Materials for the Power Industry

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> It's an issue that we need to take very seriously. I don't think we know the solution to global warming yet, and I don't think we've got all the facts before we make decisions.
> —George W. Bush,
> Presidential Debate at Wake Forest University, October 11, 2000

> Is it a fact—or have I dreamt it—that, by means of electricity, the world of matter has become a great nerve, vibrating thousands of miles in a breathless point of time?
> —Nathaniel Hawthorne,
> *The House of the Seven Gables*, 1851

> Communism is Soviet power plus electrification of the whole country.
> —V.I. Lenin, 1920

Introduction

One of the great achievements of the past century has been the rapid growth in energy use by a significant fraction of the world's population. This has been the dominant driver for industrialization and economic growth, particularly in the so-called first-world countries. In such countries, a ready supply of varied and cheap foods; access to comfort amenities such as hot water, lighting, heating, and increasingly air-conditioning; and access to a range of transport options has become the benchmark for civilized life. Such increases in living standards are also rightly being sought by the developing world, thus driving their industrialization and growth in food production. All of this is resulting in inexorable growth in the global demand for energy, raising fundamental problems of resource limitations and environmental pollution. A major challenge for the 21st century is to obtain sustainable solutions to these problems in a way that does not discriminate against the least wealthy of the world's population.

Currently, fossil fuels account for >80% of world energy use. A major component of this energy consumption is in the form of electricity, using technologies that depend largely on fossil fuels. A second major component is mechanized transport (e.g., land, sea, and air) that depends to an even greater extent on fossil fuels. There is increasing agreement that this situation is not sustainable, even in the relatively short term. The solution requires more efficient energy use, particularly by first-world countries, and moving to technologies that do not depend on fossil fuels and that have a tolerable environmental impact.

The impressive developments in condensed-matter physics and materials technology have played a central role in enabling advances in energy technologies in the 20th century. Thus, we now have a set of tools for understanding new materials through the theories of atomic bonding and the behavior of defects and fracture. The design of structural alloys, composites, and polymers is within our grasp. This is fortunate, as the current century will present even greater challenges than the last.[1] In this short article, we will look at these challenges through the eyes of the materials scientist. A central theme of the article is to develop the proposition that electricity-generation potentially provides a sustainable means for meeting the world's growing energy needs, not only in the present electrical sectors, but also as a primary stage in the supply chain of other energy usage such as for transportation. An alternative perspective can be found in the article on "Materials and the Environment" in this series (see the June 2001 issue of *MRS Bulletin*, p. 477).

Trends and Priorities

Global warming and climate change are increasingly seen worldwide both by scientific experts and politicians as a major threat that must be managed (see the sidebar, "Countering Climate Change"). There is a general acknowledgment that the problem is a consequence of the burning of fossil fuels. Thus, if fossil fuels are to continue to form a significant fraction of our energy resources, then methods will be needed to remove the carbon from the fuels before combustion, or the carbon dioxide will have to be removed after combustion (carbon sequestration). But this is clearly a stopgap measure.

A less widely acknowledged but ultimately equally limiting issue is the increasing prospect of fossil-fuel resource depletion as energy demand increases. Currently, developing countries are dependent on oil and unsustainable biomass (wood) for energy, and their demand for oil and gas will increase, as we have seen dramatically over the last 20 years in the newly industrialized economies of Asia. Oil and gas resources are starting to run out, with current proven reserves standing at about 40 years for oil and 62 years for gas at current consumption rates.[2] New reserves will be found, but consumption is increasing. The last 10 years have seen the progressive reduction in the ratio of proven reserves for both oil and gas, most notably in North America and Europe, where such reserves could be exhausted over the next 10 to 20 years. The situation is particularly acute for gas, on which there is a dangerously increasing dependence for process heat, space heating, and efficient electricity production in much of the developed world. Coupled to this is the increasing dependence of the West on the politically unstable areas of the former Soviet Union and the Middle East for its energy resources. Coal is the only fossil fuel that has reserves that will last the century. At current production rates, it will take over 200 years to exhaust proven reserves, but coal is the least attractive fuel from the point of view of CO_2 production and pollution.

Against this background, while increasing efficiency in energy generation and use is necessary to curb both environmental damage and resource depletion, it is not by itself sufficient. In the long term, we need to replace all types of fossil fuels with sources of energy that are both nonpolluting and sustainable. At present, the only significant primary-energy sources with low carbon emissions that are not dependent on fossil fuels are nuclear (at ~8% of the total primary energy production) and hydropower (at ~2%). However, while nuclear power makes up an important part of electricity generation in developed countries, further construction has been severely curtailed since the Chernobyl accident. Experimental renewable-energy sources such as solar power, wind, and sustainable biomass production have made little impact yet, but encouraging demonstrations have shown what could be done with better design and better materials.

