies currently are investing in this technology.

Meanwhile, it is important to assess the timeframes and capital requirements associated with the various stages of technology—in particular those of the deployment stage. Discovery, development, and deployment time frames are roughly 3-10 years, 5-10 years, and greater than 15 years, respectively. Investing in R&D or technology demonstration today will not yield large-scale benefits by 2020. Large-scale deployment of major technologies is critical in terms of achieving climate-change and energy-security goals. These technologies would need to be in deployment today to have an impact by 2020. For instance, the Department of Energy’s timeframe for CCS technology is such that the demonstration phase extends to 2030 (Figure 4).

**Figure 4:**
DOE/NETL’s CCS Roadmap
Further, the amount of capital required for R&D (on the order of billions of dollars) is cheap relative to large-scale deployment costs (on the order of hundreds of billions of dollars). Therefore, counting on the free market to perform the R&D and invest in deployment without public expenditure throughout the design and demonstration phase is not feasible. In general, investors are risk averse, and the uncertainty of success associated with large-scale technology deployment is too high.

3.2 INNOVATION IN THE ENERGY INDUSTRY

High capital costs and past regulation of the electricity sector are not the only barriers to innovation in the energy industry. The telecommunications industry faced these barriers, and yet it became a sector marked by high levels of innovation. However, there are key differences between the two sectors. The telecommunications industry was able to apply advances in electronics to offer new services while reducing costs. In general, the simple physics of energy do not allow for a Moore’s law reduction in cost over time.

There are several other reasons why energy innovation is unique and difficult relative to that of other sectors. First, the organization of the energy sector consists of silos where basic research, applied R&D, and commercialization are kept separate from each other. Reorganization of the structure would allow vertical integration so that R&D is insulated but not isolated and innovation is facilitated. Second, the incentive to invest in energy R&D and deployment is low, due in no small part to the price of energy being low. Today, the societal benefits of energy improvements are not captured in economic benefits to the companies providing the improvements. Decisions must be based upon economic foundations that allow companies a return on their investments. Uncertain economic benefit and technology risk combine to limit development.

3.3 THE CURRENT SYSTEM IS ALREADY AT LEAST-COST OPTIMUM

Unless new technologies produce electricity below competitive costs they will not create new industries. The energy industry already exists, and it operates at least-cost. Solar cells and fuel cells were created 50 years ago, and ethanol production is 60 years old. The energy system has evolved to minimize the cost of energy to the consumer, not to promote social good. The economy does not appear to be willing to switch from its current energy system—one that is ubiquitous and cheap—to an energy system that is more expensive but provides greater potential for social and economic benefits.
EU ENERGY POLICY

As a political entity, the European Commission (E.C.) must pursue energy policies that take into account the marked differences among member states. Specifically, the E.C. must recognize the sovereignty of individual member states in defining their own priorities as they pertain to energy sources. In this regard, decisions that establish energy policy must be made simultaneously at the E.U. level and at the level of the individual member states.

Unlike the U.S. government, the European Commission has established a strong position on climate change. Further, most E.U. countries share agreement that renewable energy resources offer considerable potential for offsetting the effects of climate change. The European Union relies substantially on hydropower generation, but the hydropower sector has remained stagnant since 2001, in part, because most large-scale opportunities for development of hydropower have already been exploited. Meanwhile, other renewable energy sources have shown growth in Europe.

Significant growth is expected for renewable energy sources other than hydropower in the European Union, including wind (both onshore and offshore) and biomass. In fact, an E.C. study conducted in 2007 shows that, apart from hydropower, wind dominates the portfolio of renewable sources needed by 2020 to meet the E.U.’s 20-percent renewable energy challenge. Growth in photovoltaics is limited, although there has been some advancement in solar power in Spain.

The E.C.’s roadmap to a low-carbon economy states that member states should commit themselves to reducing GHG emissions by 20 percent, increasing the share of renewable energy in their energy mixes to 20 percent, and achieving a 20-percent increase in energy efficiency by 2020. Currently, the first two targets appear to be within reach. The recession, and the subsequent decline in energy consumption, has slowed the need for expanded capacity with higher efficiency. As a result, the E.U. will not meet its energy-efficiency goal without further efforts.
The Seventh Framework Programme (FP7) is the major instrument for intensification of E.U. research collaboration, with a budget of 53.5b Euros. Research, development, and deployment (RD&D) is now regarded as the major instrument for recovery from the effects of the current economic crisis. One of the E.U. agenda’s major goals is to reach a ratio of 3-percent R&D investment to GDP. Furthermore, the European Union focuses on a broader concept of innovation than the United States—one that extends beyond traditional product and process innovation and includes innovations that address social challenges.

Another challenge arises from the fact that there is considerable heterogeneity in the primary consumption by fuel for each individual E.U. member state. Part of the reason is due to the differences in the geographic characteristics among member states. For example, Norway, Sweden, Switzerland, and Austria have large hydropower resources, while other E.U. members do not. The implications of such disparities also apply in the United States. Those disparities make it difficult to establish a unified and coherent energy policy (Figure 5).

