The Global Energy Landscape and Materials Innovation

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Abstract

Availability of affordable energy has enabled spectacular growth of industrialization and human development in all parts of the world. With growth now accelerating in developing countries, demands on energy sources and infrastructure are being stretched to new limits. Additional energy issues include the push for renewable resources with reduced greenhouse gas emissions and energy security affected by the uneven distribution of energy resources around the globe. Together, these issues present a field of opportunity for innovations to address energy challenges throughout the world and all along the energy flow. These energy challenges form the backdrop for this special expanded issue of *MRS Bulletin* on Harnessing Materials for Energy. This article introduces the global landscape of materials issues associated with energy. It examines the complex web of energy availability, production, storage, transmission, distribution, use, and efficiency. It focuses on the materials challenges that lie at the core of these areas and discusses how revolutionary concepts can address them. Cross-cutting topics are introduced and interrelationships between topics explored. Article topics are set in the context of the grand energy challenges that face the world into the middle of this century.

Materials and Energy

Energy and materials have a continual and mutually enriching relationship. Materials produce energy or enable energy to be transferred into useful forms. Energy, in turn, has made possible the production of a broad range of materials for society. Materials for energy come in a near continuum: Naturally occurring materials release energy through chemical or nuclear reactions. These are the fuels we extract from the ground, often burned to release their energy in the form of heat.

Then there are the engineered materials that tap externally available energy and transform it into useful forms. Photovoltaic silicon converts solar energy into electrical power. Wind turbine blades made out of fiber-reinforced plastic transform wind energy into mechanical or electrical power.

Materials also store and deliver energy—the batteries, wires and switches, hydrogen, and biofuels that convert energy from other forms.

Materials then work to realize the ultimate objective of producing energy—its use. This might be tungsten filaments in light bulbs illuminating a century of nights or high-temperature turbine blades rotating in a jet engine. Materials thus have a synergistic relationship with energy, all the way from its generation to its ultimate use.

For the past few centuries, affordable energy, mainly from fossil fuels, has enabled industrialization and human development in all parts of the world. This growth continues, now with the developing countries playing a major role in generating and consuming increasing amounts of energy. To support this growth, new resources have to be harnessed and existing ones improved. Adding to these demands are the growing concerns about the sustainability of various energy sources and the challenges of managing waste, pollution, and greenhouse gas emissions left in their wake. There are also matters of energy security, with resources unevenly distributed around the world and nations vying for energy resources to support their growth.

How can technology and materials research address these issues? This question forms the basis for this issue of *MRS Bulletin*. Whereas the articles discuss the attractions and research challenges in specific energy areas, we are conscious that all of these areas have to be seen in a broader context of developing options for generating and using energy efficiently, economically, equitably, and pristinely. There are connections that can be built between technologies which can be useful in setting the agenda not only for research but also for focused development. The scaling of some of the new technologies, and the emergence of innovations could eventually lead to their competitiveness in a market dominated by well-established but polluting energy giants.

Energy and Human Needs

The choice of materials for energy production has been dictated by the availability and accessibility of the source, its economic viability, and the convenience it offers. There has been a gradual movement toward cleaner fuels from coal to oil to natural gas. Yet, coal remains an important fuel because of its continuing widespread availability and the large infrastructure for its conversion into useful forms of energy. Thus, there is no one unique global fuel for energy generation (**Figure 1**).[1]

However, the impact of energy in improving the quality of life and economic prosperity is global. There is a modest but positive correlation between the gross domestic product (GDP) of a country and the amount of energy it consumes. Generally, developed countries consume more energy than developing countries, but over time, developed countries learn to produce and use energy far more efficiently, and the energy intensity trends downward (see **Figure 2**).

When a country is on the path of rapid growth, it needs far more energy per unit of growth than does a mature industrialized economy.[2] Compared to China, India is yet to reach this threshold of development or to post the same high growth rates.

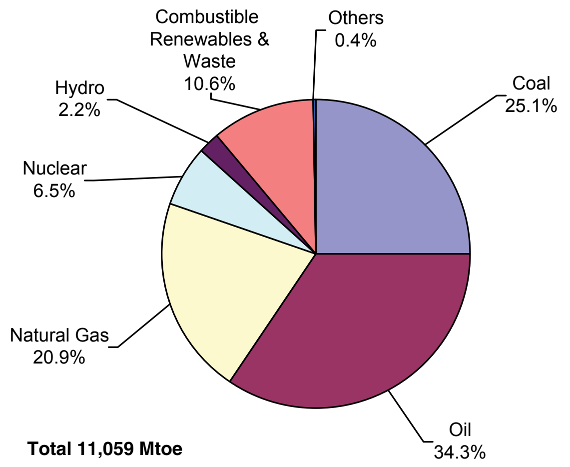

Figure 1. World total primary energy supply (2004) by source. *Note:* Mtoe is million tons of oil equivalent.[1]

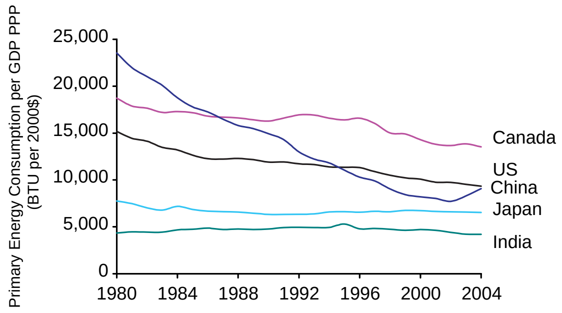

Figure 2. Total primary energy consumption per dollar of gross domestic product (GDP) (BTU per 2000 $) using purchasing power parity (PPP).[49]

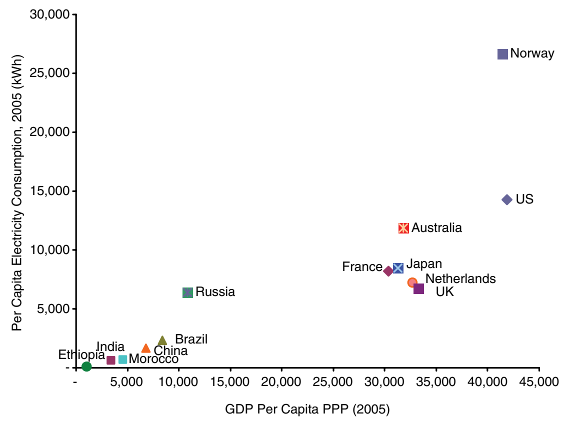

Figure 3. Per capita electricity consumption (kWh) versus GDP per capita purchasing power parity (PPP) of selected countries.[3]

Although developed countries already have well-established sources for generating large amounts of power, they too face energy challenges as they outgrow current energy infrastructures. The U.S. electrical transmission and distribution system, for example, has had an increase in the frequency and size of power outages in recent years.

There is also a welcome and positive correlation of the human development index (HDI)—measuring income, education, and health—with energy use (**Figure 3**). Norway, ranked 2nd in HDI, scores very high in both per capita annual electricity consumption (26,657 kWh) and per capita GDP [PPP] ($41,420).[3] Ethiopia, ranked 169th in HDI, has a per capita GDP [PPP] of about $1,000 and consumes a mere 36 kWh per capita—equivalent to the consumption of a 40 W electric bulb burning for a few hours per day.[3]

Industrialization increases the demands for energy dramatically. The world's total primary energy consumption grew 20 times between 1850 and 2000 to the present value of about 15 Terawatt years per year.[4] Currently, industrialized countries consume a disproportionate share of energy compared to developing countries. The United States, with a population of 300 million (4.8% of the world's population), consumes more than 21% of the world's energy production. India, with a population of one billion (16% of the world's population), consumes just 3.45% of global energy generation.[2] The article by Lave in this issue explores the economics of energy and how economics, both on a global scale and within individual technologies, adds to the materials research challenges.

If all countries of the world were to enjoy the same level of prosperity as the developed nations, would the world run out of energy? Although one might argue that the world has enough energy sources to meet these needs—coal, at the present rate of consumption, will last for 164 years[2]—it is quite likely that such demands will deplete some energy sources rapidly and make others prohibitively costly. India and China having a combined population of 2.4 billion account for only about 12% of world oil consumption.[5] Personal car ownership in China is 9 per 1,000 eligible drivers as compared to 11 in India and 1,148 in the United States.[6] However, China and India are likely to emerge as the first and second largest car markets in the world in the coming decades.[5] The recent announcement by Tata Motors of India that they would soon be marketing a $2,500 car is expected to boost India's automobile density significantly. If car ownership in India and China reaches half the present U.S. level, then another 100 million barrels per day (BPD) will be added to the present world oil consumption of about 83 million BPD.[6] This scenario describes the magnitude of just one of the many energy challenges the world faces. New discoveries and innovations will be needed to meet such challenges.

Energy and Environment

All energy technologies leave an environmental footprint, some more than others. Nuclear power, for instance, produces both long-lived and short-term radioactive waste from which the public needs to be shielded. Even biofuels that are seen as benign can adversely affect the food and feed chains by diverting crops for energy generation. Large hydroelectric dams displace populations and flood agricultural lands. Moreover, a major environmental concern relates to the emission of greenhouse gases contributing to global warming. All combusted fossil fuels emit CO_2, a long-lasting greenhouse gas that is not presently captured and removed from the stack emissions. There have been a number of scientific studies to estimate the extent of global warming. These studies suggest that a temperature rise of 0.6 ± 0.2°C has already taken place in the 20th century. A report of the Intergovernmental Panel for Climate Change estimates a temperature increase of 1.8–4.0°C in the next century.[7] This, of course, depends on the climate model used and the assumptions made about global emissions over the next century. Such temperature increases are likely to cause

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irreversible damage to life on Earth. For example, rising sea levels would pose serious risks for people living in coastal cities such as London, New York, Mumbai, and Shanghai and a few low-lying countries. Because of such concerns, many countries, and even some states and cities, have adopted regulations for limiting CO_2 emissions. There are also emerging trends toward carbon "trading," giving benefits to industries with lower CO_2 emissions and making higher emitting industries pay. Awareness is also growing among consumers to minimize their energy dependence by opting for energy-saving devices such as compact fluorescence bulbs and choosing hybrid cars and biofuels. See **Table I** for a comparison of CO_2 emissions from various energy resources.