In reaching acceptable solutions to these problems, economics will be critical, whether for developed or developing countries. In the latter case, cheap (at least initially) solutions rather than sophisticated ones will be required. An increasingly important secondary issue is the tension between large central generation of electricity and generation on a local or

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even household scale. Changes in economic structure and regulation, combined with changes in technology, now make microgeneration more attractive than in the past.

Carbon Sequestration

There are potentially two main ways of preventing CO_2 buildup in the earth's atmosphere. The first and most direct is to remove it at the source and permanently dispose of it. Some experience of the technology to achieve this has already been gained in the petroleum industry, where CO_2 is a natural contaminant of oil and gas fields. Experiments have been made on recapturing CO_2 when gas is processed and then injecting it back into geological strata. The current most efficient technique for recovering CO_2 is chemical absorption using monoethanolamine (MEA) as a solvent. Other techniques using membranes, adsorption, and cryogenics are not yet competitive. Ultimate disposal in used-oil reservoirs has been demonstrated, but a more controversial deep-sea disposal method is also a possibility. Such removal of CO_2 is only practical for centralized energy production such as electricity generation, which accounts for only about 35% of primary energy production. Moreover, using the best current technology, 40% of the thermal energy has to be used to capture and dispose of the CO_2 produced during combustion. Further developments must reduce this penalty to 15% or less if fossil-fuel combustion is continued for power generation or hydrogen production using simple oxidative reforming methods (see next section). Nevertheless, such removal and disposal technology could provide some alleviation of the problem of CO_2 buildup in the short to medium term and is worth pursuing.

A second approach is to remove CO_2 once it has been emitted to the atmosphere, and potentially this has the advantage of reducing levels whatever the source. Programs are already under way to renew and grow new forests to absorb atmospheric CO_2, but there is some question over how effective this is over the long term. Forests absorb CO_2 initially but eventually equilibrium is established between trees dying and new trees growing. The decaying organic matter can eventually emit more powerful greenhouse gases like methane. Even more controversial, due to the fact that the global effects are less predictable, is the proposal of seeding the oceans with fertilizers to promote algeal growth. These areas do not raise any significant materials issues, so we will leave further discussion to others.

Countering Climate Change

Air monitoring and samples taken from air bubbles in Antarctic ice demonstrate that CO_2 levels in the atmosphere have risen by ~30% since the industrial revolution, which started ~200 years ago. The rate of increase is such that the concentration of CO_2 in the atmosphere is expected to double before the end of the century unless extreme action is taken. This is accepted by scientists and politicians, but the consequent effects on the earth's average temperature are not agreed upon, and the effects on climate are largely unpredictable. Ice cores from Antarctica enable the study of CO_2 concentrations over the past 400,000 years.[14] During this period, there is a strong correlation between atmospheric CO_2 concentration and temperature. Modeling the effects of doubling CO_2 levels would produce an increase in temperature of between 4°C and 10°C, with an associated rise in sea level, unpredictable effects on temperature redistribution, and extreme weather conditions. Recently, it has been determined by the Intergovernmental Panel on Climate Change that a change in the average temperature at the earth's surface of about 0.6°C has occurred over the last 100 years. The effects of cyclic variations in solar output and the suppression of temperature by occasional large volcanic activity complicate the interpretation by climatologists. The retreat of alpine glaciers and other changes in weather have been observed.[15]

The dynamics of CO_2 in the atmosphere are not fully understood, and the effects of deforestation, reforestation, and the emission of other more powerful greenhouse gases like methane from decaying vegetation have still to be clarified.

Arrival at an international consensus on countering climate change has been slow and frustrating. This is a political matter[16] not to be addressed here; rather, the technical solutions to the problem will be discussed. While the release of other greenhouse gases, notably methane, must be minimized, so too must carbon emissions from fossil-fuel combustion be reduced. Following is a list of routes to achieve this.

1. *Efficiency and economy*. Comparisons of the energy and electricity needed for each dollar of the gross domestic product (GDP) in different countries reveal a huge potential for energy savings in the United States, Canada, and the former Soviet bloc, as compared with Europe.
2. *Use of waste gas (mines, landfill) and refuse-derived fuels*. This also limits release of methane into the atmosphere.
3. *Use of renewable resources such as solar, wind, and wave power*.
4. *Use of sustainable biomass and biofuels.*
5. *Reformation of fossil fuels to reduce carbon content by the production of hydrogen and methane.*
6. *Use of nuclear power from fission and fusion.*
7. *Carbon sequestration by natural sinks, such as in oceans and forests.*
8. *Carbon sequestration at both the source and disposal.*

Most of these measures are not yet economically viable in a free market. Their introduction will require international agreement, incentives, and disincentives for the use of fossil fuels (e.g., the "carbon tax," where fossil-fuel users are taxed on carbon emissions). International efforts through the Framework Convention on Climate Change are now trying to establish some rationale for carbon-emission quotas for individual countries. Carbon trading, where countries or industries who will exceed quotas can purchase unused quotas, is not a solution to the problem but a political expedient to allow countries like the United States, Australia, and Canada to cushion the large reductions that will be necessary for success.

