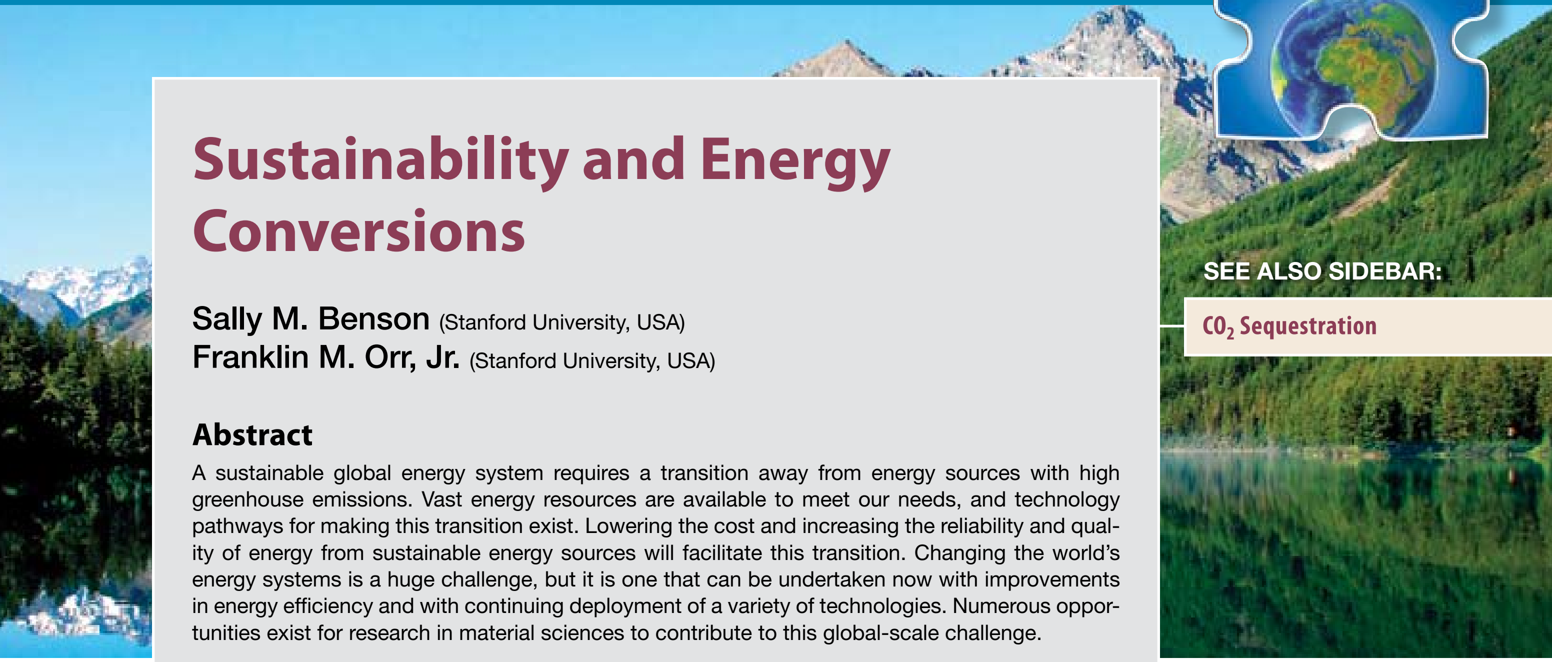

Sustainability and Energy Conversions

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SEE ALSO SIDEBAR:
CO_2 Sequestration

Abstract

A sustainable global energy system requires a transition away from energy sources with high greenhouse emissions. Vast energy resources are available to meet our needs, and technology pathways for making this transition exist. Lowering the cost and increasing the reliability and quality of energy from sustainable energy sources will facilitate this transition. Changing the world's energy systems is a huge challenge, but it is one that can be undertaken now with improvements in energy efficiency and with continuing deployment of a variety of technologies. Numerous opportunities exist for research in material sciences to contribute to this global-scale challenge.