Table I: Average Lifecycle CO_2 Emissions from Different Energy Sources.

Energy Source	Lifecycle CO_2 Emissions (g per kWh)
Coal	1,000
Oil	800
Natural gas	400–500
Solar	13–730
Wind	7–124
Nuclear	2–60

Source: References 46 and 53–55.

Reduction of CO_2 in the atmosphere can be achieved by adopting technologies that do not emit CO_2 or by capturing CO_2, compressing it into a supercritical fluid, and injecting it deep underground in specially chosen geological formations or depleted oil wells. (See the article and sidebar by Benson and Orr in this issue.) It would also be desirable to artificially emulate nature's photosynthesis to capture CO_2 from the atmosphere and turn it into fuel. Work on this materials challenge is in its early stages.

Energy Security

Some important sources of energy—such as oil, gas, and uranium—are not equitably distributed across continents. A heavy dependence for resources on just a few countries poses energy security issues. Price and supply volatility for oil and, to a lesser extent, natural gas adds an economic risk. These concerns have encouraged many countries to opt for harnessing domestic or dedicated resources. Brazil, for instance, has become the largest producer of ethanol from sugarcane as a fuel for vehicles. Similarly, Denmark is using wind power to generate 20% of its electricity and plans to increase wind power to 50% by 2025.[8,9]

In addition to the competition for resources to ensure that the needs of citizens and countries are met, another security risk relates to how spent nuclear waste is handled and the potential for its use in developing nuclear weapons. The materials challenge here is one of developing safe long-term storage or finding ways to more efficiently use the nuclear materials to result in safer and nonfissionable waste.

Human-development, environmental, and security concerns converge to make energy a major political and economic issue both locally and globally. The solutions nations pursue to satisfy their energy demands often have consequences that transcend their immediate needs and will require innovations in technology and policy that are yet to be realized.

Energy Flows and Cycles

It is convenient to model the energy system as a directional flow with all possible energy resources flowing into it as tributaries. This flow then branches into distributaries as it is consumed in many ways. Along this path, energy is transformed into convenient forms, stored where necessary, and transported in time to the places of ultimate use. Throughout the process, some of the stream is lost as waste, and some is recycled. Energy tributaries—a few large and some modest in size—come from biomass, coal, oil, gas, sunlight, wind, water, and nuclear materials and are fed to their destinations by electrical grids, pipelines, railways, trucks, and ships.

An energy flow diagram, when marked with appropriate data, provides an integrated view of where the energy comes from, how it is used, and where energy is lost along the way.[10] A conceptual view of energy flows is provided after the Preface in this issue. In addition, **Figure 4** shows two quantitative examples of energy flows, one for the United States and one for India, highlighting the differences of these flows for a developed and a developing country. Biomass, for instance, continues to be a major fuel for primary energy generation in India. What will be the consequences for energy security and greenhouse gas emissions when developing India opts for more efficient fuel? The low automobile penetration in India is reflected in the modest consumption of gasoline in preference to diesel, as diesel has many applications from truck transport to standby power generation. Agriculture in India consumes around 30% of electricity generation, mainly for pumping underground water for irrigation. In this sector, system losses and inefficiencies and proper utilization of government subsidies are difficult to monitor. Can solar energy help? What might be the long-term consequences of underground reservoir depletion? These energy flow diagrams enable us to locate such areas of concern and identify research opportunities to make a tributary contribute more to the energy flow and distributaries work to minimize waste and CO_2 emissions.

Resources (Energy Tributaries)

The resource base for energy production is large and impressive. From biomass to nuclear fusion, the total energy availability can be far higher than the global consumption today. The various fuel resources differ in their energy content, prices, conversion efficiency, waste, and CO_2 emissions.[46, 53–55]

Tables II and **III** summarize the energy content and present availability, respectively, of various energy resources. Evidently, enough resources are available so that the world will not "run out of energy."[4] However, some of the fuels show high price volatility (oil and natural gas), whereas others are more stable (coal and to some extent uranium) (**Figure 5**).

Table IV compares the cost of electric power generation from some of these resources. Still others are covered in the article by Sims in this issue. Some of the resources tend to be highly polluting, with coal, for example, emitting around 1 kg (2.24 lb) of CO_2 for every kilowatt-hour of power generated (**Table I**). There is also environmentally clean solar energy, but it has yet to realize its full potential.

It is convenient to divide the resources into three categories: (1) those presently in use, (2) emerging technologies, and (3) long-term opportunities. In the first category, we consider options and technologies for improving efficiency and environmental performance for sources such as biomass, hydro and geothermal power, coal, oil, gas, and uranium. In the second category, which overlaps the first, are solar thermal and photovoltaics, wind power, nuclear breeder reactors, and biofuels. The third category includes harnessing the power of nuclear fusion and extraction of methane hydrates from ocean beds, technologies that are yet to be fully explored and developed but that embody extensive energy reservoirs.

Coal

Coal continues to be the most heavily used fuel in the world for electric power generation. About 50% of the electricity in the United States and 80% of that in China are generated from this resource. In 2006 alone, the use of coal increased by 4.5%, and China contributed the maximum, around 8.7%, of the total increase.[11]

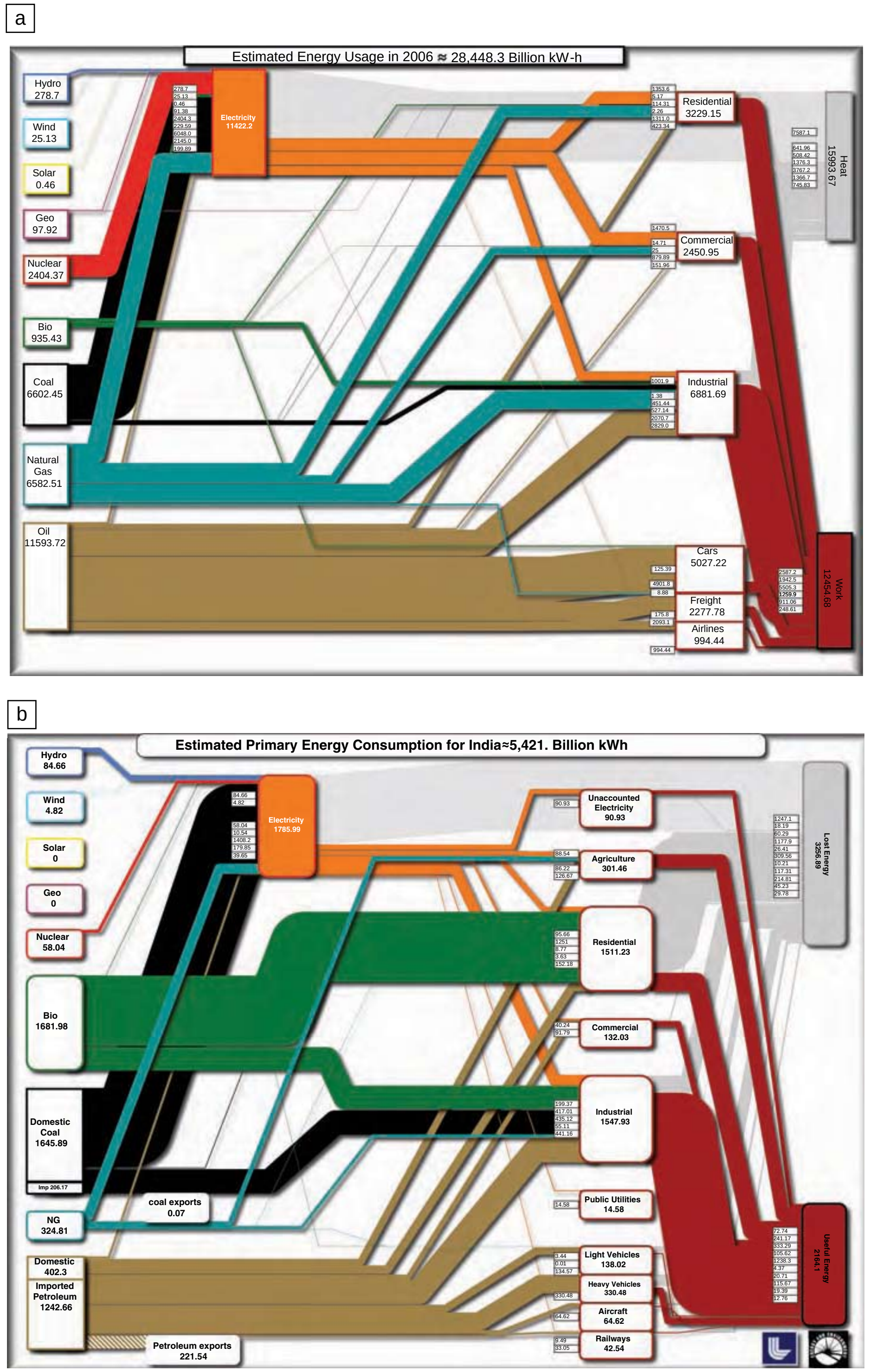

Figure 4. Energy flow diagrams (EFDs) for (a) the United States (2006) and (b) India (2004–2005).[10,50] (Units: Billion kilowatt-hours.)

The attractions of coal are many: It is cheap and widely available, and the cost of power from it is low, at under 5 cents per kilowatt-hour (¢/kWh). Innovations in flue gas cleanup have led to the trapping of pollutants such as particulates, mercury, nitrogen oxides, and sulfur dioxide. However, CO_2 emissions continue to be vented to the environment. Apart from injecting CO_2 into the ground, as previously described, a few options are available for containing this CO_2. These options include locking up the CO_2 by reacting it with minerals such as basalt to produce carbonate minerals, although the kinetics for such a reaction is expected to be slow and might not prove to be practicable. Studies are also being conducted on the possibility of injecting carbonic acid deep into the oceanic sediments for the liquid to form clathrates. In such structures, CO_2 is trapped in a cage of ice crystals that appears to settle down on the sea floor. However, its long-term stability and impact on marine ecology are not known. Although these options are being evaluated for their technical and economic viability, the role of coal in a carbon-constrained energy portfolio will also depend on the costs of CO_2 sequestration. Cost calculations based on a few assumptions suggest that the price of electricity would increase by 50–100% if CO_2 capture and sequestration stages were incorporated into new plant designs;[11] a recent study suggests that the increase could be as low as 30%.[12]

Table V shows how the capital cost and cost of energy change when sequestration stages are included in coal-fired power plants.[11] These costs should decrease with increased experience and learning.