Clean Power Generation

By "clean power," we mean the generation of electricity without the emission of greenhouse gases, and by definition, this precludes fossil fuels. To account for all greenhouse gases associated with electricity generation, we should include those generated by the processes used in the building of power plants (e.g., steel making and fabrication). Thus, the aim should be to use fossil-fuel-free energy for such processes. On the current basis, there is the potential for 35–40% of global primary energy to be free of greenhouse-gas emissions at the point of generation. There is already a trend toward increased electricity use for industrial and domestic applications, and as we shall see, there is the prospect for transport to be based on electricity generation using hydrogen and battery technology. Thus, the prize for moving to fossil-fuel-free generation is considerable, and it could be the basis for overcoming the threat of potentially devastating global climate change. There are two main options, namely, nuclear power and renewable-energy sources. We will consider these, focusing on future developments and materials requirements.

Nuclear Power

Currently there are 438 fission nuclear power stations,[3] mostly sited in the industrialized countries of the West and Asia, supplying some 17% of the world's electricity. Thus, nuclear power is an established technology. However, as already mentioned, new investment in nuclear power has virtually ceased since Chernobyl, particularly in the current environment of deregulation in many developed countries, which is causing utility companies to be risk-averse in their new plant investments. Only a handful of countries—like France, Japan, and Korea—having a centrally regulated energy policy are committed to its continuing use, although the United States announced this year an energy policy that would include a new nuclear-power construction program. It is widely recognized both by the nuclear-power industry and more generally that for a new generation of nuclear-power stations to be built, a number of issues impacting on public acceptability and economic viability will have to be addressed.[4] These include safety, waste and spent-fuel management, decommissioning, and high capital costs. In the longer term, fusion power offers the prospect of an alternative approach to nuclear power that could overcome some of the objections to fission power.

Fission. A majority of the world's current population of power reactors are of the pressurized-water and boiling-water designs. To benefit from economies of scale, most reactors generate 1.0–1.2 GW of electric power. Although the nuclear reactors themselves are basically simple in design, protection from the potentially severe consequences of an accident resulting in a major loss of coolant requires the inclusion of complex, engineered safety-protection systems. This results in high capital costs and long construction times, although this latter factor has become less significant with the introduction of modern manufacturing and construction technology. Moreover, the performance of light-water reactors (LWRs) have in general greatly improved in recent years, and many utilities now have the objective of increasing plant operating lifetimes to 60 years to maximize the return on capital investment.

New developments are mostly based on smaller reactor designs, with less dependence on engineered safety-protection systems, lower capital costs, and short construction times owing to more off-site fabrication of components. One route is through advanced pressurized-water reactor (PWR) and boiling-water reactor (BWR) designs that are based on the existing systems.[5] While these incorporate a greater degree of intrinsic safety protection, such as gravity-fed coolant water make-up systems, they retain the same core designs with their vulnerability to rapid loss of coolant.

> It will be an impressive and far-reaching societal breakthrough when solar-power space stations begin contributing to the alleviation of global power-hunger, similar to what the communications satellites have done for global communications.

A more radical and exciting prospect is a South African-led pebble bed modular reactor (PBMR) design,[6] based on a resurrection of the high-temperature reactor concept as developed in Germany. The current design power output is 100–120 MW of electric power, and it is envisaged that utility companies can combine modules to meet their generation requirements. The PBMR is attracting increasing attention internationally, and investment has been secured from the United Kingdom and the United States as well as from South Africa. It offers a number of fundamental advantages that could counter many of the present objections and provide the basis for a resurgence of nuclear power. The core design is based on a continuously circulating pebble-bed configuration, with the fuel elements comprised of a composite of small, coated fuel particles embedded in graphite spheres. The fuel-kernel coating provides the main pressure boundary preventing the escape of fission products and has been shown, particularly by the German experience, to have high reliability. The core maintains negative reactivity under all accident scenarios, which together with the high heat capacity of the fuel and the ability to remove decay heat, means that fuel integrity is retained and safety of the core is assured. The reactor is cooled with helium gas, and power conversion occurs through a direct gas-driven power turbine, which gives significantly higher thermal efficiency than do LWRs. The design is generally based on proven technology and does not immediately give rise to novel materials problems. There is, of course, the need to ensure a high level of structural integrity to secure high availability. In the longer term, there is the prospect of further significant improvements in thermal efficiency from the present 40% to levels more typical of combined-cycle gas-turbine plants (i.e., >50%). As well as improving the economics, such an advance would also significantly reduce spent-fuel and waste production per megawatt of electricity generated. To increase the thermal efficiency of the cycle requires higher gas temperatures with challenging materials requirements for both core and circuit components, particularly in the power turbine. Thus, there will be the need to introduce ceramic-based composites and coatings such as those developed for aero-engine gas-turbine technology.