Introduction

More than six billion people occupy our planet at present, and in this century, several billion more will join us. Feeding, clothing, and housing all of us will be a significant challenge, as will supplying the fresh water, heat, lights, and transportation that we will need to live comfortable and productive lives, while also maintaining and preserving habitats for the species with whom we share the planet. It is also clear that we humans are interacting at local, regional, and global scales with the natural systems that we count on to provide us with many services. Local air and water quality depend strongly on the way we transport ourselves, manufacture all manner of products, grow food, and handle the wastes we generate. Humans now use a significant fraction of the fresh water available on Earth, and we recognize that air pollution emitted in one location can affect air quality over large distances. A decades-long effort in developed economies to reduce impacts on local and regional air and water quality has been very successful (although challenges remain); efforts to address global-scale environmental impacts are just beginning.

Energy use, along with agriculture, which makes heavy use of energy for fertilizers, cultivation, and transportation of products, is a prime component of the interaction of human activities with global-scale natural systems through the emissions of greenhouse gases. As an example of the global impact of our energy systems, **Figure 1** shows concentrations of important greenhouse gases over the past 20,000 years.[1] Significant increases in atmospheric concentrations of the key greenhouse gases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have been observed over the 250 years since the beginning of the industrial revolution. Increasing greenhouse gas concentrations cause capture of additional energy in the atmosphere over pre-industrial levels, with climate change as one result. In addition, the pH of the upper ocean has declined as the additional CO_2 in the atmosphere slowly equilibrates with seawater.[2] Lowering pH (i.e., increasing acidity) affects the concentrations of key ions, carbonate and bicarbonate, which, in turn, affect the formation of calcium carbonate by a variety of marine organisms in the upper ocean. Thus, population balances of these organisms are likely to be affected as the concentration of CO_2 in the atmosphere continues to increase.

As we seek to provide and use the energy that is a fundamental underpinning of modern societies, we humans need to bring that use into balance with natural systems that cycle carbon, much of it in the form of CO_2. That will require significant reductions in emissions of greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and assorted chlorofluorocarbons, and other materials such as black soot. At the same time, in meeting our energy needs, we must not disrupt the natural processes that provide other important resources such as food and water—and ecosystems that provide habitat and sustenance for the myriad of species who share the planet with us. The carbon cycle is not the only system that will need attention in this century. Human perturbations of the nitrogen cycle, largely through the use of fertilizers for agriculture, also have significant impacts, as agricultural runoff has created large "dead zones" at some locations in the ocean. Balancing the need to grow food while sustaining natural ecosystems will also require changes in the way human activities interact with large-scale natural systems. We humans are just beginning to see ourselves as a global biogeochemical force—a first step toward more sustainable development requires managing our activities more effectively.

One element of energy sustainability involves curtailing emissions of greenhouse gases from energy use while providing adequate energy supplies to meet the needs of the developing and developed world. This will be a tremendous challenge for a number of reasons. Our current socioeconomic infrastructure is built around fossil fuels, needed reductions in greenhouse gas emissions are large, and the time frame to begin reducing emissions is short.

In fact, demand for energy from oil, coal, and natural gas continues to increase rapidly, as shown in **Figure 2**.[3] Renewable sources of energy such as hydroelectric power, wind energy, and solar photovoltaics are a small fraction of the worldwide energy supply. Today, wind energy and photovoltaics have high growth rates (27% and 40% annual growth rates in installed