Whereas the installation of CO_2 sequestration systems in existing units is difficult and economically unattractive, it might be possible to erect such systems as an integrated unit in newly commissioned plants. There are a few technology options for designing new plants amenable for CO_2 capture, including integrated gasification combined-cycle (IGCC) plants and oxygen-fired pulverized coal combustion power plants.[11] The IGCC process involves gasifying coal to a combustible gas (syngas) consisting of a mixture of CO, H_2, CO_2, H_2O, and other trace species. The syngas is combusted in a gas turbine, and the waste heat is used to power a steam genera-

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Table II: Higher Heating Values of Various Energy Resources.

Resource	Higher Heating Value (MJ/kg)
Hydrogen	142.0
Natural gas	50.0
Light diesel	46.1
Gasoline	47.3
Ethanol	29.7
Methanol	22.7
Biomass (e.g., wood)	10–20
Coal	14–30

Source: References 11 and 56.
Note: The higher heating value of a fuel is the amount of heat released (MJ) through combustion from 1 kg of fuel source, assuming that the water released in combustion has been condensed to liquid form.

Table III: World Energy Resources and Availability.

Resource	Energy Potential (TWy)
Oil and gas (conventional)	1,000
Oil and gas (unconventional)	2,000
Coal	5,000
Methane clathrates	20,000
Oil shale	30,000
Uranium (conventional)	370
Uranium (breeder)	7,400
Sunlight on land	30,000 per year
Wind	2,000 per year
Fusion (if successful)	250,000,000,000

Source: Reference 57 for uranium and Reference 4 for all other resources.
Note: Current world energy use is about 15 TWy per year.

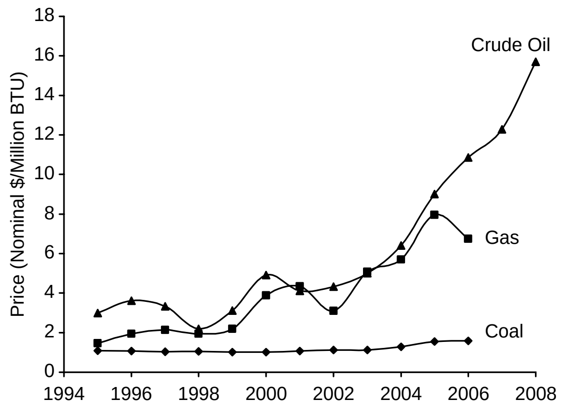

Figure 5. Prices per unit energy of various fuel resources (nominal $/million BTU).[51,52]

Table IV: Costs of Electric Power from Several Sources.

Resource	Overnight Construction Cost ($/kW)	Levelized Cost of Energy (¢/kWh)
Coal	1,300	4.2
Natural gas	500	5.6
Nuclear	2,000	6.7

Source: Reference 29.

Table V: Costs and Efficiencies of Coal Power Plants with and without Carbon Capture and Sequestration.

Energy Source	Capital Cost per kWh	Cost of Energy (¢/kWh)	Efficiency (Higher Heating Value)
Coal (subcritical)	$1,280	4.84	34.3%
Coal with CCS (subcritical)	$2,230	8.16	25.1%
Coal (supercritical)	$1,330	4.78	38.5%
Coal with CCS (supercritical)	$2,140	7.69	29.3%

Source: Reference 11.
Note: CCS, carbon capture and sequestration; subcritical, operating at steam temperatures and pressures below the critical point (generally at 540°C and 16.5 MPa); supercritical, operating at steam temperatures and/or pressures above the critical point (generally at 540–566°C and 25 MPa).

tor. IGCC power plants can operate at higher efficiencies (40–45% higher heating value) than conventional coal plants (35%). Ultrasupercritical pulverized coal units use steam at high pressures and temperatures, leading to higher efficiencies of up to 46%.[11] These conditions would require development of oxidation- and corrosion-resistant high-temperature materials for gas turbines. See the article by Powell and Morreale in this issue on coal combustion technologies for an in-depth look at the materials and processes associated with coal.

Also being studied is underground gasification, where the coal seams themselves would form *in situ* gasifiers expelling carbon monoxide and hydrogen (syngas) used in a gas turbine.[13] Preliminary economic analysis suggests that carrying out gasification underground could prove to be more economical than building gasifiers above ground. The environmental consequences of underground gasification require further analysis.

Coal gasifiers can also be integrated with high-temperature, ceramic-based, solid-oxide fuel cells. These fuel cells can utilize the syngas directly from the gasifier. Details of these processes and the materials challenges involved both in building the combustors and turbines and in purifying hydrogen are discussed in the article by Crabtree and Dresselhaus in this issue.

Oil/Gas to Biofuels

Oil industry professionals use a construct known as Hubbert's peak to estimate the amount of recoverable oil from known reserves. This construct is based on the observation that the rate of extraction from a finite source peaks when half of the oil reserves have been exploited, and then the extraction declines to uneconomical levels.[14] Based on known reserves, it has been estimated both that the peak for world production of oil should have already occurred[15] and that it will not occur in the near future.[16] In either scenario, without new oil discoveries or methods of extraction, oil production would start to decline after the peak has been reached. There is even less unanimity on when world oil production will reach its peak when new discoveries of accessible oil are included in the discussion: Saudi Arabia reports no end in sight for at least 60 more years. The recent BP Statistical Review of World Energy quotes the proven reserves-to-production ratio to be 40.5 years, with the reserves estimated to be over one trillion barrels.[17] Regardless, the rate of use of oil consumption continues to grow, with nations vying with one another to sign agreements for guaranteed supply. The world consumption has grown to 83 million barrels per day from 48 million barrels per day in 1970.[18] A recent report by the National Petroleum Council addressed some of the "hard truths" facing the oil and gas industry this century, and these findings are addressed in the article by Holditch and Chianelli in this issue.

Natural gas entered as an attractive alternative fuel and has replaced oil for many applications. The cost of liquefying natural gas has come down significantly in recent years, and transportation of liquefied natural gas aboard large ocean-going tankers has extended the availability of natural gas beyond the limits of pipelines. The CO_2 emission is low (about 500 grams per kWh as compared to 1,000 grams per kWh for coal), and the proven reserves-to-production is over 60 years at the present rate of consumption.[17] The Russian Federation is the largest producer and also the largest consumer of natural gas. As in the case of oil, the Middle East has large reservoirs of natural gas. When the price of natural gas was low, many countries chose it for electric power generation. However, as the demand for this resource increased, so did its price.

If the oil extracted from conventional wells becomes scarce and costly, are there other options? Canadian and Venezuelan oil-containing sands are seen as potential substitutes. Oil sands contain clay, sand, water, and bitumen (a very heavy condensate of oil), and the Canadian reserves alone are estimated to contain around 175 billion barrels of oil.[19] Because of the low concentration of hydrocarbons, the extraction processes are more involved, including mining of the sands and technologies for stripping bitumen from them and refining the heavy oil. The environmental sustainability of such extraction processes has been questioned because of the demands made on water, energy for extraction, and disposal of waste sands. Availability of appropriate structural materials that can resist hot corrosion and high temperatures can also be an issue.

Yet another stash of fossil fuel deposits is described by Rath, in a sidebar to the article on oil and gas in this issue. Methane hydrates—essentially ice-like cages with methane trapped inside—line most of the continental shelves, kept cool in ocean sediments and permafrost regions. Estimates suggest that this resource exceeds twice the amount of all other recoverable and nonrecoverable fossil fuels. However, the risks, benefits, and methods of extracting these deposits are still being weighed, so this resource is not ready to contribute to energy needs in the near future.

There is also the option to produce liquid fuel from coal, using Fischer–Tropsch (FT) synthesis. This process involves the gasification of coal, mentioned earlier, to produce syngas. Using the water–gas shift reaction to adjust the ratio between CO and H_2 in the syngas to desired levels and using appropriate FT catalysts, synthetic fuels (popularly known as synfuels) ranging from light hydrocarbons to waxes can be produced. However, the process of making liquid fuels involves CO_2 emissions. Without carbon capture and sequestration, synthesis of liquid fuels from coal emits about 50% more CO_2 than use of conventional gasoline or diesel.[11] The advantage of FT synthesis for some countries appears to be the ability to use a plentiful, locally available raw material (coal) to produce liquid fuels, thereby reducing dependence on nondomestic oil sources. China is known to be building two plants with South African collaboration, each with a capacity of over 80,000 barrels a day. If India and China opt for this route, CO_2 emissions from the two countries would increase significantly.

Are there alternate strategies for replacing fossil fuels using sustainable sources without CO_2 penalties? Many countries are now exploring such opportunities for making biofuels from agricultural produce and wastes, as described in the article on biofuels by Farrell and Gopal in this issue.

Brazil has been the first country to commercially produce large amounts of ethanol from its sugarcane harvests as a substitute for gasoline. Various grades of fuel ranging from 5% ethanol in gasoline to nearly 100% ethanol are now in production and use. Brazilian industries are also manufacturing fuel-flexible vehicles that can run on gasoline, ethanol, or any mixture of the two. Because ethanol is corrosive to some of the materials used in the automobile engine, engines resistant to such deterioration have been produced. Whereas Brazil is producing ethanol from sugarcane where the ratio of energy output to input is greater than five, this ratio for ethanol produced in the United States from corn is more modest at 1.34,[20] for net energy production of 4–5 MJ per liter.[21] Questions have been raised about the desirability of diverting produce now used for human consumption and animal feed from the food chain to ethanol production. For example, there have been reports about the escalating cost of corn and scarcity of soybean planting, which was abandoned because of the attractive marketability of corn for ethanol. Also recent studies have suggested that a "biofuel carbon debt" could result, depending on the type of vegetation that the biofuel crops replace.[22,23]

However, the real race for plant-based ethanol is in developing an economically viable and socially sustainable route for producing it from cellulose (see the sidebar by Wyman in this issue). If successful, the energy payback can be as high as 14:1. Several technological pathways are available, some of which are shown in **Figure 6**.[24] A few large-scale experiments on the production of cellulosic ethanol have been reported.[25,26] These developments are of increasing interest because such processes would not interfere with the food chain and the energy inputs for cultivation would be minimal. Moving toward even greater levels of engineering, Gust et al., in a sidebar to the biofuels article, discuss engineered and artificial photosynthesis to learn from and enhance what Nature creates.