A major issue for nuclear power, particularly in the context of proliferation, is the disposal of plutonium. Over the past 50 years, several hundred tons of plutonium have been produced by thermal reactors. Some of this has been specifically for nuclear-weapons production. Much greater quantities are a by-product of power-station operation, and this is subject to safeguards supervised by the International Atomic Energy Agency. France and the United Kingdom operate reprocessing plants to separate plutonium from spent fuel from both their own power stations and from other plants in Japan, Germany, and Switzerland. (Russia also operates reprocessing plants to separate plutonium from its thermal-reactor spent fuel.) A number of countries, and particularly France and Japan, are pursuing a strategy of recycling the separated plutonium as mixed oxide fuel in thermal reactors. But this is not a sustainable solution, since not all of the added plutonium is destroyed and new plutonium is produced in such MOX cycles. Moreover, it has not proven to be economically viable so far.

An alternative to recycling plutonium in thermal reactors is to dispose of spent fuel by converting it to a more stable waste form such as encapsulation in glass and burial in deep repositories. The United States, which is strongly opposed to a recycling strategy based on reprocessing, favors this option for both the spent fuel from its nuclear power stations and for the separated plutonium from its weapons program. However, concerns have been expressed about the eventual leakage of plutonium from disposal sites into the biosphere or its access for future weapons production. A second alternative is to permanently dispose of plutonium by burning it in fast neutron reactors or, more speculatively, in hybrid-accelerator or even fusion systems. Avoiding ^{238}U in the fuel circumvents the problem of the thermal reactor cycle of producing fresh plutonium.

This latter option, together with the MOX cycle, illustrates that rather than being an undesirable by-product of nuclear power, plutonium is potentially a valuable fuel. If the nuclear power component of power generation were to substantially grow in response to the need to phase out fossil-fuel use, then exhaustion of uranium resources could be a real threat. This is a consequence of natural uranium only containing 0.7% of the fissile isotope ^{235}U. To optimize the energy content of the uranium resource, it is necessary to convert ^{238}U to the fissile isotopes of plutonium and burn it in a fast neutron reactor. Substantial investments have already been made in fast reactor technology, and it has been demonstrated that once sufficient plutonium has been produced to fuel, the first fast reactors of a self-sustaining breeding cycle that utilizes a mixed oxide fuel containing plutonium and uranium is viable. Although less developed, an alternative breeding cycle through the conversion of thorium to 233 uranium is possible. Both of these options would provide access to a very long-lived energy resource.

A strategy based on such closed cycles provides a sustainable way forward for nuclear power as well as a potential solution to the problem of proliferation. However, major problems have been encountered in the development of fast reactors based on sodium cooling in spite of a major investment by the leading industrialized countries. Although the fuel based on a mixed oxide of uranium and plutonium worked well, formidable problems were encountered that mainly related to materials integrity in the circuit components having a sodium–water interface. As a result, sodium-cooled fast reactor development programs have now largely been abandoned, both because of these technical problems and the view that with the currently virtual standstill in nuclear-power uranium, resource limitation is not an issue. A return to fast reactor technology or a thorium-based cycle is likely to require a new approach, and the development of appropriate materials technologies will play a key role. Alternatives include a lead-cooled fast reactor[7] and a low-power-density gas-cooled cycle using helium as the coolant. Either would provide a much more benign environment as compared with sodium. The helium-cooled route also has the potential advantage of having a consistent technology linking thermal to fast neutron-driven plutonium or thorium cycles that could provide a more feasible and acceptable way forward.

Fusion. In principle, the key to long-term large-scale energy supply might be the development of controlled thermonuclear fusion, initially based on the reaction between the deuterium and tritium isotopes of hydrogen. Deuterium is found as a natural isotope of hydrogen with an abundance of 1.5%, and tritium has to be manufactured by neutron capture by lithium, which is also a relatively common element. Such fusion reactions occur in the sun, therefore providing the source of the solar energy that is vital to life on earth. There has been a massive worldwide investment in fusion research and development, and there is little doubt that controlled fusion produced by magnetic confinement or by laser compression of a plasma is feasible. But what is not so certain is our ability to construct economical fusion systems before the end of the century.