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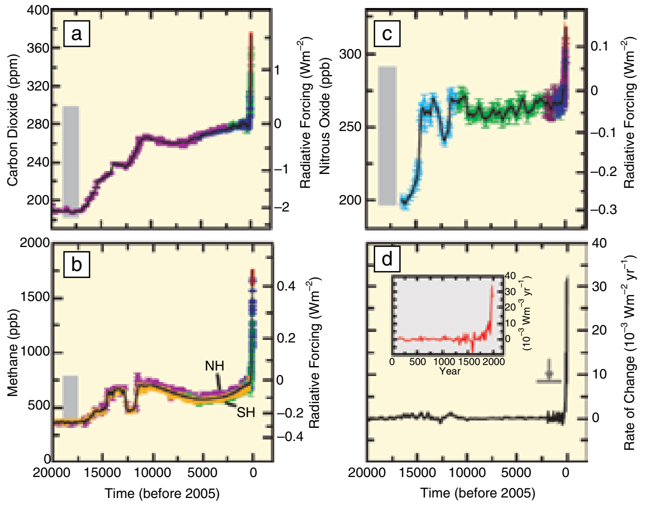
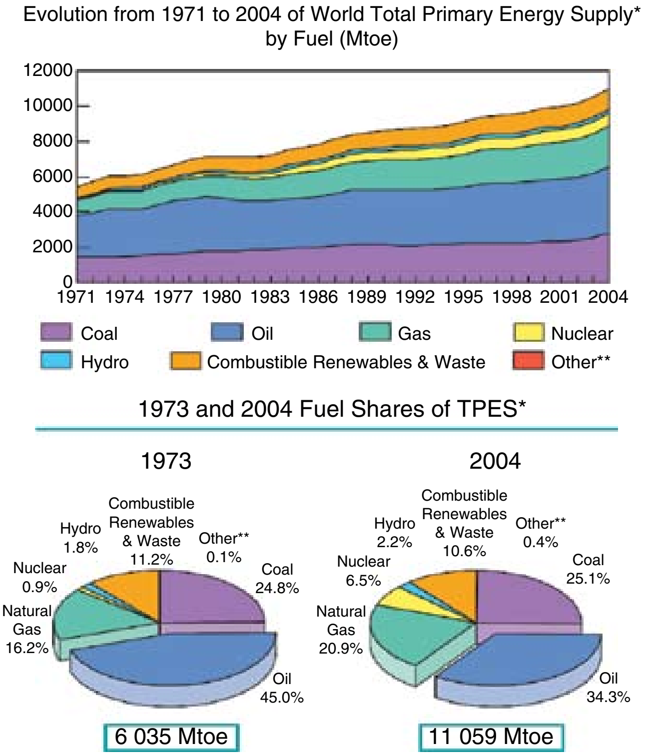


Figure 1. Changes in greenhouse gases from ice core and modern data. Concentrations and radiative forcing by (a) carbon dioxide (CO_2), (b) methane (CH_4), and (c) nitrous oxide (N_2O) and (d) the rate of change in their combined radiative forcing over the past 20,000 years reconstructed from antarctic and Greenland ice and firn data (symbols) and direct atmospheric measurements (panels a–c, red lines). The gray bars show the reconstructed ranges of natural variability for the past 650,000 years (from Reference 1). The radiative forcing due to a change in greenhouse gas concentrations is the change in net irradiance at the tropopause. NH is Northern hemisphere and SH is Southern hemisphere.

capacity, respectively),[4] but even if annual growth rates of 15% (of the installed base) could be sustained over the coming decades, it could take nearly 20 years before renewable energy sources (not including large-scale hydropower) provide more than 20% of overall global electricity consumption.

The reductions in greenhouse gas emissions required to stabilize atmospheric concentrations of CO_2 and global mean temperature will be large, and they will need to begin quickly if we are to avoid the most serious predicted consequences of global climate change and changes in ocean geochemistry. For example, **Figure 3** shows the range of emissions estimated to achieve stabilization of atmospheric concentrations at 450, 550, 650, 750, and 1000 ppm.[5] There is a growing consensus that avoiding the most serious effects of climate change will require limiting the global mean temperature rise to 2°C.[6] In March 2007, the European Council accepted this target as the basis for an aggressive plan to reduce greenhouse gas emissions. A recent assessment concluded: ". . . limiting warming to 2°C above pre-industrial levels with a relatively high certainty requires the equivalent concentration of CO_2 to stay below 400 ppm. Conversely, if concentrations were to rise to 550 ppm CO_2 equivalent, then it is unlikely that the global mean temperature increase would stay below 2°C. Limiting climate change to 2°C above pre-industrial implies limiting the atmospheric concentration of all greenhouse gases. Based on new insights into the uncertainty ranges of climate sensitivity, stabilization at 450 ppm CO_2 equivalent would imply a medium likelihood (~50%) of staying below 2°C warming."[6,7]

The summary provided in **Table I**[7] indicates that, to achieve this goal, the peak emissions would need to occur within the next decade, emissions would have to return to year-2000 levels by several decades from now, and emissions in 2050 would need to be reduced by 50–85% compared to emissions in 2000.