Meanwhile, a number of initiatives to use the fruits of oil-bearing plants to produce biodiesel have been launched. Jatropha, a hardy plant that grows wild in many parts of the tropics, is attracting a great deal of attention. The energy input required to grow this plant is not large, nor is this crop in the food chain. Detailed economic analysis of the manufacturing of jatropha-derived diesel is not yet available. Even though the acreage required for cultivating jatropha is large—for India, it would be the third largest after rice and wheat—it has been suggested that wastelands could be brought under jatropha cultivation.[27]

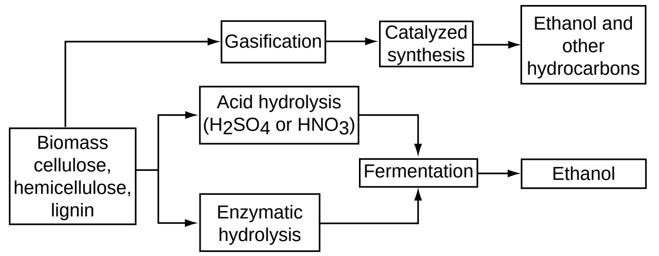

Figure 6. Conversion pathways for ethanol from cellulosic biomass feedstock.[24]

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Nuclear Power

After many years, nuclear power is re-emerging from the shadows in the United States, whereas France already obtains 78% and Japan 27% of their electric power from nuclear sources.[28] Nuclear power reactors do not emit CO_2, and the entire nuclear cycle has a modest CO_2 footprint. Although fears still linger after the Three Mile Island (1979) and Chernobyl (1986) accidents, the safety record and energy production of nuclear power plants since that time provide a new perspective. Worldwide, 443 power reactors with an installed capacity of 370 GW of electrical power have produced over 2,600 billion kWh annually without a major accident in over 20 years.[28] However, reactor safety is still an important factor in nuclear plant development, along with issues concerning nuclear waste disposal and prevention of nuclear weapons proliferation. Cost is also an issue. Nuclear power stations tend to be at least 15–30% costlier than conventional coal generation and are also capital intensive.[29]

Nevertheless, nuclear power is an established technology that has the resources and the potential to meet a significant part of global energy needs in the coming decades, until the world fully realizes the potential of other low-CO_2-emitting energy sources. The world uranium reserves are estimated to be 4.7 million tons. At the current annual rate of use, the present proven resources are adequate for over 85 years of operation.[30] If the capacity is increased to 530 GW electrical, the annual consumption of uranium would be 100,000 tons, adequate for about 40 years.

Materials options can help extend the service life of presently operating reactors. Most of the nondestructive testing technologies specially developed for examining the integrity of structural components suggest that the lifetimes of the presently operating nuclear reactors (specifically light water reactors) can be extended by about 20 years. Economists estimate that this extension of service life alone is equivalent to 40% of the cost of building a new reactor.[31] The lessons learned from the life extension exercise suggest that, for newly designed light water reactors, the steel of the pressure vessel that contains the core and its components could be compositionally tailored to handle high temperatures and radiation levels without failure. Components that are more tolerant to radiation will reduce degradation, allowing the reactors to operate up to a burn-up of over 100,000 megawatt-days per ton of uranium fuel,[29] almost double that of current reactors.

Furthermore, there are ways to extend the useful energy extracted from nuclear materials. Light water reactors and pressurized heavy water reactors use natural uranium or slightly enriched uranium containing about 4% of the ^{235}U isotope as the fuel. In natural uranium, the isotopic content of ^{235}U is ~0.7%. The rest of the fuel is ^{238}U, which is not fissionable. However, during irradiation in the reactor, ^{238}U is transmuted to plutonium, which is fissionable and can be used as a fuel. In the open-cycle system, the spent fuel is not reprocessed to extract plutonium. Instead, it is treated as nuclear waste and safe-guarded. In the closed-cycle system, the spent fuel is reprocessed to extract plutonium which can amount to a few kilograms per every ton of spent fuel. The plutonium can be used as the fuel for enriching uranium—substituting for ^{238}U—or as a highly enriched fuel in itself. In highly enriched fuel, it is possible to transform more ^{235}U into plutonium and thus "breed" more plutonium in the reactor. Such reactors, known as breeders, can also be designed to produce ^{233}U—another fissionable isotope of uranium—from the naturally occurring element thorium; this approach is under study in India, a country rich in this resource. See the article in this issue by Raj et al. for more information on nuclear power.

A prototype fast breeder of 500 MW capacity is presently under construction in India. Breeder reactors offer opportunities for extending the fuel resource base by at least a factor of 60. However, some major concerns arise in terms of reprocessing the spent fuel. Plutonium is an ideal material for nuclear weapons, and reprocessing of the spent fuel could make this material more readily available to terrorists and to states keen on acquiring nuclear weapons. This concern is discussed by Hecker in a sidebar to the article on nuclear power in this issue. The other major concern about the safe handling of nuclear wastes is discussed in the sidebar by Ewing.

For nuclear power without the issues regarding radioactive uranium and plutonium, one can turn to nuclear fusion. In fusion, nuclei of smaller atoms are fused into a larger nucleus, releasing a large amount of energy. The ITER project, which is an international program to demonstrate the scientific and technological feasibility of fusion energy, is a next step toward determining the materials that would be needed to contain such a reaction, although results from this project are not expected for decades. According to ongoing progress reports, the ITER program (http://www.iter.org/) expects to be able to build a prototype fusion power plant of 1.5 gigawatts electrical, based on magnetic confinement of plasma by about 2050.

The economics might prove to be the determining factor in choosing nuclear power. Recent studies have suggested that, depending on local conditions, nuclear power has the potential to become cost competitive and could be a major route for containing CO_2 emissions.[32] In addition to accounting for CO_2 reduction and decommissioning costs, the economic analysis would also have to account for the risks and uncertainties associated with nuclear waste and the potential for nuclear weapons proliferation. Such a detailed cost analysis is not presently available.

Solar

Unlike other resources, solar energy is almost limitless. Several parts of Earth receive good solar radiation of about 600–800 watts/square meter. An hour of solar radiation on Earth provides 14 terawatt-years of energy, almost the same as the world's total annual energy consumption.[33,34] Solar energy is nonpolluting and is available on all continents. If only it were easy to capture the solar radiation and store the energy efficiently, there would be no global scarcity of renewable and clean energy. Presently, solar collection contributes only a tiny amount (about 0.03%)[17] to the world's energy needs, but the annual growth of solar cell market is impressive, at about 40% per year, led in particular by Germany and Japan. The article by Ginley, Green, and Collins in this issue focuses broadly on a range of solar developments.

There are two routes for solar energy generation: solar thermal and solar photovoltaics. In the solar thermal approach, the sun's radiation is converted to heat that is either used directly, for instance, for passive water heaters, or concentrated, known more commonly as concentrating solar power (CSP). In CSP technologies, the heat is used to operate a steam generator to produce electricity. In solar photovoltaics, semiconductors are used to convert solar radiation into electric energy, which can be either used locally in autonomous systems or connected to central power grids.

The efficiency of CSP plants can be around 15–20%, but the installation and generation costs are high, almost five times those of coal.[35] To generate about 12 terawatt-years of energy, large land areas are needed, around 50–75 million hectares. More information on CSP can be found in the sidebar by Mehos in this issue. Thermal energy from the sun can be converted into energy using thermoelectric materials. Waste heat from other industrial processes can also be used to generate thermoelectric energy. Thermoelectric materials are covered by Tritt, Böttner, and Chen in another sidebar in this issue.

The specifications for solar photovoltaics developments are multifold. The cells have to be efficient and stable, and the cost of manufacturing should be competitive. Semiconductor photovoltaics are showing recent impressive efficiency gains. The first generation of solar sells based on single-crystalline silicon can attain conversion efficiencies of 10–15%, and solar cells made from cadmium telluride (CdTe) can attain even higher efficiencies, around 20%. Multijunction thin films, with several layers matched to capture different wavelengths of light, can achieve 40% conversion efficiency.[36,37]

The solar cell family includes thin films, amorphous structures, and polycrystalline materials, each providing its own advantages either in cost or in the efficiency of conversion. Furthermore, quantum-dot structures with very high efficiencies approach theoretical limits. Organic photovoltaics, on the other hand, compensate for their low efficiencies with the promise of lower manufacturing costs.

Although the performance of solar power is impressive, its costs continue to be daunting: an average of $0.25 per kilowatt-hour versus $0.05–0.08 for various biomass-based fuels.[38] **Figure 7** compares the costs and performance of solar energy to those of biofuels and wind from the same land mass.[39]

The U.S. Department of Energy specifies that the initial capital cost to the end user of grid-tied photovoltaic systems should be reduced to $3.30 per peak watt from $6.25 per peak watt in 2000.[38] Another requirement has to do with toxicity concerns about materials used in the manufacturing of photovoltaic modules. The use of CdTe, which can be toxic at high levels of lung exposure, is a case in point.

To make photovoltaics affordable, it is necessary to bring down the manufacturing costs by using polycrystalline materials and thin films that can be grown into long amorphous ribbons, amenable to large-scale production.

A major competitor to inorganic photovoltaics is the emergence of organic-based photovoltaics, which have very different operating mechanisms. Excitons—closely bound electron–hole pairs—are first generated and then decomposed into free charge carriers at interfaces. The active layers of such systems have to be kept very thin because of the low mobility of charge carriers.