Specifically, it is claimed that the magnetic confinement route is well understood and that a demonstration power plant could be built within the next 30 years and commercial power produced within 50 years,[8] but this will depend on the availability of materials that permit economical designs. The materials problems for inertial and magnetic-confinement devices are similar, the main difference lying in the need for large superconducting magnets outside the main structures in the first case and the pulsed nature of operation in the second case. The common elements include a plasma facing structure (first wall) that takes the brunt of the radiation fluxes and neutron damage and a blanket structure that breeds new tritium but at the same time absorbs the energy carried by the neutrons from the plasma. In both cases, the power conversion is by heat exchangers producing steam to drive power turbines for electric generation.

Design studies have been carried out for fusion-reactor concepts based on the Tokamak magnetic-confinement device.[9] A prime consideration is the propensity for materials to become severely radioactive under neutron irradiation. Thus, common alloy elements, notably nickel, are excluded. The austenitic stainless steel that was selected for earlier designs is replaced by low-activation ferritic steel or vanadium alloys. All parts of the reactor structure are subjected to severe fast-neutron damage, and this causes a number of problems. The combination of helium and hydrogen production through n-α and n-p reactions simultaneously with much larger numbers of point defects produces void swelling in many materials. Moreover, the damage causes irradiation hardening and embrittlement of the metals and ceramics envisaged for the first wall and associated components. Thermal conductivity tends to decrease in all materials, and disordering of superconductors decreases the transition temperature and critical current. Components facing the plasma can be eroded by contact with the plasma and have to be coated with armor. Contamination of the plasma by high-atomic-number elements has to be avoided, but refractory metals like tungsten have better resistance to erosion by the plasma than alternatives such as beryllium. Table I summarizes current thinking on materials that could be used in a demonstration reactor.

Table I: Materials Options for the First Magnetically Confined Fusion Power Generating Systems.

Variants	Water-Cooled Lithium Lead Blanket	Liquid-Lithium Blanket	Helium-Cooled Pebble-Bed Blanket	High-Temperature Helium-Cooled
Armors	W and Be			
Heat sinks	Dispersion-hardened Cu, CuBeNi			
Plasma facing material	Carbon fiber-carbon composites			
First-wall structure	Ferritic-martensitic steel			
Blanket structure	Ferritic-martensitic steel	Vanadium alloys	Ferritic-martensitic steel	SiC-SiC fiber composite
Breeder	Pb-Li	Li	Li ceramics	Li ceramics
Coolant	Water	Liquid Li	He	He
Neutron multiplier	Pb-Li	Li	Be	Be

Renewable-Energy Sources

A major expansion is widely advocated of all forms of renewable energy using locally available sources. A range of technologies are either available or under development. The technology requirements range from fairly conventional engineering to advanced technologies, including novel and advanced materials. In this overview, we summarize the main renewable systems and the associated materials technology requirements.

Hydropower. Hydropower is an established technology and currently accounts for about 18% of the world's electricity supply.[10] However, the number of suitable sites is limited, and there is increasing concern regarding their environmental impact and safety. Nevertheless, there may be some opportunity for expansion in developing countries and for small local schemes in developed countries. The scope for innovative use of materials in this technology is limited.

New Renewables. New renewable-energy sources based on wind, wave, and tidal power are more dispersed, and capital costs are a major element governing their competitive position relative to more conventional energy technologies. Reductions in capital costs will depend both on good design and improved materials, but the low energy densities mean that structures are generally large and occupy large areas. Structures for wind, tidal, and wave power generators will generally be based on conventional civil engineering with fixed concrete emplacements. Their large size also means that the materials have to be low-cost and maintenance-free if they are to be successful. Most experience has been gained on land-based wind turbines, and on favorable sites, these are now close to being competitive with fossil fuels. Wind speed and direction is generally more constant at sea, and developments are under way to site wind power generators offshore. However, this presents additional challenges, not least of all for materials that can withstand the harsh environmental conditions. Less success has been achieved on wave power generators that face similarly harsh environments. Attempts at producing lighter, floating devices have been problematic, as they are difficult to secure safely and are vulnerable to extreme sea conditions, so attention has shifted to fixed installations. The moving parts of these generators require more innovative designs and materials to survive the cyclic loading and corrosive wet environment of the ocean. In addition, both offshore wind and wave generators need low-resistance cabling to improve efficiency. Tidal power is limited to particular sites where barrages can be constructed. The technology is similar to conventional hydropower, but the specific capital cost (in relation to power output) is large because of the relatively low water heads associated with tidal flows. Despite this, favored sites have been investigated, and some small-scale schemes have been constructed. There is the opportunity to look at high-strength, reinforced-concrete shells supporting earth barrages as a way of reducing construction costs. More generally, development of suitable high-strength, lightweight composites for selective components—for example, for wind turbine blades—could offer advantages if they can be produced at a low cost.

Geothermal Power. Geothermal power is very site-specific, as it requires either a sustainable source of hot water or a suitable fractured hot-rock structure that permits injection of water to generate energy. So far, this has been limited to a few small plants, for example, in Iceland. Elsewhere, the problem of creating a permeable rock structure to allow water injection has not yet been solved.