**Excludes international marine bunkers and electricity trade.*
***Other includes geothermal, solar, wind, heat, etc.*

Figure 2. World primary energy consumption by fuel type (from Reference 3).

Urgent and large-scale action is needed to stem the growing concentrations of CO_2 in the atmosphere. Fortunately, there are steps that can be taken on a variety of time scales to meet those challenges.

Sources of Sustainable Energy

What are the sustainable sources of energy that can meet our current and future needs? **Figure 4** shows estimates of energy resources that might be converted into some usable form of mechanical work, heating, or electricity. Two types of energy resources are represented in **Figure 4**: energy flows, representing energy resources such as solar energy that will be sustained over the foreseeable future, and stored energy such as fossil fuels that will be depleted in the course of use.

The values shown in **Figure 4** are estimates of energy flows in terawatts (TW, 10^{12} J/s) and stored energy in zetajoules (ZJ, 10^{21} joules). They are totals, not necessarily what could be recovered or converted at reasonable cost. Amounts shown are estimates of exergy, the theoretical maximum amount of energy that can be converted to mechanical work, electricity, or heating based on an assumed equilibrium state.[8] Any real conversion process will have an efficiency of less than 100%, and the cost of conversion will set limits, as well. Reservoirs of stored exergy (say, as geothermal energy, fossil fuels, or nuclear resources) are shown as ovals. Flows of energy are shown as arrows, with the size scaled approximately to the magnitude of the flow. For example, there is a large energy flux from the sun with 162,000 TW reaching the top of Earth's atmosphere. Of that, 31,000 TW is absorbed in the atmosphere, and 41,000 TW evaporates water on the surface of the Earth (creating the

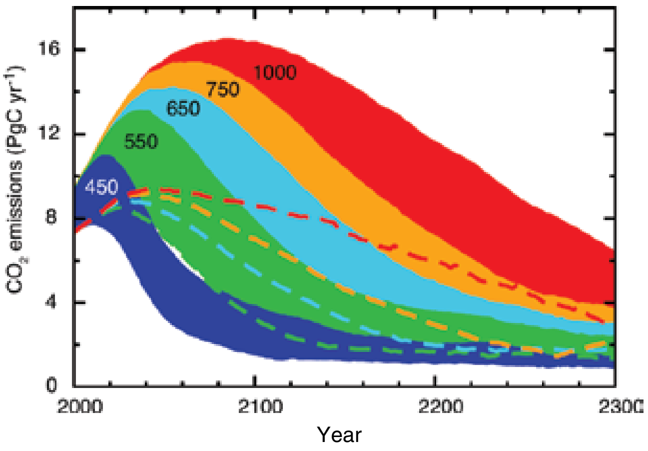


Figure 3. Estimates of greenhouse gas emissions needed to achieve stabilization at a range of concentrations and temperatures (from Reference 5, p. 792). The dashed lines indicate the lower end of the estimated range needed to achieve stabilization at the respective values. The range of values reflects the uncertainty in predicting stabilization based on emissions profiles and the associated climate feedbacks.

Table I: Estimated Global Mean Temperature Increases, Years for Peak Emissions, and Reduction in Global Emissions Needed to Achieve These Stabilization Levels.

Stabilization Level (CO$_2$-eq. [ppm])	Global Mean Temperature Increase (°C)	Year Global CO$_2$ Needs to Peak	Year Global CO$_2$ Emissions Return to 2000 Levels	Reduction in 2050 Global CO$_2$ Emissions Compared to 2000 (%)
445–490	2.0–2.4	2000–2015	2000–2030	–85 to –50
490–535	2.4–2.8	2000–2020	2000–2040	–60 to –30
535–590	2.8–3.2	2010–2030	2020–2060	–30 to +5
590–710	3.2–4.0	2020–2060	2050–2100	+10 to +60
710–855	4.0–4.9	2050–2080		+25 to +85
855–1130	4.9–6.1	2060–2090		+90 to +140

Source: Reference 7.

potential energy that forms the hydropower resource). Another 43,000 TW warms the surface and could be used to provide heat, electricity, and fuels. Today, of the large solar flux of exergy at the surface of the Earth, we convert only about 0.016 TW to electricity by photovoltaic and solar thermal methods. This tiny fraction of the solar flux is converted because photovoltaic and solar thermal methods are currently more expensive to convert sunlight to electricity than other resources such as fossil fuels. Some of the solar energy flux at the Earth's surface is converted by photosynthesis to plant material, some of which (about 1.2 TW) is used directly for cooking and heating. A small fraction of that has accumulated over millions of years as the fossil fuel resources (coal, natural gas, and oil) that we use extensively at present; the combination of coal, oil, and gas use totals about 11.8 TW. Another portion of the solar flux is converted into wind, creating a significant energy flux of 870 TW.