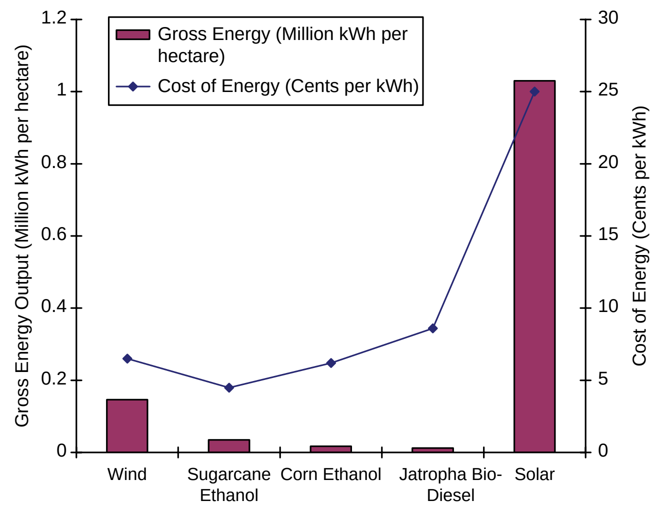

Figure 7. Gross energy output (million kWh per hectare) and cost (cents per kWh) of resource produced from 1 hectare of land for several renewable sources of energy.[39] In the case of wind and solar, the output resource is electricity, whereas in other cases, it is the energy contained in biofuel.

A few new schemes attempt to solve some of the intrinsic deficiencies of organic photovoltaics and include the incorporation of dyes that enable better absorption and conversion of the solar spectrum, organic–inorganic composites, and nanocomposites that help add more charge carriers. Even though some of the initial problems, such as rapid degradation of performance, have been overcome, many technical and manufacturing challenges remain to be addressed. The efficiency has to be improved to better than the 5% presently obtained in laboratories, the operating lifetime has to be raised without degradation of performance, and the manufacturing of polymers containing mixtures of inorganic nanostructures will have to be manufactured efficiently and cheaply at a large scale. Considering the speed with which liquid crystal displays (LCDs) are replacing conventional displays (some have predicted that LCDs will soon become as cheap as acrylic paints used for painting homes), organic semiconductors are ripe for becoming a similarly disruptive technology.

Because of the cyclical nature of solar radiation, it is necessary to install adequate storage systems to match supply and demand. In an earlier article in *MRS Bulletin*, Smalley recommended distributed storage systems to provide for base-load needs.[40] The attractions of sustainability and clean energy without any greenhouse gas emissions make solar energy a compelling option.

As research continues toward achieving higher efficiencies, lowering costs, and developing novel materials, diverse regions of the world are embracing current solar technologies. A sidebar by Palucka covers the California Solar Initiative, a $3.3 billion program to generate 3 GW of electricity by 2017 by encouraging solar cell installations on the roofs of residential and commercial buildings. Soboyejo and Taylor, in a sidebar about off-grid solar power, focus instead on the two billion people on the planet who do not have reliable electric services. They describe how simple solar-electric systems can help some of the rural populations in Africa, Latin America, Asia, and island nations obtain basic services.

Wind Energy

In contrast to solar power, wind power is a mature technology, contributing over 73 GW of capacity in 2006.[41] The global annual wind energy generation at locations with wind speeds in excess of 6.9 m/s at 80 m above ground is estimated to be around 72 terawatt-years.[42] Thus, 20% of this resource can meet the world's total energy requirements; however, several practical barriers prevent its full potential from being tapped.[42] Because of its dependence on wind speed, the locations where wind power generators can be installed are limited. Although there have been impressive innovations in control engineering in directing the fans toward the wind direction and even altering the pitch of the blades to suit wind speeds, the limiting factors of this energy resource are inherent to the nature of wind power itself, namely, their dependence on location and the intermittence of power generation. The efficiency of wind power is about 20%. Off-shore turbines are an option, but they might prove to be expensive because of the challenges of accessing these locations and the harsh environments that must be tolerated.

To increase efficiency, wind turbine rotor diameters have increased to as long as 110 m. Such sizes demand materials with stable mechanical and environmental properties. Composites such as fiber-reinforced plastics and foam structures are now the mainstay. Carbon composites have also become popular because of their availability—made possible as a result of their use in the aerospace industry. However, the needs of wind energy turbines are different from aerospace requirements. The blades have to be stiff to prevent excessive deflection and strong to prevent buckling failure. Fatigue can become a major problem because of alternating stress due to rotation. The article by

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Hayman, Wedel-Heinen, and Brøndsted in this issue discusses the materials issues related to wind power.

Carriers, Storage, and Transformations

Hydrogen as a Fuel?

To many, calling hydrogen a source of energy is wrong, as free hydrogen does not occur in nature but rather has to be derived from other primary energy sources. Instead, it should be seen as an energy carrier just like electricity. Unlike electric power, however, hydrogen can be stored, though not yet at high energy density. Despite these limitations, the use of hydrogen as a prime mover is being pursued in laboratories and pilot experiments, because hydrogen, once produced, is a clean fuel and its use is nonpolluting. Its energy content on a weight basis is almost triple that of natural gas. It is also an ideal fuel for fuel cells, which can, under many conditions, generate electric power more efficiently than a combined-cycle gas turbine.[43] The challenges, then, are to generate hydrogen efficiently with minimum CO_2 emissions and to store it efficiently. The density of hydrogen is so low that, even in its liquid state, its volumetric energy density is one-third that of gasoline. The use of hydrogen as a fuel for transportation would require technologies that can store enough hydrogen to provide power for a distance of 300–400 miles (480–640 km).[44] This goal calls for storage either as a liquid (although 30–40% of its energy is sacrificed in liquefying it) or as complex metal hydrides that would be able to store the gas with a volumetric density of 81 kg/m^3 and release it efficiently near 70–100°C. Such storage materials would also need to be recyclable and to have rapid kinetics for hydrogen release and absorption. Presently, no chemical compounds have emerged that meet all of these conditions.

Crabtree and Dresselhaus, in an article in this issue, estimate that the world hydrogen production will have to increase from the present 60 million tons to 600 million tons to power the global fleet of cars and light trucks by 2030. Where would we get this hydrogen? Because hydrogen is not a primary energy source, it has to be produced from other sources such as coal, natural gas, or water. Some of these sources contain carbon, meaning that the hydrogen production process would involve CO_2 emissions. Steam reforming of natural gas is a commercially available technology and accounts for the bulk of hydrogen production today. Our estimates based on results in References 45 and 46 suggest that about 2,000 million tons of natural gas would be required to generate the desired quantity of hydrogen. Present world production of natural gas is about 2,100 million tons, and thus, this process would double the demand for natural gas. This process would also involve about 5,000 million tons of CO_2 emissions, which would have to be captured and sequestered. One potential advantage of this option, though, is that CO_2 emissions are concentrated at the source and hence more amenable for capture.

Coal gasification followed by the water–gas shift reaction is another technology option for hydrogen production. We estimate that it would require about 4,500 million tons of coal to produce 600 million tons of hydrogen based on results in References 45 and 46. Present world coal production is 6,400 million tons. This process is more carbon intensive than the use of natural gas; CO_2 emissions would be in excess of 10,000–15,000 million tons and would have to be sequestered.

Extracting hydrogen from water is theoretically the "heart" of the hydrogen economy. Water molecules could be split to generate hydrogen, which would then be oxidized in a fuel cell to produce electric power at high efficiency, emitting pure water. However, electricity for splitting water molecules must come from renewable sources, or it will be coming from the very fossil fuels that hydrogen aims to replace. About 31,000 billion kWh of electricity would be required to produce 600 million tons of hydrogen from water. Present world electricity generation is about 18,000 billion kWh, and electricity from renewable sources is a mere 370 billion kWh. Clearly, renewable sources are nowhere near the level required to make the required amounts of hydrogen. Both major innovations for generating hydrogen free from CO_2 and commercially viable technologies for storing it are needed before hydrogen can substitute for fossil fuels.

Fuel Cells

Hydrogen as a fuel or carrier of energy is never discussed without invoking fuel cells, its prime mover. Fuel cells have a high efficiency of about 50–60% and low emissions. They are modular and can be distributed. They cause no noise pollution. But they are expensive. For fuel cells to become competitive, the cost must be reduced to the same level as that of an internal combustion engine, taking into account the cost of fuel and the efficiency of operation. In a fuel cell, electro-oxidation of hydrogen takes place at the anode, thereby liberating protons and electrons; the protons migrate through the electrolyte to the cathode and participate in the electro-reduction of oxygen. Electric power generation results from the flow of electrons through an outside circuit. Electrolytes are available through which protons, hydronium ions, hydroxide ions, or carbonate ions are mobile, giving rise to different types of fuel cells. Fuel cells are complex because of the restrictions imposed on materials, that is, the electrodes and electrolytes used and their design. A number of auxiliary components are needed such as systems for gas purification to eliminate CO and CO_2, pressurization, and cooling. Often, it is an auxiliary component, and not the fuel cell itself, that fails. However, recent breakthroughs in both electrolyte and electrode materials for solid electrolyte systems are envisioned to greatly simplify fuel cell design.

Solid-oxide fuel cells are reliable for continuous operation. Although they have to be operated at high temperatures, around 600°C, a 100 kW system can typically run for 20,000 h without degradation. A variety of hydrocarbons can be used as fuel, and yttria-stabilized zirconia is commonly used as the electrolyte. The other candidate electrolyte materials are doped ceria, doped lanthanum gallate, and doped barium zirconate. Current research focuses on direct electrochemical oxidation of fuels at anodes, where the hydrocarbon fuels react directly with oxygen ions without intermediate reaction steps involving water. Electrolytes are being replaced with solid acids with properties intermediate between those of normal acids and normal salts. Research on materials for solid-oxide fuel cells and polymer electrolyte membrane fuel cells are expected to result in simpler designs and more reliable operation. Large-scale deployment of fuel cells awaits advances in hydrogen production, storage, and use, as well as understanding of phenomena at the nanoscale. The growth of the fuel cell industry will depend on how efficient and robust the cells become and how the scale of production brings down the cost.