Solar Power. Solar power has the potential for making a major contribution to meeting energy needs—particularly those of developing countries that have sufficient sun, but also more generally. Passive solar heating to provide hot water and some space heating is already widely used in sunny countries and even on a more limited scale in the United Kingdom. Such methods rely on good design and can use existing construction materials, but heat-trapping films or plastics offer the possibility to improve efficiencies. However, solar electricity generation using photovoltaic cells presents greater materials challenges, particularly if it is to be competitive. Currently, there are two types of photovoltaic materials: cheaper, low-efficiency materials like amorphous silicon (11% efficiency), CdS or CdTe (13%), and Cu(Ga,In)Te (17%); and more expensive but more efficient materials (25–30% efficient), such as crystalline Si, GAs, and GaInP. The challenge is to improve these materials or to develop new materials that can be manufactured cheaply and have higher efficiencies. The search is on for optimized materials; computational modeling of the properties of candidate materials may become the standard method used to screen candidates.

Solar power will become a strong competitor in the coming decades once we are able to solve two major problems, one on earth and the other in space. If the efficiency of solar cells could be increased, with an attendant decrease in costs, it would be possible to integrate them extensively in buildings and other structures. S. Ovshinsky and his colleagues, using amorphous silicon, have built solar shingles as roof materials for homes and even solar screens for windows (see G.N. Gupta's article on "Materials for the Human Habitat" in this series, published in the April 2000 issue of *MRS Bulletin*, p. 60). But we need better efficiencies and affordable pricing of these materials before they can become commonplace.

Huge arrays of solar-cell structures circling in geostationary orbits can be turned into efficient and large generators of electric power if appropriate technologies can be developed to radiate the electric power as microwave energy to receiving stations on earth. Major issues relating to costs and environmental concerns will also have to be addressed before space-based power stations can become a reality. It will be an impressive and far-reaching societal breakthrough when solar-power space stations begin contributing to the alleviation of global power-hunger, similar to what the communications satellites have done for global communications.

Energy Storage

For effective use of renewable-energy sources, a reliable means of storing energy is required because the energy supply will fluctuate and the load must be matched to demand. For electricity generation, pumped hydraulic storage has been very effective, but the number of suitable sites for this is limited. As we shall show, hydrogen provides one route for storing energy. Alternatives, particularly for transport applications, are efficient batteries or flywheel storage systems. As an interim step to eliminating fossil fuels for transport, manufacturers have developed prototypes linking energy storage with a high-performance internal-combustion engine or gas turbines in vehicles that allow regenerative braking to optimize fuel efficiency and minimize pollution.

Flywheel systems in vacuum with high-strength composite rotors are being used in some public service vehicles and for fixed load leveling, but they do not have much potential for use in smaller vehicles. Other possibilities are compressed-air systems using high-pressure, low-weight composite vessels and superconducting magnets which, at present, need cryogenic systems until the elusive room-temperature superconducting material is found.

The storage capacity of batteries has increased significantly in the last 10 years with the introduction of the nickel-metal hydride cells and particularly the lithium-ion system. Lithium cells have over twice the voltage of nickel cells, doubling the specific capacity of secondary batteries. This has been made possible through the use of cathodes of transition-metal oxides and anodes of graphite in which lithium can be intercalated. Most current commercial batteries are based on carbon anodes and lithium cobalt oxide cathodes. Although Li-ion batteries now dominate the consumer electronics market, price is a key barrier to their use in replacing cheaper but less effective lead-acid or nickel-metal hydride cells for load-leveling or vehicle batteries. The next development is the production of compact, high-storage density cells that replace the gel electrolyte with a suitable electrolytic polymer membrane. This lithium-polymer battery can be produced in bulk, making a robust, effective, and safe battery, but the technology is still more expensive than the gel electrolyte case. The technology has been available in the laboratory for about 10 years, but manufacture is limited to specialized electronic and aerospace applications where the flexibility of shape and thinness of the cell elements have advantages and cost is not so important. It is now possible to hide a battery in the case of a device or as part of clothing such as a belt. There is also the possibility of making cheaper cathodes from other suitable oxides such as lithium manganese or nickel oxides, or changing the cell chemistry to use fluorinated graphite or sulfur rather than oxide cathodes. Low-cost lithium-based batteries will almost certainly be used in larger-scale and automotive applications in the next 10 years.

For stationary electrical storage and load leveling, there is the possibility of using the multiple of valency states of metals like vanadium and uranium to make a flow-redox battery. In this system, a tank of the solution of a salt of the metal at one valence state is pumped between the electrodes of the battery to generate power, and the system is reversed to store power.[11] The advantage of this system is that the cost of increasing the storage capacity is controlled by the size of the storage tanks and salts and not the whole cell assembly. Vanadium for this purpose can be recovered from the soot of Venezuelan Orimulsion, which is an aqueous slurry of bitumens from natural tar sand deposits.

