Alternative energy technologies

M. S. Dresselhaus* & I. L. Thomas†

*Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA
†Office of Basic Energy Sciences, U.S. Department of Energy, 19901 Germantown Road, Germantown, Maryland 20874-1290, USA

Fossil fuels currently supply most of the world's energy needs, and however unacceptable their long-term consequences, the supplies are likely to remain adequate for the next few generations. Scientists and policy makers must make use of this period of grace to assess alternative sources of energy and determine what is scientifically possible, environmentally acceptable and technologically promising.

Modern lifestyles demand a steady, reliable supply of energy: it lies at the heart of our mobility, our prosperity and our daily comfort. But we should not take this energy security for granted. Energy sources can be divided into three broad categories. The first derives from chemical or photophysical energy that relies on oxidizing some reduced substance, usually a hydrocarbon, or absorbing sunlight to generate either heat or electricity. The energy involved is that of a chemical bond or fractions of an electron volt (eV). The second involves nuclear reactions that release energy either by splitting heavy nuclei or by fusing light nuclei. The energy involved in nuclear reactions is in the region of 10^6 electron volts (MeV) per nuclear reaction. The third is thermomechanical in the form of wind, water, or geological sources of steam or hot water. The energy involved is in the milli-electron-volt (meV) region from, for example, water falling several tens of metres. The current usage of these various energy sources is depicted in Fig. 1.

Each energy source has some undesirable characteristics. Any process using fossil fuels produces carbon dioxide, and perhaps also other contaminants, such as nitrogen oxides, sulphur oxides and ash. Nuclear plants produce radioactive fission products. Hydroelectric plants require dams and large lakes. Solar energy and wind energy require large areas and are limited geographically. Geothermal sources are limited to very few locations. Schemes using small temperature gradients in the earth or oceans have low thermal efficiencies, and hence require very large heat-exchanger areas.

At present most of the world's energy supply comes from fossil and nuclear sources (see Fig. 1). And although mankind is increasingly having to face the issues of resource limitation and environmental pollution, these sources will continue to be important in providing energy worldwide for the next few generations. Below, accordingly, we look briefly at the prospects for these energy sources, emphasizing the importance of addressing the issue of CO_2 sequestration now, and keeping the nuclear energy option open. But to meet increasing global demands for energy and to allow for the depletion of fossil fuel supplies in the coming years, alternative 'clean' energy sources, which do not depend on fossil fuels and which have a tolerable