Energy Storage and Flow

Energy must be moved from its source to where it is needed. In the case of liquid fuels, transportation occurs by means of pipelines, trucks, and other carriers. In the case of electricity, movement occurs through the electrical grid. For renewable sources, storage systems are needed to convey the energy produced to the grid and for use in mobile electronics. in each case, there are losses along the way. The collective electrical transmission and distribution losses are on the order of 7%, although they vary from country to country. There are losses in the case of petroleum and natural gas due to spills and leakage, with environmental consequences. In all cases, conversion of matter to facilitate transport or storage adds further to the inefficiencies of getting energy from source to use.

With the increase in demand for electricity and multiple sources of energy feeding into the flow, the grids must become versatile. In their article in this issue, Amin and Stringer present the concept of a smart, self-healing grid that quickly senses and switches the flow as needed. Such a system would identify surges, downed lines, and outages; control damage instantaneously; balance loads reliably and dynamically; and be less vulnerable to terrorist attack. Although upgrading the grid to digital technology will have the most significant effect, materials are important enablers. Nanomaterials for small but sensitive sensors, piezoelectric materials that respond to electrical signals, and semiconductors that can endure high powers and high temperatures are entering the mix, bringing strength and agility to the grid. The future might hold opportunities for wires strengthened with carbon nanotubes, superconducting wires with no losses, or systems in space to capture and beam energy back to Earth. Additionally, the concept of micropower sources, for example, salvaging energy from the environment for self-sufficient wireless sensor nodes and networks, have a role, which is considered in the sidebar by Steingart, Roundy, Wright, and Evans.

Although electricity is a versatile transporter, it cannot be stored like fuel. Batteries are a convenient way to tap into electrical energy and carry bits of it away from the outlet, but their capacity and power is insufficient for handling the demands of large power generators. Remarkably, one of the most cost-effective ways to store large amounts of energy is to use it to pump water uphill, recovering as much as 75% of the energy as hydropower as it later flows downhill. However, this option is impractical, for instance, for driving a car.

Battery technology has progressed through lead acid and nickel–cadmium systems, to nickel–metal hydride batteries, and now to lithium-based systems and systems based on nanomaterials. (See the article by Whittingham in this issue.) Sodium–sulfur systems are being used for large-scale applications, and supercapacitors are beginning to find a role when high power is involved. Whether for portable applications such as cells phones and hybrid cars or for static applications such as backup systems, load leveling, and storing energy generated by alternative energy devices, the growing demands on energy storage require leaps in storage capacity and power output, as well as reductions in cost, paralleling Moore's law in the semiconducting industry that has guided rapid doubling of computing power for many decades. Recent progress in batteries includes development of compounds with crystal structures that promote Li ion mobility, use of silicon nanowire anodes that can contain higher amounts of Li without breaking during charge/discharge cycles, and "just-in-time" batteries in which silicon nanograss is used as an electrode. The contact angle of a liquid on the nanograss is modified so as to isolate the liquid electrolyte, and electrochemical reactions do not take place until power is actually needed.

Catalysts

In addition to the flow and storage of energy, reactions and transformations among types of energy occur. Although not a source, carrier, or user of energy, catalysts play an important role in facilitating the transformation of materials. From the refining of oil and breakdown of cellulose to the liquefaction of coal and operation of fuel cells, this unique brand of materials orchestrates the chemistry of reactions while remaining hidden from view. By opening new reaction pathways and forming intermediary compounds in a chemical dance, catalysts speed reactions by orders of magnitude, lower energy barriers, and increase efficiency. They take many forms, such as porous materials and oxides, and face challenges of their own. The article by Gates et al. in this issue covers the basics of catalysts, particularly as applied to oil and biofuels. The table in that article lists the catalysts used in petroleum refining, sulfur and nitrogen removal, the water–gas shift reaction, and methanol synthesis, for example. The recent approach of modifying the subsurface of a platinum catalyst while retaining the platinum skin holds much promise. In the solar route to splitting water to produce hydrogen, a few photocatalysts are under scrutiny. There is also the possibility of catalytic conversion of CO_2—a case of a distributory (or adversary) turning into a tributary?

Energy Use and Efficiency

In earlier sections, we focused on energy generation and distribution, the so-called supply side. There is also another dimension for increasing the availability of energy, namely, the demand side. Here, achieving efficiency in delivery and consumption is the imperative. Judkoff, in his article in this issue on buildings, provides an example of a commercial building that uses 65% less energy than other buildings under equivalent building codes; it saves energy through a range of features including photovoltaics, passive heating, and sensors. Likewise, Kusakabe, in a sidebar to the buildings article, describes a "super-green factory" in Japan that makes use of a distributed power system that reduced CO_2 emissions significantly. Bonfield, in another sidebar, details the role of materials scientists in seeking low-environmental-impact alternatives to the raw materials for construction.

The majority of innovations for improving efficiency tend to be incremental, but there are a few exceptions. For instance, high-strength low-alloy steels can substitute for heavy steel in automobiles. A more radical innovation involves integrating the automotive bodies with the frames, which reduces the weight of the vehicles significantly and thus saves energy.[47] The article in this issue by Carpenter et al. on road transportation explores lightweight materials for power trains, hybrids, and tires. Reducing the weight of materials while maintaining strength and durability is particularly important for air travel. The sidebar to the transportation article by Banerjee focuses on the unique materials needs in aviation.

The hybrid engine is an outstanding example of radical innovation. Here, the electric motor, under certain driving conditions, substitutes for the internal combustion engine and also improves energy efficiency by charging the battery with the energy dissipated during braking. More importantly, CO_2 emissions are reduced when the electric motor takes over. With all-electric automobiles, now under development and in use in small numbers, no CO_2 is emitted during driving, although total CO_2 emissions depend on the electricity source. Even if energy from coal-fired power stations were used for charging, the CO_2 production would be shifted from tailpipes to large generating stations, which would facilitate carbon capture and sequestration by centralizing the CO_2 emissions. However, the benefits of this approach would be dependent on the ability to achieve such capture. Large-scale substitution of hydrogen for gasoline and fuel cells for internal combustion engines will have to wait for the development of efficient storage and distribution systems for hydrogen. Fuel cells will also have to become more robust and cost-effective.

Another case ripe for substitution is the switch from incandescent light bulbs with more efficient light sources such as light-emitting diodes (LEDs). Lighting consumes more than 20% of generated energy in many countries. Tungsten filament bulbs continue to be fragile, with a lifetime of a mere 1,000 h and an efficiency of 5%. Compact florescence lamps have an efficiency of over 15%, but contain mercury. LEDs have

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efficiencies of 30% and above and can last as long as 100,000 hours of continuous operation—but they cost more, and thus, it takes years to recover the cost of the bulb. The illumination from LEDs is also more directional than that from filament bulbs, so further developments might be needed to obtain a quality of light acceptable to the consumer. The article by Humphreys in this issue discusses in detail the materials issues that must be resolved to enable the generation of white light with acceptable characteristics and a higher efficiency of around 50%.

As described by Gielen, Newman, and Patel in their article in this issue, industry accounts for one-third of the primary energy supply and provides opportunities for innovation not only to improve efficiency but also to reduce carbon emissions. Achieving increased efficiency and reduced emissions in industry feeds back to the very start of the energy cycle: industry refines the energy sources and makes the materials that supply new (and old) technologies. The iron and steel industry consumes over 19% of the total industrial energy supply. Many pilot-plant experiments have been aimed at improving the energy efficiency in iron making by substituting blast furnaces with reactors that would not require the coking of coal or iron ore agglomerates or sinters. A recent innovation, Finex®—developed by a South Korean Corporation, Posco—for instance, operates with ordinary coal and iron ore fines. Even coke oven batteries in integrated steel plants can be made more energy efficient by utilizing coke oven gases for hydrogen recovery, methanol synthesis, and electric power generation. Coke oven gases could also possibly be used for direct reduction of iron ores.

Cement manufacturing competes with iron and steel in annual CO_2 emissions, at around 1.7 trillion kg per year. A large fraction of the emissions comes not from energy generation but from the process itself, specifically the making of clinkers at high temperatures. When the process is not optimized, CO_2 emissions can be as high as 1 kg of CO_2 for every kilogram of cement produced. Many attempts have been made to minimize energy consumption and reduce CO_2 emissions by opting for substitute materials such as blast furnace slag and fly ash from coal-fired power stations instead of clinkers.

If these innovations enhance performance and are energy-efficient, why are they not widely adopted as they are developed? The dissemination of innovations is a complex process. Some, such as the Internet, have had a remarkable penetration into the market. These are the disruptive technologies that provide goods and services in new ways in areas where none existed or where those that did exist were not profitable. Most innovations, however, are incremental and tend to be costly in the beginning. They are perceived as being for the public good rather than for private profitability. For instance, minimizing CO_2 emissions, in the absence of commercial benefits, might not be seen by firms as necessary for a company's profitability. According to Paul David, a professor of economics at Stanford University, even electricity took more than 100 years to become commonplace in the U.S. industrial infrastructure.[48]

Part of the reluctance to implement new technologies might relate to the associated efforts required to create new supply chains and develop appropriate inspection protocols and structures. With an industry as immense as energy, even small changes involve large risks. New processes, to start with, are not economical and might also not realize their full potential. Unless there are market externalities, barriers associated with the new technologies might not be surmounted. The externalities can be in the form of tax incentives or the imposition of taxes that make the old processes less competitive and give newer technologies a boost toward the benefits of mass production. Both Germany and Japan are providing incentives to sustainable energy generators whereby electricity grids are mandated to buy power from such providers at costs that are attractive to the producers of power. In Bangalore, India, new home builders are mandated to install solar water heaters in preference to heaters powered by electricity. Externalities can also take into account costs to society that are not explicitly paid during production. Carbon pricing, for instance, can make newer innovations competitive if they have reduced carbon dioxide emissions. Will such incentives make solar energy competitive? Solar energy proponents maintain that there has not been a sufficient increase in the scale of production nor has there been clearly defined market support from many governments that could have brought the cost of the resource down. Likewise, what factors might make LEDs commonplace for general lighting? Both the market support and new technologies that can bring down the learning curve dramatically (**Figure 8**) are part of this process.