There is a large nuclear resource, as well, although much of it is widely dispersed (uranium or deuterium in seawater, for example). The flux of geothermal energy, about 32 TW, is roughly equivalent to projected human use of energy by mid-century, but there is an enormous (1.5×10^7 ZJ) geothermal resource stored in hot rock in the upper 40 km of Earth's crust around the planet. Although the stored geothermal resource is extremely large, converting it to electricity or useable heat is impractical with today's technology except for regions with anomalously high heat flow and near-surface temperatures such as occur in volcanic provinces. Tidal energy and wave energy fluxes are relatively small, a reflection of the relatively small gravitational potential associated with tides and the heights of waves.

Technology Pathways for a Sustainable Energy Future

Transitioning from today's energy system to a more sustainable one will require a number of technological approaches—there is no single solution to this challenge (see Pacala and Socolow[9] or the September 2006 issue of *Scientific American*[10] for discussions of many of the options available for energy systems of the future).

One option is to improve the efficiency of energy conversions and end uses. There are numerous opportunities to improve significantly the efficiency of energy conversions—from improving the efficiency of engines and chemical processing to improving the efficiency of lighting, heating, cooling, and other energy uses in buildings. All improvements in efficiency reduce the amount of energy supply needed, as well as the associated environmental impacts. More efficient use of energy, especially in buildings and transportation, offers significant reductions that reduce costs, substantially in the case of building insulation and improved air conditioning and water heating, for example. According to recent estimates, emissions reductions approaching 25% of current emissions could be achieved at negative cost through the implementation of energy efficiency measures. Globally, the most cost-effective options for reducing greenhouse gas emissions include efficiency improvements such as improving insulation, increasing the efficiency of commercial vehicles, and replacing existing lighting with high-efficiency lighting.[11]

Another option is to conserve energy. The availability of low-cost and abundant energy has led to unneeded use of energy—such as energy consumed while electronic equipment is in standby mode; lighting, heating, and cooling systems in buildings that are not optimized; use of energy during peak demand periods when less efficient methods are used to produce power; and driving during periods of high traffic congestion. In addition to behavioral changes to reduce energy consumption, advanced communications and control technology can play a role in conservation by providing real-time pricing and emissions signals, optimizing heating and cooling systems in buildings, and providing "intelligent" transportation systems that increase transit efficiency.

A third option is to increase the fraction of the energy supply coming from sustainable energy flows rather than stored resources. Stored energy resources are those for which the replacement rate is lower than the rate of use. Any stored resource, therefore, has some limit on total use (even coal).

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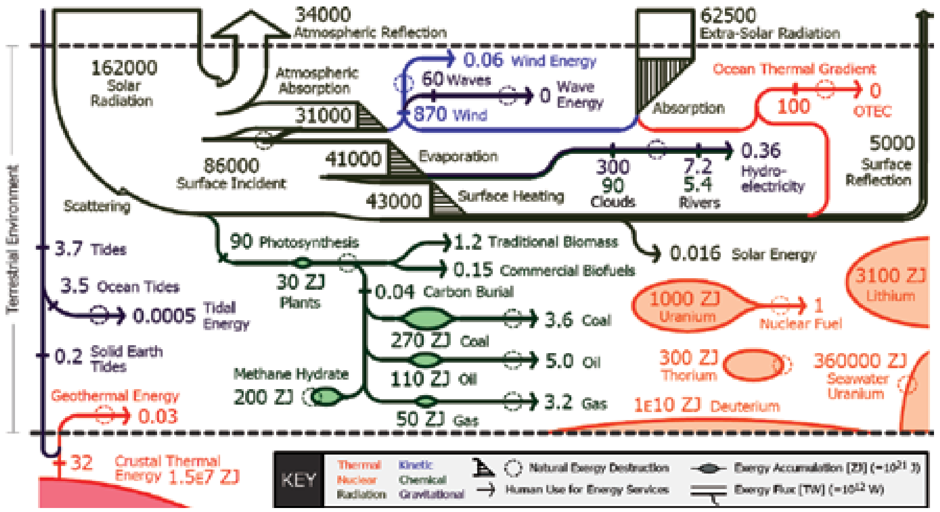