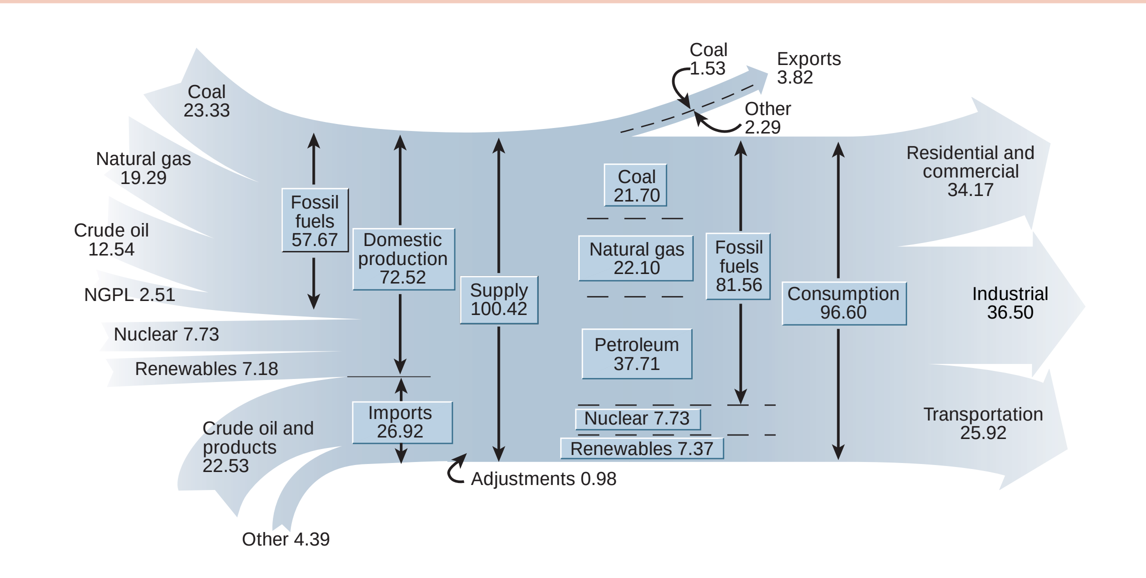

Figure 1 Energy flow diagram for the United States for 1999, in quads (1 quad = 10^{15} British thermal units = 2.9×10^{11} kWh). The average energy consumption in the United States is 0.4×10^{-6} quads per person per year, and the US population is about 5% of that on planet Earth. Energy consumption is large compared with food consumption (1.2×10^4 kJ per day per person , which translates to only 0.4×10^{-8} quads per person per year). Some corresponding numbers for world energy consumption for 1999, in quads, are: petroleum 149.7; natural gas 87.3; coal 84.9; nuclear 25.2; hydro, geothermal, solar, wind and other renewables 29.9; total world energy production is 377.1 quads (ref. 8).

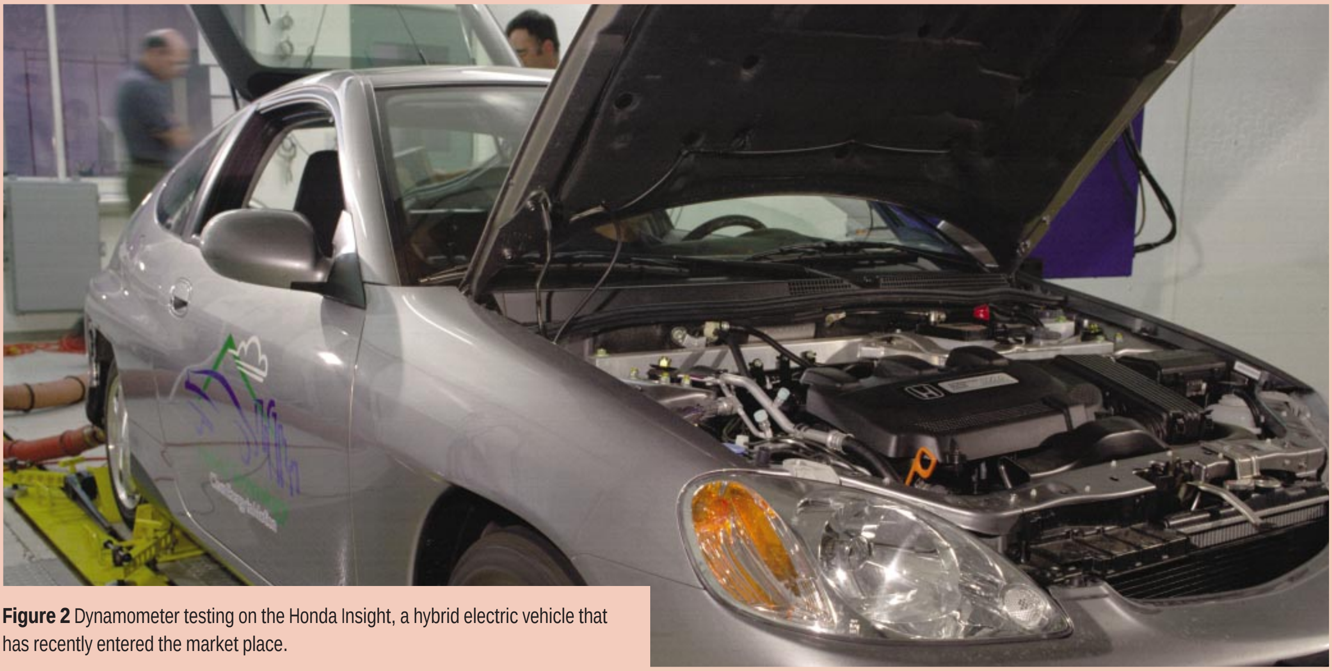

Figure 2 Dynamometer testing on the Honda Insight, a hybrid electric vehicle that has recently entered the market place.

environmental impact, must be developed. The five following articles[1–5] review the present status of several such sources. Renewable means of producing and storing electricity are expected to be increasingly important in the future and, given the recent strides in condensed-matter physics and materials technology, could compete with existing technologies. For technologies using renewable energy sources, remarkable steps forward are taking place in the fields of fuel cells and solar cells. To use renewable sources effectively, reliable ways of storing energy are needed: exciting developments are being made in hydrogen storage, rechargeable batteries and high-temperature superconductivity. In this overview, we comment on the challenges and opportunities offered by the various alternative energy sources. . Ultimately, the energy security of future generations will not only depend on reaching acceptable scientific and technological solutions, but will also require international cooperation on science policies to ensure continued prosperity and the safety of our environment.