The articles in this issue describe many of the scientific challenges in materials research that can enhance performance and lead to disruptive innovations. It might be too early to fully know which technologies will be the winners and which the losers. But understanding the energy landscape can guide the development of well-chosen experiments—in the laboratory and in the marketplace—that will build into the energy infrastructure far into this century.

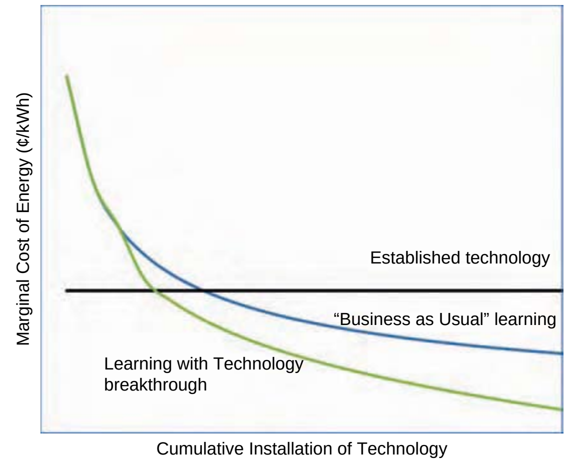

Figure 8. Learning curves of energy technologies to show the impact of technology breakthroughs (green line).

A Concluding Note

The Industrial Revolution of the 18th and 19th centuries was enabled by the discovery of energy resources and the making of materials to harness that energy. Over many years, the list of the materials and properties that we seek has grown: from coal and iron to uranium, silicon, nickel-based superalloys, and so on. The underlying science for these enablers is the thermodynamic, electrical, electronic, catalytic, and mechanical properties of materials. But the vision of enriching human society with 40 terawatts of power in 30 years calls also for our understanding of materials properties that were hitherto unexplored and tailoring those properties for the performance we require. This list is diverse and includes nanomaterials, biomaterials, materials for catalysts and hydrogen storage, and materials that efficiently and economically convert solar energy into usable forms. The sheer scale of the scientific challenges in the energy sector is overwhelming. The driver for the coming decades is not just the harnessing of new energy sources, but also the development of energy technologies from source to use with optimized efficiency and no or minimal CO_2 emissions. There should also be an improved understanding of the behavior of materials and structures that can sequester CO_2 or convert it into benign products—for coal might have to be used for many more decades. How materials scientists and engineers respond to these challenges will determine how successful our society is going to be in generating sustainable and pollution-free energy for the world in the coming decades.

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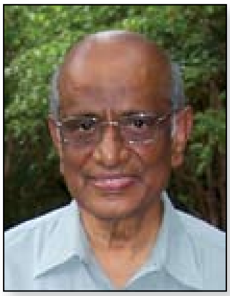

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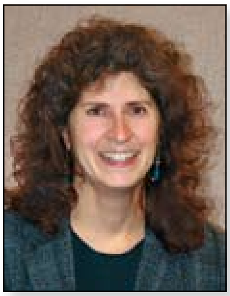

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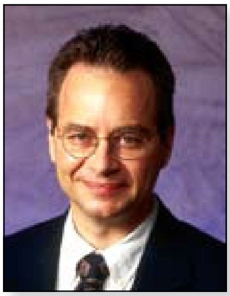
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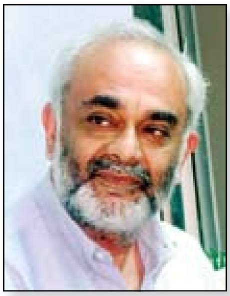

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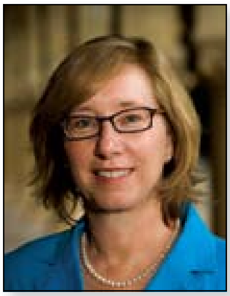

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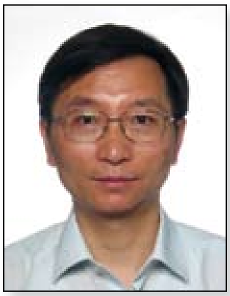

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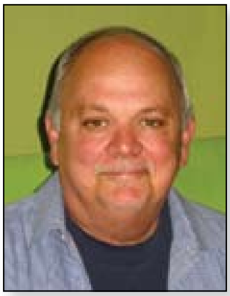

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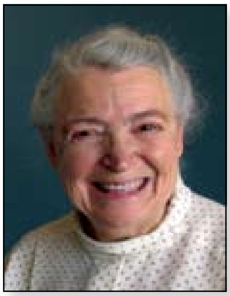

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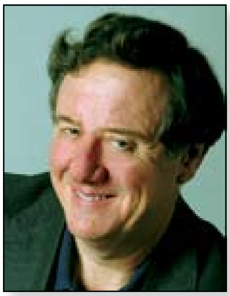

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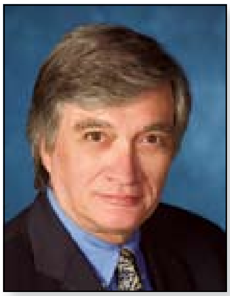
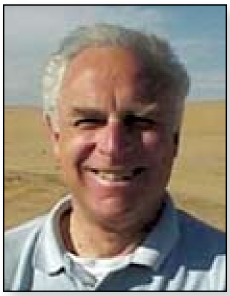


Rodney C. Ewing

Alexander E. Farrell



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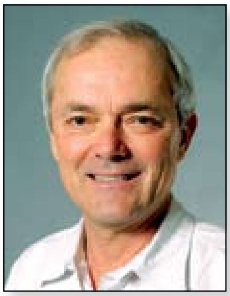

Devens Gust

concerning material, structural, and joining technologies, with emphasis on lightweight structures—particularly sandwich composites.

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His awards include the R&D 100 Award in 2005 for development of the TREAT with SUNREL simulation software, in collaboration with New York State ERDA. Judkoff also has received the 2001 AIA Committee on the Environment Top Ten Green Building Award for energy design of the Zion National Park Visitor Center; the ASHRAE Technology Award, first place, in 1999 for energy design of the NREL TTF lab building; and the 1991 Federal Laboratory Consortium Award for developing a calorimetric method to rapidly evaluate the thermal performance of manufactured buildings, thereby achieving a five-fold increase in the cost effectiveness of retrofits for the National Low-Income Weatherization Program.

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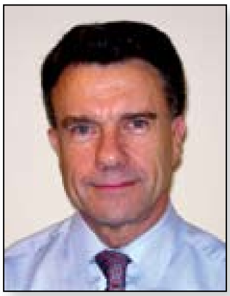
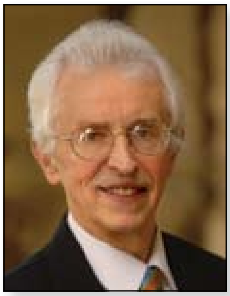
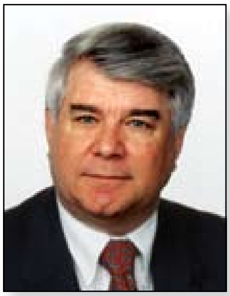


Brian Hayman



Siegfried S. Hecker



Stephen A. Holditch

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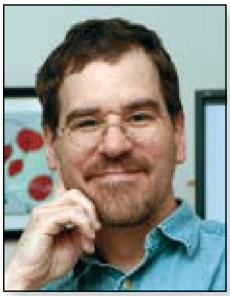

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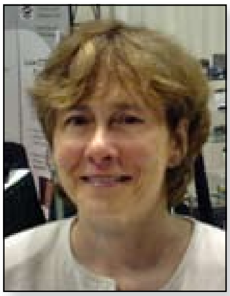
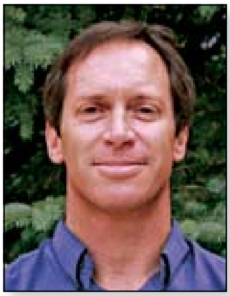


Laura Marlino



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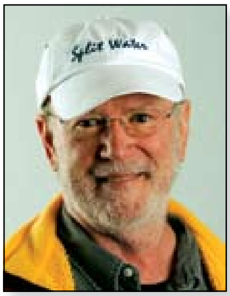
Ana Moore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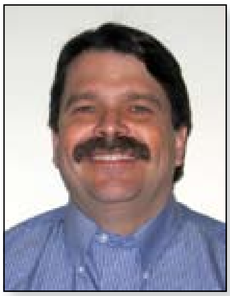
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Pesaran has worked at the National Renewable Energy Laboratory since 1983 in various energy efficiency technologies in building, advanced air conditioning, and automotive batteries. He holds a PhD degree in mechanical engineering from University of California, Los Angeles. Pesaran started working on batteries, hybrid electric, and fuel-cell vehicles in 1995, collaborating with car and battery manufacturers on battery thermal analysis and battery-pack thermal management issues as part of the U.S. Department of Energy's Vehicle Technologies Programs. He currently leads several projects for the Department of Energy and industrial partners, which include thermal characterization and analysis of batteries, modeling and simulation of batteries, and ultracapacitors for hybrid and plug-in vehicles. He is an active member of the FreedomCAR Electrochemical Energy Storage Technical Team and is a member of the Society of Automotive Engineers and the American Society of Mechanical Engineers.

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Powell is the Materials Science Focus Area lead for the Office of Research and Development at the US Department of Energy's National Energy Technology Laboratory (NETL). She received her PhD degree in materials science from Case Western Reserve University in 1989, preceded by MS and BS degrees in ceramic engineering from Clemson University, in 1985 and 1983, respectively. Powell has more than 15 years of research experience in the areas of high-temperature phase and microstructural development in ceramic materials, particularly refractories, and the effect of these phase changes on the bulk properties of the material.

At NETL, her research focuses on the development of improved performance materials that will enable the next generation of fossil-fuel power plants. Her research also has addressed microstructure/property and microstructure/processing relationships in a wide range of intermetallic, metallic, and composite materials, and the influence of microstructure on the tribological performance of ceramics and ceramic-based composites. Powell has more than 40 publications in these areas. She also is listed as co-inventor on a U.S. patent, which describes an improved material engineered for slagging gasifier applications.