Figure 4. Global reservoirs and fluxes of exergy, energy that can be used for human activities, by converting the resource or flux to some other useful form or mechanical work (modified from Reference 8).

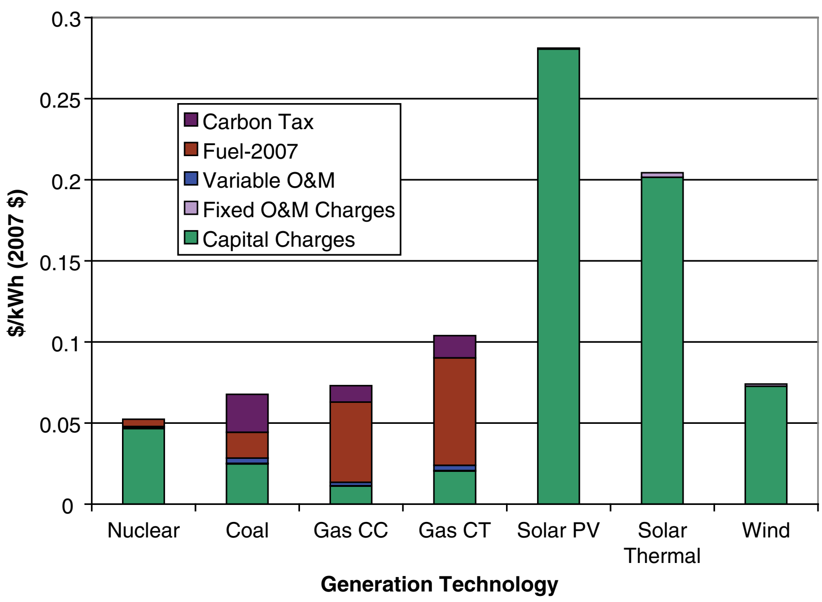

Figure 5. Comparison of the costs for various electricity generation options, including the cost of a $100 per ton price on carbon emissions. (Courtesy of John Weyant, Stanford University.) *Note:* O&M is operations and maintenance, CC is combined cycle, CT is combustion turbine, and PV is photovoltaics.

A transition away from relying so heavily on stored reservoirs of energy (e.g., fossil fuels) to using sustainable energy flows such as solar and wind power that reduce greenhouse gas emissions will put us on a more sustainable energy pathway. Determining whether a particular resource is sustainable requires careful consideration of both the resource flow and the ways in which it is converted. For example, biofuels made from the solar flux can be sustainable or not depending on how water and fertilizers are used and how the energy stored temporarily in biomaterials is converted to fuel. **Figure 4** shows that solar and wind resources are very large compared to current and projected energy demands. However, as shown in **Figure 5**, the costs of solar photovoltaics and solar thermal are very high compared to those of other electricity generation sources, even with a $100 per ton carbon tax. Although the cost of wind power is more competitive, large-scale deployment is still more costly than many other options for reducing greenhouse gas emissions[11]. Driving down costs, increasing reliability, and developing the infrastructure to take advantage of these sustainable resources will require significant technological advances, experience, and time, given that, today, less than 1% of the current worldwide energy supply comes from these resources (see **Figure 2**).

A fourth option is to understand and minimize the lifecycle impact of energy supply and end-use technologies on the environment. All energy systems and human activities have environmental impacts. An essential element of a sustainable energy future involves understanding the full lifecycle environmental impacts of energy systems and making choices that minimize these impacts. It is not sufficient to consider only greenhouse gas emissions and environmental impacts associated with the use of fuels; we must also understand and limit the emissions and impacts that occur during fuel production. For example, the process of manufacturing liquid fuels from coal releases as much carbon dioxide into the atmosphere as is released when the fuels are finally used, nearly doubling lifecycle emissions for coal-derived transportation fuels. All energy conversions have some environmental impact, of course. **Table II** summarizes some of the impacts of technologies that might be employed in global energy systems with lower greenhouse gas emissions.