Fossil energy

Although supplies are finite, currently there is no shortage of fossil fuels. World reserves of oil are about 1.6×10^{14} l (1×10^{12} barrels). World consumption is about 1.2×10^{10} l a day. World reserves of natural gas are about 1.4×10^{14} m^3; gross production of gas is about 2.4×10^{12} m^3 per year. World coal reserves are about 9.1×10^{11} tonnes; annual consumption is about 4.5×10^9 tonnes per year. The problems with fossil fuels for the near term are distribution and recovery, and these problems differ in detail for each of the fuel types. Much of the oil in a reservoir is not recovered because of surface tension. After primary recovery and water injection, most of the oil is left in pores as oil drops that are larger than the connecting necks of the porous formation. More could be recovered by injecting surfactants or pressurized CO_2 to reduce surface tension, but these approaches are expensive and technically challenging. Ultimately, the oil reservoir becomes a complicated research problem in the physics of multi-phase flow through porous bodies, solution chemistry, and critical phenomena in multi-component fluids. Underground coal mines have to leave large amounts of coal as structure to support the mine. Strip mining, which can remove essentially all of the coal, can have substantial environmental downsides. Gas is difficult to transport except through pipelines, and pipelines are not viable across oceans. It can be liquefied and transported more easily as a cryogenic liquid, or converted to liquid fuels; however, better catalysts with greater selectivity are needed to make these processes cost-effective.

Finally, there are vast reserves of ‘unconventional’ fossil fuels, such as tar sands, oil shale and gas hydrates. Much research would need to be done to be able to extract energy from these economically and in an environmentally acceptable way. It is likely that the environmental cost of extracting and burning fossil fuels will mount too high, well before we run out of fossil fuels, and it is expected that it will take a long time to develop and deploy viable alternatives.

The main difficulty with fossil fuels is that they all produce CO_2 — natural gas the least, coal the most. It is possible to sequester the CO_2 — storing it as a gas or in solution underground or in the deep ocean, for example — but at some cost, both in money and in the energy expended in pumping the CO_2 from where it is produced to where it will be stored. The very idea of sequestration also raises questions. Would it prove stable in the long term? If there were a sudden release of sequestered CO_2, what would be the short-term consequences? Only increased research in geosciences can answer these questions. As fossil fuels will remain a dominant energy source for the near term, national policy to support research into CO_2 sequestration now is essential.

Electric cars represent one approach to reducing undesirable emissions from conventional internal combustion engines in heavily populated areas. As about two-thirds of the world's total electric power is generated from fossil fuels, electric cars ultimately consume mostly fossil fuels. But it is possible to produce electricity in areas of low population density, and electricity can be generated from sources, such as hydroelectric and nuclear energy, that do not produce greenhouse gases. The problem with electric cars is the storage of electric power. As yet, there is no battery that has the energy density of petrol, and battery recharging is far slower than filling a petrol tank. Also, the lifetimes of batteries need to be improved, and much lighter and non-toxic battery materials must be found to replace heavy metals like lead. An interesting concept that is now being tested is a hybrid vehicle with a small, very efficient petrol engine to recharge its batteries and to drive the vehicle after the electric motor has accelerated it. Braking also helps to charge the batteries; and because of the reserve electric motor, the petrol engine can be quickly restarted after every stop and need not idle, thereby resulting in high fuel efficiency (Fig. 2). Basic science is also playing an important role in,