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Raj is a distinguished scientist and director of Indira Gandhi Centre for Atomic Research in Kalpakkam. Raj holds BE, PhD, and DSc(hc) degrees. He has specialized in materials research and technology and fast reactor technology and associated fuel cycle. In addition, his interests include technology management, heritage, philosophy, theosophy, and education. Raj has significant contributions in many national and international committees. He has more than 700 publications in journals, 12 books, five Indian standards, and 18 patents to his credit. Raj also has co-edited 28 books and special journal volumes. He is a recipient of the Padma Shri award from the Government of India. Raj is an active member of the Academy of Sciences in India and a fellow of the Third World Academy of Sciences.

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Rao is currently heading the chemistry, metallurgy, and materials programs at the Indira Gandhi Centre for Atomic Research in Kalpakkam. A specialist in actinide separations, Rao has been working on various chemical aspects of fast reactor fuel cycles for more than 30 years. He also is an author of more than 150 publications in international journals.

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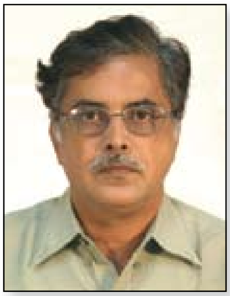
Cynthia A. Powell


Baldev Raj


K. Bhanu Sankara Rao


P.R. Vasudeva Rao


Bhakta B. Rath


Philip N. Ross, Jr.


Shad Roundy

Science and Component Technology Directorate at the Naval Research Laboratory in Washington, DC. He received a PhD degree from the Illinois Institute of Technology, an MS degree from the Michigan Technological University, and a BS degree from Utkal University in India. Rath's research interests include alternate energy resources and the behavior of materials. He served as the president of ASM International and has received numerous awards and honors, including the Distinguished Presidential Rank Award—the highest distinction presented to a senior executive of the U.S government—from President George W. Bush.

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Ross recently retired from the Lawrence Berkeley National Laboratory of the University of California, where he was a senior scientist in the Materials Sciences Division and program leader of the electrochemical basic science program in the Environmental Energy Technologies Division. He received his BS degree in chemical engineering from Yale University in 1965, his MS degree in chemical engineering from the University of Delaware in 1969, and his PhD degree in engineering and applied science from Yale in 1973. Ross worked at United Technologies Corporation before moving to Berkeley. His research has focused on fuel cell technologies, lithium batteries, and fundamental electrochemistry. Ross is co-editor of the *Frontiers in Electrochemistry* series published by Wiley-VCH.

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Sims is professor of sustainable energy at Massey University, New Zealand. Over a 35-year career working in renewable energy, he has served on various boards, is a fellow of the NZ Institute of Professional Engineers, and a Companion of the Royal Society of New Zealand. Sims also was a lead author in the IPCC 3rd Assessment Report – Mitigation (2001) and is the coordinating lead author for the energy supply chapter of the 4th Assessment Report (2007).

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Steingart is a lecturer and post-doctoral researcher at University of California at Berkeley, as well as co-founder and CTO of Wireless Industrial Technologies. He received his PhD degree in materials science and engineering in 2006 from UC Berkeley. Steingart's research interests include power generation, storage, and management for individual sensor nodes, as well as tailoring groups of nodes for industrial and environmental monitoring. He also is interested in minimal manufacturing through additive printing techniques.

John Stringer can be reached by e-mail at jstringer@izambard.com.

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Jeffrey J. Siirola

Ralph E.H. Sims

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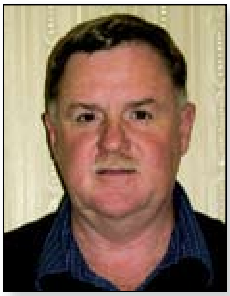
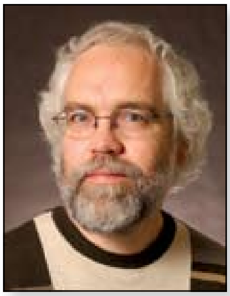


Terry M. Tritt



Wim Vermaas

M. Vijayalakshmi

Columbus Laboratories, he was appointed to the Chair of Materials Science at Liverpool. In 1977 he joined the Electric Power Research Institute in Palo Alto, California, remaing there until his retirement in 2004. He received a Chauncey Award from EPRI for his research in biomimetic approaches to CO_2 sequestration in 2000, and a Lifetime Achievement Award from EPRI in 2002. For much of his time at EPRI he was Executive Technical Fellow in charge of Exploratory Research. In addition, during the period 1977 to 1999 he was a Consulting Professor at Stanford University. He is a fellow of the American Association for the Advancement of Science, the Institute of Energy (U.K.), the Minerals, Metals, and Materials Society of AIME, ASM International, the National Association of Corrosion Engineers, and the Royal Society of Arts. In addition, he is honorary fellow of the Institute of Corrosion (U.K.) He is also a Chartered Engineer in the U.K. His personal research interests include high temperature oxidation of metals and alloys, high temperature materials, smart materials and structures, nanotechnology, biomimesis and biomimetic materials, and solid-state theory. He has received the Ulick R. Evans Award of the Institute of Corrosion (U.K.), the Campbell Memorial Lectureship of ASM International, and the Whitney Award of NACE International. He has participated in a number of advisory committees, in particular the National Materials Advisory Board and DOE's Basic Energy Science Advisory Committee. He acted as Chairman of BESAC from 1996 to 1998. He was a member of Panel 6, Materials for Fusion Reactors of DOE's Fusion Energy Advisory Committee, and a member of the University of Chicago Review Committee for the Chemical Technology Division of Argonne National Laboratory, 1987–1993; and Chair for his final two years. He has also been involved in a number of management committees within ASM, AIME, and NACE.

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Taylor manages the State, Local and Tribal Integrated Applications Group at the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) in Golden, Colorado. Prior to his current position at NREL, Taylor spent a decade working in international rural development and six years working with Native American communities throughout the U.S. With 30 years of experience in renewable energy technology development and application, his quest has been to expand and promote the use of renewable energy to support sustainable economic development both domestically and internationally.

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Tritt is a professor of physics at Clemson University. The focus of the program is on electrical and thermal transport in new and novel materials, with current interests in materials for thermoelectric refrigeration and power generation applications. Tritt is considered an international expert in the field of thermoelectric materials research. His primary research expertise lies in electrical and thermal transport properties and phenomena (especially in measurement and characterization techniques) in new and novel materials. In addition, Tritt has recently become involved in the synthesis and characterization of thermoelectric nanomaterials. He has extensive expertise in measurement science and has built an internationally known laboratory for the measurement and characterization of thermoelectric materials parameters, particularly thermal conductivity. Tritt has served as lead organizer of three Materials Research Society symposia on thermoelectrics materials (MRS Volumes 478, 545 and 626). Tritt will serve as an MRS Meeting Chair for the Spring 2009 Meeting. He has been a member of the executive board of the International Thermoelectrics Society (ITS) since 1999, and served as chairman and host of the 24th ITC-2005 at Clemson in June of 2005. Tritt has written more than 150 journal publications and regularly gives invited presentations at national and international meetings. He also was recently an author and lead editor of a *MRS Bulletin* theme (March 2006) on thermoelectric materials and devices. Tritt edited a three-volume set on "*Recent Trends in Thermoelectric Materials Research*" (Academic Press-2000) and has recently edited a book by Kluwer Press on thermal conductivity.

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Vijayalakshmi is head of the Physical Metallurgy Division at Indira Gandhi Centre for Atomic Research in Kalpakkam. She has specialized in alloy development for nuclear industry, structure-property correlations, and phase transformations for nearly 30 years. Vijayalakshmi has published a book, chapters in several books and an encyclopedia, and

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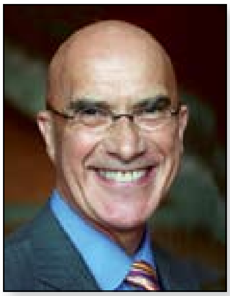

Paul Wright

Charles E. Wyman

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Whittingham is a professor of materials science and director of the Materials Science Program and Institute for Materials Research at the State University of New York at Binghamton. Whittingham received his BA and PhD degrees in chemistry from Oxford University, working with Peter Dickens. In 1968, he joined professor Robert A. Huggins' research group in the Materials Science Department at Stanford University as a postdoctoral research associate to study fast-ion transport in solids. In 1972, Whittingham joined Exxon Research and Engineering Company to initiate a program in alternative energy production and storage. After 16 years in industry, he joined the Binghamton campus of the State University of New York as a professor of chemistry to initiate an academic program in materials chemistry. His recent work focuses on the synthesis and characterization of novel microporous and nano-oxides and phosphates for possible electrochemical and sensor applications. Whittingham was principal editor of the Journal *Solid State Ionics* for 20 years. He also was elected a fellow of the Electrochemical Society in 2004. In addition, Whittingham was awarded the Young Author Award of the Electrochemical Society in 1971, a JSPS fellowship in the Physics Department of the University of Tokyo in 1993, and the Battery Research Award of the Electrochemical Society in 2002.

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Wright assumed the position of chief scientist for the Center for Information Technology Research in the Interest of Society (CITRIS) at University of California at Berkeley in January 2006 and also is a professor in the mechanical engineering department, where he holds the A. Martin Berlin chair. Wright attended Birmingham and Cambridge Universities prior to previous faculty positions at New York University and Carnegie Mellon University. Currently, he and his colleagues are designing and prototyping wireless systems for "demand response power management" throughout California, funded by Public Interest Energy Research (PIER) program of the California Energy Commission (CEC).

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Wyman is currently the Ford Motor Company Chair in Environmental Engineering and Professor in the Chemical and Environmental Engineering Department at the University of California at Riverside. He also is co-founder, chief development officer, and chair of the Scientific Advisory Board for Mascoma Corporation, a startup cellulosic ethanol company. Wyman holds a BS degree from the University of Massachusetts and MA and PhD degrees from Princeton University, all in chemical engineering plus an MBA from the University of Denver. He has devoted most of his career to leading advancement of biological conversion of cellulosic biomass to ethanol in academia, a government laboratory, and industry. In addition, Wyman has contributed numerous papers and book chapters, many presentations, and several patents. ☐

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