![Bar chart showing consumption by fuel type for select countries](http://www.bp.com/assets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/pdf/statistical_review_of_world_energy_full_report_2011.pdf)

**Figure 5:** Primary Consumption by Fuel Type, United States and EU Member States
COMMERCIALIZATION OF NEW ENERGY TECHNOLOGIES

Once a scientific breakthrough with potential commercial application is achieved, the next step is to transfer it to industry for commercialization. Institutions such as research hubs and the Advanced Research Projects Agency-Energy (ARPA-E) are designed to accelerate the path to commercialize, but not to deploy, technology. Some progress has been made in the alignment between government and industry in terms of commercializing new technologies, although the “valley of death” continues to be a major obstacle. This needs to be addressed.

The extensive length of a project—from research to development to deployment—means that it is prone to be affected by changes in policy. Fortunately, most technologies have built-in design margins, which reduce the impact of new policies that, for instance, increase originally mandated emissions reductions. On the other hand, new, more stringent policies may disrupt existing projects by adding cost and delays.

ENERGY EFFICIENCY POLICIES IN THE EU AND US

Policies that achieve energy conservation by prompting change in consumer behavior not only reduce dependence on imported oil but also have significant potential for creating markets for innovation. Examples include mandating the types of light bulbs used in buildings, implementing gasoline taxes or other incentives that encourage carpooling or use of public transportation, and providing incentives for improved energy efficiency of existing residential/business structures. Much policy that seeks to alter consumer behavior imposes on consumers higher prices for the goods they buy (e.g., Energy Star appliances and gasoline tax). It is questionable whether consumers would embrace these policies—particularly when they must pay more for products without gaining any direct individual benefit. In the United States, people are not accustomed to paying a premium for energy. Policies that attempt to control the price of energy, through such measures as taxes, are more acceptable in the European Union, where such measures have been in place for decades, than in the United States.

For instance, incandescent light bulbs are banned in the European Union. Switzerland has a high level of detailed regulations that the public accepts, including requirements on insulation and mandatory annual fuel checks on heating systems. Further, income tax reductions are offered if homeowners invest in energy-efficient products. An important part of the success of such policies in Europe results from the public’s attitude. Everyone is used to
paying a tax on energy. These differences in attitude may explain why it may be difficult to organize something similar in the United States. Nevertheless, the U.S. government needs to consider these and other measures—U.S. per capita energy consumption is twice that of the European Union.

There are other barriers to voluntary adoption of energy-efficiency measures. Among them is the tendency for people to be unwilling to pay more for something now that may (or may not) benefit them in the future, since the future is inherently uncertain. For example, consider a gasoline tax and the decision to purchase an energy-efficient car, as opposed to a less-efficient vehicle. It might be expected that a consumer would choose to purchase an energy-efficient vehicle over a less-efficient—but also less-costly—vehicle if the life-time cost savings of driving a fuel-efficient car offset its higher purchase price. In practice, this is not the case. A study conducted by the University of California\textsuperscript{21} found that very few people calculate the actual value of fuel savings over time when they consider buying a more-efficient car. Instead, they put more weight on the uncertainty associated with changing energy prices, the ambiguity surrounding the true energy efficiency of the vehicle, and the possibility that far superior technologies may soon come along. All of these considerations reduce the value of the purchase of a fuel-efficient car in today's dollars.

**R&D FUNDING NEEDS**

Currently, public and private energy-related R&D is underfunded globally by a factor of three to eight.\textsuperscript{22,23,24} Despite the clear need for increased funding for energy R&D, attaining energy goals will require more than a one-shot, large increase in funding from $3b to $9b in the United States, for example. Instead, funding for energy RD&D should be increased gradually. Nevertheless, it is essential that the funding be stable and predictable. Indeed, volatility in funding deters innovation. Historically, funding for energy RD&D has been notoriously unstable. Consider, for instance, that between 1992 and 2008, the year-to-year variation in the federal investment in energy R&D has been significant. For, hydropower, federal investment in energy R&D has varied up to 150 percent from year to year; for biomass, up to 100 percent; and for solar power, up to 85 percent (Figure 6).

According to the International Energy Agency’s Energy Technology Perspectives 450 (Blue) Scenario, the fuel savings that result from R&D investments in energy more than pay for the investments, even if a 10-percent discount rate is used. A key target for R&D funding is the electricity-production sector. A look at average annual additions to electricity capacity to 2020 suggests that the annual growth rate in many low-carbon technologies must achieve 40 percent per year for many years for the United States to achieve the 20-percent goal that Europe has adopted.
UNIVERSITY-INDUSTRY-GOVERNMENT COLLABORATION

Industry seems more than willing to deploy sustainable technologies—when they are available and cost-effective. The barrier, it appears, is the science that develops these technologies. In contrast, the barriers to implementation of fossil-fuel technologies are, for the most part, engineering-based. Most people understand the concept behind solar cells, but increasing the efficiency of these devices is a challenge for science. Policies that promote partnerships between industry and the purveyors of basic science—often researchers at universities and public laboratories—improve communications between researchers and developers and facilitate innovation and deployment of new technologies.