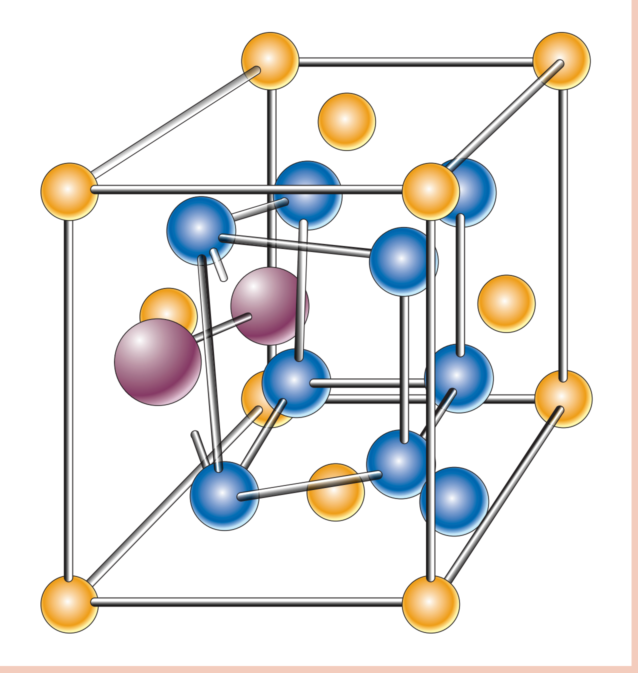

Figure 3 The structure of CeO_2 used in automobile catalytic converters as an oxygen source. Recent basic research[9] using pulsed neutron scattering techniques combined with model calculations shows that the 'active oxygen' ion pairs for oxygenation are those found at interstices in the lattice – the octahedral sites (shown in purple). This result explains how to control oxygen in the catalytic converter so that NO_x can be reduced and CO can be oxidized in the same device. It also highlights how research at the most fundamental level is needed to address the problem of finding better catalytic materials.

for example, developing better catalytic converters for removing toxic species from automobile exhausts, while optimizing fuel efficiency. Even highly efficient engines produce oxides of nitrogen and carbon monoxide and will need catalytic converters (Fig. 3).

Nuclear energy

In the United States, nuclear energy from fission is now at a crossroads from which it will either set off on the path of recovery as a practical energy source, or slowly see each of its nuclear plants shut down as they reach the end of their useful life. The fission process does not emit any CO_2, and from the standpoint of global warming, nuclear energy provides an ideal source. But the public has very real fears of nuclear energy that must be respected, understood and alleviated if this energy source is to remain viable (Fig. 1). Because of public sentiment, few nuclear power plants have been built worldwide in recent years. Reactors have to be made inherently safe and the problem of nuclear waste disposal must be solved. The scientific issues here are mostly in understanding long-term effects in the waste itself and in the repository, such as salt formation or stable rock formations. In the United States, the proposed site in Yucca Mountain is based on a volcanic rock called tuff. We need much better models to predict the stability of materials, such as glass, being irradiated for millennia and to predict the behaviour of the repositories under various situations that might arise (for example, a repository may flood or its humidity may change) until the radioactive elements decay to background levels. To extend reactor lifetimes, it is also important to understand the effect of radiation on the materials within operating reactors. Radiation continuously alters the structure of the material by displacing atoms and creating vacancies, often making a ductile material brittle. Nonetheless, science policy must be aligned with keeping the nuclear energy option open to address uncertain future energy needs.

Fusion is another nuclear process that, in principle, could provide essentially limitless power. The Sun demonstrates that fusion works, but the engineering problem of confining ions at temperatures high enough to overcome the Coulomb repulsion and achieve net energy output has not yet been solved on Earth. Although fusion is basically a physics problem, the engineering challenges are substantial. Fusion reactors using magnetic confinement technology as currently envisaged would use a mixture of deuterium and tritium as fuel. Tritium can be produced by bombarding lithium (either ^6Li or ^7Li) with a neutron to yield tritium (T) and an α-particle (^4He), and would have to be recovered and injected into the plasma. Many difficult materials problems arise because of radiation damage, especially to the materials exposed to the energetic plasma. Those materials will be bombarded by 14 MeV neutrons and by energetic neutral atoms that escape from the plasma. The first wall of the fusion reactor will have to withstand the high stresses that could occur if the plasma lost confinement. Again, much needs to be done to demonstrate the feasibility of fusion technology and to make it competitive with other options.

Alternative energy sources

As fossil fuel supplies are expected to be less available, more expensive and of increasing environmental concern in the coming century, increasing dependence on energy conservation and alternative energy sources is expected. The most obvious alternative energy source is the Sun. When the Sun is directly overhead and the sky is clear, radiation on a horizontal surface is about 1,000 W m^{-2}. To take the United States as an example, the total amount of solar energy falling on the continental 48 states is about 4.67×10^4 quads per year (a quad, derived from 'quadrillion', is 1.05×10^{18} J or 2.9×10^{11} kWh), well in excess of the 98.6 quads that the United States consumes annually (Fig. 1). Currently about 0.08 quads is produced each year in the United States from solar thermal energy and from solar photovoltaics, which convert sunlight to electrical energy. Photovoltaics and solar cells have, in fact, provided reliable electrical power to space missions for many years. Sunlight can be used for heating, lighting and electricity generation, and it can be concentrated to provide steam to run turbines. In the summer and in the hotter areas of the United States, the availability of solar energy peaks when the demand for electricity peaks. The principal disadvantages of solar energy are that at present the conversion efficiency of sunlight to electric power is not high, and sunlight varies with time of day, weather conditions and season.