The Hydrogen Economy

The use of hydrogen potentially offers a solution to two of the key problems in future energy management—the replacement of petroleum-based fuels for transportation and the smoothing of inherent fluctuations in the supply of renewable-energy sources. The widespread use of hydrogen will require new technologies, including novel materials. The main steps in the production and use of hydrogen are illustrated schematically in Figure 1.

Hydrogen Production

Electrolysis is an efficient process for the production of hydrogen, and by using a clean CO_2-free source of electric power, this technology could provide a major breakthrough in overcoming the global warming and fossil-fuel resource problems. See the earlier section on clean, electric power generation.

The alternative of extracting hydrogen from hydrocarbons or biomass is more difficult. Most common reforming methods, such as steam reforming of natural gas, produce CO_2 as well as hydrogen as by-products. Removing the CO_2 during reforming can enhance hydrogen production, and more sophisticated methods using a ceramic membrane reactor would be more efficient than conventional reformers. Pyrolysis of long-chain hydrocarbons or biomass by itself can reduce carbon content, but the end product is a range of hydrocarbons and only a little hydrogen. The solution could well be plasma reforming in the absence of oxygen, which can produce pure hydrogen and carbon black. Some experiments have demonstrated the process using electric power with 20% of the calorific value of the hydrocarbon input.[12] To make the process attractive, the energy requirements must be reduced to around 5% of the calorific value. Two different operating regimes are possible, each with its own materials requirements: low-pressure, nonequilibrium corona discharges, and high-pressure, higher-temperature electric arcs. Disposal of carbon black and other cokey materials from reformers and pyrolysis is simple, and reoxidation is unlikely unless the disposal sites were to catch fire.

Direct production of hydrogen from water by solar energy is a potentially attractive objective that could be reached by a number of processes. One process being investigated is thermal decomposition of water in a plasma jet, where solar radiation is concentrated by a parabolic mirror onto a jet of water vapor excited by an electrical glow discharge. Dissociated hydrogen could be separated from oxygen and water vapor by a skimming technique using the large molecular-weight difference between the components. The technique has yet to be demonstrated, and substantial increases in efficiency will be required to make it attractive. A particularly difficult materials issue is the ceramic dissociator nozzle where the solar radiation is concentrated. Other routes to direct hydrogen production from solar radiation include photovoltaic reduction of water and photobiological production using suitable algae or bacteria.

Hydrogen Storage and Use

It has been remarked that storage and transport of hydrogen is the Achilles' heel of the hydrogen economy. For most purposes, storage of liquid hydrogen is acceptable, although it is energy-inefficient, and in contrast to liquid petroleum gas, cryogenic facilities are necessary. This makes it less satisfactory for domestic use or small-scale transport. One solution is to use high-pressure, ambient-temperature storage, but conventional gas cylinders only hold about 2% of their weight in hydrogen. Very-high-pressure (400 atm) light vessels are being developed using a carbon-fiber overwrap on a relatively weak alloy inner membrane. Such a vessel can hold more than 12% of its weight of hydrogen.

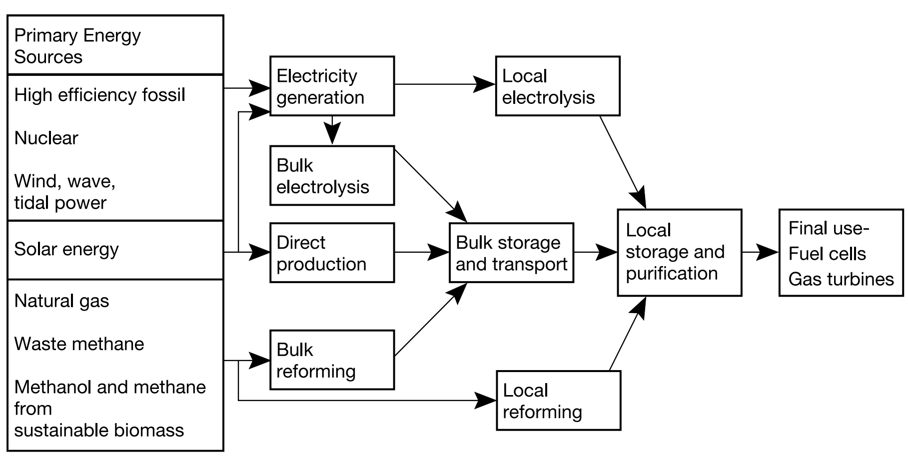

Figure 1. Main processes and options for achieving the hydrogen economy.