A fifth option is to mitigate the undesired environmental impacts of energy production and use with technologies such as capturing and sequestering carbon dioxide from the use of fossil fuels. The pathway toward a sustainable energy future will inevitably require economic trade-offs and societal decisions that reflect the state of the existing energy systems, the cost of advanced energy systems, the desired pace of change, and the ability to build new infrastructure to support advanced energy systems. For example, coal-fired electricity generation provides abundant and relatively low-cost (if not low-impact) energy in many parts of the world, and its use is growing rapidly in China and India. Capturing and sequestering carbon dioxide from these facilities (see the sidebar by Benson and Orr) provides a means of

Table II: Examples of Environmental Benefits and Drawbacks of Technologies for Producing Electricity.

	Energy Supply	Environmental Considerations	
		Benefits	**Drawbacks**
Electricity Production	Coal power production (PC)	High energy density of primary energy supply	Large GHG emissions Mining impacts Air pollution if controls not used (e.g., SO_x, NO_x, Hg)
	Natural gas power production	Small footprint of primary energy supply High energy density of primary energy supply	Moderate to high GHG emissions
	Fossil fuel power production with CCS	Small footprint of primary energy supply High energy density of primary energy supply 80–90% reduction in GHG emissions	Mining impacts Potential groundwater impacts from brine migration or CO_2
	Nuclear fission	Small footprint of primary energy supply Small waste volume High density of power supply	Potential contamination from nuclear accidents Potential for groundwater contamination from waste disposal
	Solar PV and solar thermal power production	No significant GHG emissions No air pollution Sustainable energy supply	Low energy density for power supply Large footprint for solar collectors Competing uses for land Local changes in surface albedo
	Hydropower	No significant GHG emissions No air pollution Sustainable energy supply	Impacts to fish habitat Loss of terrestrial habitat
	Wind turbines	No significant GHG emissions No air pollution Sustainable energy supply	Large footprint needed for primary energy supply Potential impacts to birds depending on siting Noise and visual impacts
	Geothermal energy	None to small GHG emissions No significant air pollutions	Potential impacts to water resources from brine disposal Microseismicity from water or brine injection
	Biomass power production	Net GHG emissions can be reduced, depending on the lifecycle GHG emissions from biomass production, transport, and use Might be sustainable depending on agricultural practices and continued availability of water resource	Low spatial energy density for power supply Groundwater impacts from agricultural chemicals Competition with other uses for land and water resources GHG emissions from biomass production and processing Potential to increase GHG emissions from land conversion (e.g., rainforest to biofuels)

Note: CCS is carbon dioxide capture and sequestration. PV is photovoltaics. GHG is greenhouse gas.

mitigating some of the impacts of coal-fired power generation while supporting economic growth and providing electricity to improve the quality of life as people move out of poverty.

The changes in the energy systems of the planet are likely to include multiple linked pathways. For example, a transportation system that relies on electric vehicles could be imagined. That system would require use of one of several potential energy resources, conversion of those resources to some form that could be stored on a vehicle, transportation of the energy carrier to the vehicle, storage on the vehicle, and then conversion to mechanical work to move the vehicle. The primary resources could be solar (including photovoltaics or bioconversions to chemically stored energy), wind, nuclear, waves, tides, geothermal, or a fossil fuel with carbon capture and storage. The energy carrier could be electricity, hydrogen, or a biofuel. A variety of energy conversions could be used for each. Electricity can be made by nuclear power or solar thermal with a steam turbine, whereas photovoltaics produce electrons directly. Biomass can be converted to a liquid fuel such as ethanol by fermentation or by gasification followed by fuel synthesis. Hydrogen can be made by electrolysis or by gasification of biomass. Electrons could be transported by a grid to users or converted to hydrogen. Hydrogen can be stored in tanks (or various storage materials) and burned directly in an internal combustion engine, or it could be converted in a fuel cell to electrons, which could then be stored in a battery and used to drive an electric motor. Finally, electric motors could convert the electricity to mechanical work. Each of the many other energy conversion pathways we use to provide energy services to humans offers similar sets of options, and reinvention of the world's energy systems will offer many opportunities to improve efficiency and reduce greenhouse gas emissions.