Photovoltaics and photoelectrochemical cells have not yet made a strong contribution to the energy supply because of their low conversion efficiencies and relatively high cost. Therefore, research has focused on developing materials with improved performance. Steady progress has been made in this quest. Grätzel, in this issue[1], provides a concise review of the historical background, and the physics and materials science issues that are involved in photoelectrochemical cells (Fig. 4). He also points to a number of newly emerging research opportunities that could substantially improve the performance and reduce the cost of photoelectrochemical cells or photovoltaics, thereby making it practical, for example, to use existing roofs as solar collectors. On average, over a large enough region, solar roofs tied to a grid could reduce peak daily electricity demand significantly. With the use of electronic band theory and modern computational capabilities, multi-junction photoelectric devices have been designed that use III–V compound semiconductors[6,7] (Fig. 5) to achieve conversion efficiencies of over 30%. These impressive advances with inorganic solid-state junction devices are now being strongly challenged by new classes of materials, such as films containing nanocrystalline structures, quantum dots and nanostructured conducting polymers. These films typically contain nanoparticles with a size distribution showing a wide range of electronic band gaps (it is this gap that determines which wavelengths are absorbed), so that much of the solar spectrum can be captured by the solar cell. If such films can be made cheaply, with an

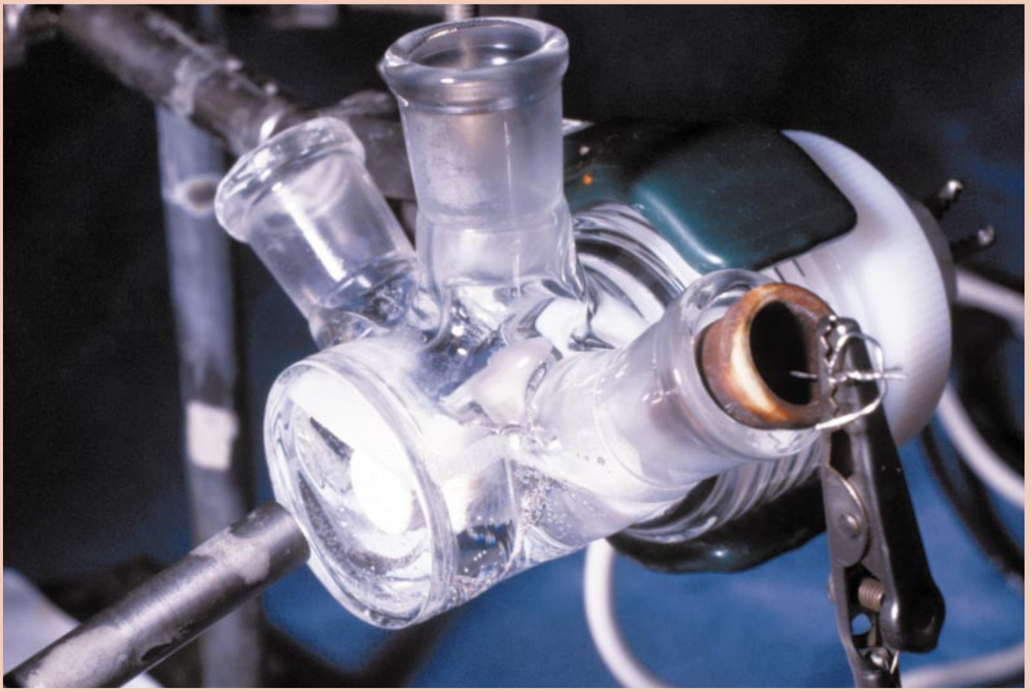

Figure 4 Photoelectrolysis occurring in a multi-junction cell, as a concentrated light source on the left is used to dissociate water to hydrogen and oxygen (which are observed as bubbles). The theoretical efficiency for tandem junction systems is 42% in converting the absorbed light into hydrogen production. Practical systems could achieve 18–24% efficiency; and low-cost multi-junction systems could achieve 5–12% efficiency[10,11].

optimized distribution of nanoparticle diameters, and can be properly aligned, one might have an ideal solar collector. This field is still very young, and is moving rapidly[1].