Hydride storage is also possible, and there is the exciting prospect of delivering hydrogen to cars in the form of a hydride slurry at a central fueling station. So far, hydrogen storage densities of only 3–5% by weight are possible, and for most suitable hydrides, temperatures ~300°C are needed to liberate the hydrogen. Also possible is adsorption storage on a material with a high internal surface area. An extremely important future prospect is based on the observation that carbon nanotubes can adsorb a large fraction of their weight of hydrogen at moderate pressures without the use of very low temperatures.[13] Currently, carbon nanotubes are expensive but the use of laser vaporization should eventually enable the production of the material in large quantities at a manageable cost.

The development of low emission cars is stimulating the development of fuel cells. The concept of directly producing electricity by oxidation of fuels has been around for over 150 years and fuels cells have been effectively used in space applications. There are a number of options for fuel cells. Previous attention has been focused on high-temperature fuel cells using either solid oxide (zirconia) or molten carbonate electrolytes. The solid oxide is attractive since it is relatively resistant to contamination by hydrocarbons and indeed can use fossil or biofuels instead of hydrogen, but it runs at ~500°C. Such fuels cells have a long way to go to be competitive with hydrogen-driven, internal-combustion engines or microturbines.

Attention is now turning to the proton-exchange-membrane fuel cell. This has a polymer membrane that allows protons but not oxygen or electrons to pass. A platinum catalyst dissociates the hydrogen. This type of fuel cell is easily contaminated and needs purified hydrogen. Prices of such a fuel cell have dropped substantially in the last 10 years, and the technology promises to be competitive with the internal-combustion engine in the foreseeable future. Further development rests on the low-cost production of multiple-layer membrane units to make stacks of cells.

Hydrogen has an important advantage for aviation—it has a specific energy over 3× that of current aviation fuels, which means (taking into account the energy saved in carrying the fuel) that fuel loads could cut by up to a factor of 5. This more than compensates for the factor of 4 difference in energy content per unit volume for liquid hydrogen, which is the obvious way of storing the fuel. Current turbojet designs have been adapted for hydrogen burning, and there is the potential for even cleaner, more efficient engines if suitable materials for combustion chambers and turbine blades can be developed. The question remains as to why hydrogen has not yet been adopted. The current price of liquid hydrogen is close to the value needed to displace conventional aviation fuel if the other factors inhibiting a change can be overcome. Perception of safety is a key factor, and work is needed on establishing safety procedures at airports and in flight. There is also the inertia of providing the facilities for hydrogen fueling and the need to establish cheap, reliable sources of hydrogen, as described earlier. The change to hydrogen for civil aviation could begin in the next 30 years, and by the end of the century, there is the prospect of making hydrogen-fueled, hypersonic, suborbital flight commonplace.

A generic issue associated with the increasing use of hydrogen that directly affects materials choice and operating regimes is hydrogen embrittlement and hydride cracking of structures. These problems have received considerable attention over many years, and a good basis of understanding has been achieved.

Conclusions

This overview has illustrated the complex needs for innovative materials for application to energy systems. Table II offers a concise summary of the position.

Table II: Summary of Requirements for Innovative Technology and Materials in Energy Use.

Primary Energy	Fossil Fuels: Gas, coal, oil, waste methane Methane and methanol from sustainable biomass		Renewables: Wind, wave, and tidal power Solar Hydropower Geothermal		Nuclear Power: Fission and fusion
Technology Requirements	Carbon dioxide removal Carbon storage Carbon fixation	Reforming and pyrolysis for hydrogen production Direct hydrogen production Hydrogen storage and transport	Gas turbines High-efficiency internal-combustion engines Flywheel storage Fuel cells Batteries	Large structures for generation Drilling and rock fracture technologies	High-temperature gas-cooled reactors Plutonium and actinide waste-burning reactors and hybrid systems Tokamak fusion reactors Inertial confinement systems
Materials Requirements	Specialized membranes Polymer electrolytes, catalysts, and electrodes Advanced photovoltaic materials Optical-spectrum-tailored plastics and coatings Carbon nanotubes Metal hydride slurries High-temperature superconductors		Low-cost, low-energy civil engineering materials Light, cheap, efficient insulating materials Light, strong, composite structures Very-high-temperature alloys, ceramics, and composites		Radiation-resistant materials Low activation materials Corrosion-resistant and stress-corrosion cracking-resistant materials Mechanical and plasma erosion-resistant materials

The membranes, coatings, composites, and structured alloys that will have to be developed to satisfy these requirements increasingly depend on the ability to control composition and structure at the nanoscale level. The real challenge lies in the design and fabrication of materials optimized to meet the demands for energy technologies. Although great progress has been made in the last 100 years, materials science is at the threshold of even greater improvements in the capacity of materials to cope with extreme environments and exotic electronic behavior. Our continued prosperity, the future development of less fortunate parts of the world, and the safety of our environment depend on the progress that can be made with these advanced materials.

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