Research and Development Needs for Sustainable Energy

Each energy conversion has an efficiency, a cost, and an environmental footprint that will influence where and to what extent it is used, and for some energy conversions, considerable additional development of materials and technologies will be required. Moreover, virtually all energy resources offer interesting research opportunities for the materials science community. For example, much of the work underway now to improve the efficiency and reduce the cost of photovoltaics is aimed at the fundamental science and engineering of the materials used to convert solar photons to electrons (see the article on solar energy by Ginley et al., along with the accompanying sidebars, in this issue), and efficient conversion of electrons to photons for lighting will impact overall energy use (see the article on solid-state lighting by Humphreys in this issue). Advances in fundamental understanding and the ability to create ordered and disordered nanostructures (nanowires and quantum dots, for example) offer many potential paths to adjust bandgaps, increase photon absorption, enhance electron and hole transport, create photonic devices that distribute light, and reduce energy requirements and costs to make devices. Many of the same ideas will find application in fuel cells, which offer the potential of high energy conversion efficiencies. Nanostructured materials will also play a role in electrochemical energy storage; media that are efficient in weight and volume could transform transportation, through advanced battery electrochemistry derived from abundant elements with reduced use of toxic materials (see the article on electrical energy storage by Whittingham, along with the accompanying sidebar, in this issue). The common thread that connects all of these efforts is the ability to optimize the properties of materials in new ways by controlling structure at nano- and microscales and creating very high surface area materials with the potential for high-efficiency electrochemical cycling.

More widespread use of nuclear power will require improved fuel cycles, more efficient conversions of neutron fluxes to electricity, and waste storage isolation for nuclear power, all of which imply development and selection of advanced materials with properties that can tolerate harsh environments (see the article on nuclear power by Raj et al., as well as the accompanying sidebars, in this issue). Materials with high creep strength at high temperature would allow more efficient operation in a variety of power plant settings, and materials that retain their properties in the face of high radiation fluxes will be required if fusion power is to find its way into commercial use.

Questions of biomaterials and related separations abound in the conversion of solar photons to fuels through biological processes (see the article on biofuels by Farrell and Gopal, as well as the accompanying sidebars, in this issue), and improved knowledge of genetics and the ability to design enzymes offers many opportunities to improve the efficiency of biological processes that self-assemble the molecular structures that convert sunlight to electrons and subsequently store energy in chemical bonds. Whether hydrogen is used as an energy carrier will depend on the development of advanced materials for storage, efficient and less expensive catalysts for fuel cells, and methods to produce hydrogen with low greenhouse gas emissions (e.g., solar water splitting) (see the article on hydrogen and fuel cells by Crabtree and Dresselhaus in this issue). Use of abundant elements in new catalytic structures offer potential cost reductions needed for commodity-scale applications of improved electrodes. Catalysts will also continue to play important roles in many chemical reactions, including those that transform biofeedstocks to fuels and other products (see the article on catalysis by Gates in this issue). Improved solid-state electrolytes that allow efficient transport of ions at modest temperatures would expand the range of fuel cell applications and might offer opportunities for separations of oxygen or CO_2 from other gases. Finally, reductions in emissions of CO_2 to the atmosphere could be achieved by use of novel materials that balance selectivity and permeance in the separation of CO_2 from product gases of combustion or gasification processes (that make hydrogen, for example) followed by geologic storage of CO_2.

Summary

Observed changes in the concentrations of greenhouse gases in the atmosphere and in the pH of the upper ocean and observed and projected impacts of those changes indicate that significant action is needed to reduce emissions of greenhouse gases from fossil fuels. Changing the world's energy systems is a huge challenge, but it is one that can be undertaken now with improvements in energy efficiency and with continuing deployment of a variety of technologies now and over the decades to come. Abundant sustainable energy resources are available. However, there are many barriers in terms of efficiencies, impacts, and costs that will have to be overcome. Doing so will require worldwide focus on the challenge and the talents of many participants, and significant contributions from the materials science community will be essential.

Acknowledgments

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