Closely related to solar cells are fuel cells, which convert fuel or chemical energy directly to electric energy. The main chemical reactions involve the oxidation of CO and H_2. As explained in the review article by Steele and Heinzel[2], fuel cells consist of an anode, cathode and electrolyte, just as in a typical battery. Although fuel cells have been operated reliably and efficiently in space missions for more than 40 years, they have not yet been widely used on the Earth, largely because of their cost. To make this technology commercially competitive, better anode, cathode and electrolyte materials and processes are needed[2]. The various types of fuel cells now under development are critically reviewed by Steele and Heinzel[2], including polymeric electrolyte membranes and phosphoric acid fuel cells, both operating under ambient conditions, and the solid oxide and molten carbonate fuel cells, operating at higher temperatures. The efficiency of fuel cells is limited primarily by the diffusion of the fuel, oxygen and combustion products to and from the electrodes through the electrolyte. Phosphoric acid fuel cells are commercially available today and generate electricity at more than 40% efficiency. Polymer or proton-exchange-membrane fuel cells operating at about 90 °C are currently the best candidates for automotive use[2].

If we had better ways of storing the hydrogen, then hydrogen-based fuel cells would look much more promising[2]. Most hydrogen is currently made by steam reforming of hydrocarbons. Hydrogen can also be made by heating coal to about 1,000 °C in the absence of oxygen, by partial burning of coal in the presence of steam, or by electrolysis. The reactions with coal make a mixture of H_2 with CO, CO_2 and other gases, which have to be separated from hydrogen. Generation of CO_2 can be avoided only if the electricity is generated from nuclear, hydroelectric, wind, solar or geothermal energy. The potential for photochemical production of hydrogen, using sunlight to dissociate water, is assessed in the review by Grätzel[1]. Also under consideration are microbial pathways for the production of hydrogen (Fig. 6), a hint of the increasing role that the biosciences are expected to play in alternative energy technologies.

Hydrogen is attractive as a fuel because its oxidation product (water) is environmentally benign, it is lightweight and it is highly abundant. But storage is a problem, as Schlapbach and Züttel[4] strongly emphasize. In their review article, the characteristics of hydrogen as a fuel are discussed, but the focus is on how we would store the hydrogen to be used as fuel for a fleet of automobiles, or for fuel cells. Recent interest in using carbon nanotubes as a storage medium, making use of their high surface area and light weight, is critically reviewed[4], but the authors are not convinced that reversible hydrogen storage can be achieved in carbon nanotubes under

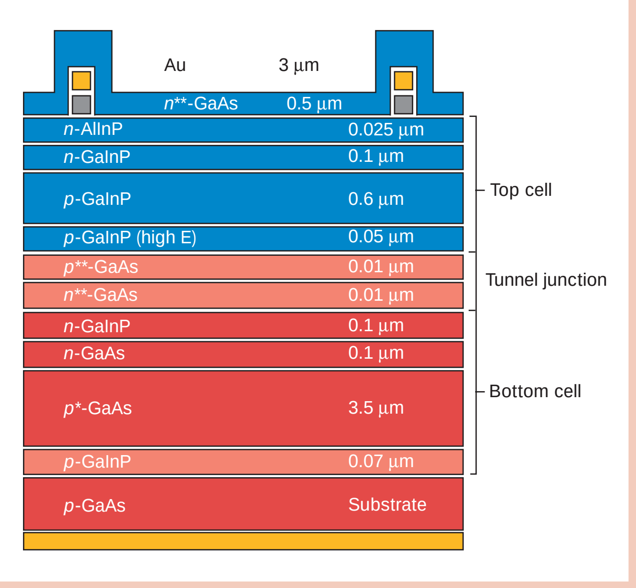

Figure 5 This multi-junction device uses a top cell of gallium indium phosphide and aluminium indium phosphide to absorb high-energy photons, transmitting lower-energy photons to the bottom cell where they are absorbed by the gallium arsenide and gallium indium phosphide junctions. A 'tunnel junction' is used in the middle of the device to aid the flow of electrons between the top and bottom cells. The different band gaps of the top and bottom junctions permit more efficient absorption of the solar spectrum. An anti-reflection coating and gold contacts are used above the top cell. This kind of solar cell has achieved over 30% efficiency under concentrated light[6,7].