Through creation of European Innovation Partnerships (EIP), the European Union has achieved some success in bringing together the public and private sectors at all levels of government. Each EIP focuses on a specific societal issue. One of the goals of such partnerships is creation of more-efficient ways of transferring knowledge among the actors involved, including scientists, experts and professionals, industry and government representatives, and citizens.

**Figure 6:** Year-to-Year Variation in DOE Energy RD&D Funding (1992-2008)
As governments develop energy policies, they should bear several tenets in mind. First, to this point, alternative energy has been supplemental and has not provided a substitute for coal or liquid fuels. In other words, alternative energy systems have not replaced, but rather have complemented, the current system. Second, the scale of energy use is enormous, and energy must remain cheap. Indeed, the developed world regards energy as a commodity, and expects and relies on its availability. Third, to most consumers, energy is energy, and there is limited willingness to switch to higher-cost options. As a consequence, our current energy system is optimized to achieve the lowest cost. Fourth, investment in new technologies and research is needed, but industry will only invest if there is an expected return on that investment.

Based on these considerations and the background information included in this report, the panel makes the following recommendations:

- As a broad spectrum of national studies have concluded, major new investments in energy-related areas, including education in science, technology, engineering, and mathematics, need to be undertaken by the federal government. Special attention is needed for additional R&D investments in new and emerging energy technologies and for new retraining programs for the workforce affected by globalization and technological change. See the new American Energy Innovation Council report, http://americanenergyinnovation.org/wp-content/uploads/2012/04/AEIC_Catalyzing_Ingenuity_2011.pdf

- The United States and the European Union need well-defined long-term energy policies that reduce uncertainties for industry investment in new and emerging technologies. In some cases, governments may need to help create an actual market, as Germany has done in solar energy.
• More effective private-public partnerships are needed for large energy demonstration and deployment projects. Such projects are so long-term and expensive that private enterprise cannot assume the risk and cost alone. A process to commercialize government-funded R&D advances, such as those generated by ARPA-E, needs to be developed.

• New models for moving scientific discoveries from the bench into the innovation process should be developed to complement the Energy Innovation Hubs, which are designed to move discoveries only to the demonstration stage.

• Government agencies should support innovative energy technology development and deployment. Prudent risk taking is important for government agencies, and ARPA-E is a good model to follow.

• Electricity will continue to be the backbone of energy delivery, but the United States and the European Union are not prepared to exploit fully the opportunities offered. To capture the full potential of new renewable sources of electricity generation and provide appropriate price incentives at the retail level, policy and technology barriers must be overcome.

• An integrated technology roadmap for biofuels from R&D through crop cultivation and fuel production should be developed. The roadmap should include an examination of the impacts on the environment and food production for all development paths.

• Nuclear approaches that increase safety and reduce the regulatory and financial risks, such as standardized designs for reactors, need to be developed, tested, and approved by the regulatory agencies. Such approved reactor designs need no additional approval; only the proposed sites for new nuclear plants require review and approval by the NRC to ensure the reactor is not located on high risk sites (e.g., areas of high seismic and earthquake activity or vulnerable to water damage, etc.).

• A complete review of the nuclear fuel cycle needs to be undertaken, and options such as reprocessing spent fuel should be re-examined.
• In light of recent developments in Japan, detailed interaction with the public to address questions and concerns about nuclear power is needed.

• In view of the volatile market for fossil fuels and the relative immaturity of alternative energy technologies, policy should not seek to address short-term issues but, rather, seek to facilitate a relatively gentle and lower-cost transition to a more sustainable energy regime over the longer term. That is, policymakers should establish clear energy and environmental goals for the future and then determine which pathways will best enable us to reach those goals. One option is to promote policies that prompt demand-side changes and then to complement those policies with increased investment in science and technology R&D. As R&D incentives improve, more potential technologies will emerge. Each of these technologies may have a relatively small impact, but collectively, their impact can be considerable, especially if they are combined with demand-side policies that promote their acceptance and adoption. Further gains will result if these measures are bolstered through policies that promote energy conservation. On all of these fronts, there is much that all nations, both individually and collectively, can do, as they develop and implement policies for a sustainable energy future.
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1. For example, current reports include the Basic Energy Sciences Advisory Committee’s (BESAC) *Science for Energy Technology: Strengthening the Link between Basic Research and Industry* (2010) and the Office of Science and Technology Policy’s (OSTP) *Report to the President on Accelerating the Pace of Change in Energy Technologies through an Integrated Federal Energy Policy* (2010). BESAC reports can be found at http://science.energy.gov/bes/news-and-resources/reports/basic-research-needs/.

2. Nearly two-thirds of the consumption of oil can be attributed to transportation. One cannot imagine a Western civilization without automobiles; making an impact in this sector would make a significant impact on the reduction on oil dependence (i.e., switch to biofuels, electricity, or solar fuels).


19. Ibid.


A Report on the Deliberations of
“SCIENCE, ENERGY, AND SUSTAINABLE ECONOMIC GROWTH”

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