Figure 6 Certain algae, whose chlorophyll give a green colour to the fluid, produce hydrogen in the presence of light. In engineered systems available today, 24% of the photosynthetic product is hydrogen rather than glucose. The photosynthesis process itself is about 1% efficient in converting light into chemical energy[10].

reasonable operating conditions. They conclude that metal hydrides are the most promising materials for hydrogen storage, especially the lightweight metal alloy hydrides. Getting high hydrogen uptake is only part of the problem: much materials research will be needed to obtain controlled hydrogen release under practical conditions of temperature and pressure, and rapid hydrogen filling of the storage medium by recycling. Despite the interest and activity in hydrogen storage research, no breakthrough is yet in sight.

One alternative energy storage technology that has already taken off in a big way is the rechargeable lithium-ion battery. This technology has become a commercial reality through the efforts of the Sony Corporation and others, and is used widely today in portable computer and telecommunications devices, especially as these devices get smaller and more efficient. Demand and competition is driving the quest for higher storage capacity, longer operating times, faster recharging times, and other optimization of performance. Steady progress has been made by using improved materials for the anode, cathode and electrolyte, and the interfaces between them. Tarascon and Armand[3] present an optimistic review of the technology, covering its historical background, its present status, and the challenges and opportunities now on the horizon. Three areas of opportunity, also common to most of the other alternative energy technologies, are compellingly presented: advances in nanostructured materials provide a chance to improve both anode and cathode performance; new *in situ* characterization techniques are helping to identify materials problems in a format that permits rapid assessment of possible solutions; and advanced computer simulation modelling promises rapid progress in surveying new combinations of materials and geometries.

To get the best out of any alternate energy technology, improvements need to be made in energy storage and energy transmission. Superconductors are being seriously considered for both roles. For superconducting magnetic energy storage (SMES), electric energy is stored by circulating a current in a superconducting coil. Because there are no resistive losses, the current persists indefinitely. The efficiency of charging and discharging is very high because no energy conversion is involved, and for the same reason SMES can respond rapidly, with a response that is limited by the time required for conversion between d.c. and a.c. power. SMES can also be used for load levelling and for frequency and voltage control, which will probably be the first applications of this technology. Superconducting transmission lines could reduce resistive losses, but require energy for cryogenic cooling of the cables. It should be possible to use existing tunnels for these cables, thereby reducing cost while increasing the transmission capacity.

All large-scale applications of superconductors to energy storage and transmission will depend on achieving high critical current densities (J_{ct}) to be cost-competitive with other technologies. At present, niobium–titanium alloys are used for both storage and transmission at liquid helium temperatures. To use superconducting materials with higher critical temperatures for these energy-related applications will require additional research and development. Larbalestier[5], in his review, considers strategies for increasing J_{ct}: in particular, by increasing the 'pinning' of magnetic flux lines to avoid energy losses from movement of magnetic vortices, while reducing losses owing to grain boundary and other defects. He also considers desirable attributes and criteria for selecting materials. Research is aimed at increasing the fraction of the cross-sectional area of the superconducting wire that is actually carrying the high current density. Both physics and materials science issues are being tackled. For all of these applications, high powers will be involved, so careful consideration must be given to the consequences of an accidental loss of coolant: an enormous amount of energy would be released the instant the superconductor became a normal conductor (10 MWh of stored energy is equivalent to 1.18 tonnes of TNT).

Research and science policy considerations

There is a great lack of public appreciation of the scientific and technological difficulties in supplying energy once fossil fuel sources become seriously depleted. The supply is adequate now and this gives us time to develop alternatives, but the scale of research in physics, chemistry, biology and engineering will need to be stepped up, because it will take sustained effort to solve the problem of long-term global energy security. To replace petrol or diesel oil with fuels of equivalent energy densities is going to take much greater understanding and control of chemical reactivity than we have now. To recycle CO_2, energy has to be converted to chemical bonds, and this conversion must be done very efficiently, for example as nature converts CO_2 and water to glucose using light. We need to understand energy and charge transport in molecular assemblies and across interfaces and membranes. We need to understand transition-state chemistry well enough to make selective and high-activity catalysts, essentially the equivalent of enzymes. And we need to understand how van der Waals forces, electrostatic forces and hydrogen bonding can be used to control molecular assembly and restrict reaction pathways.

Further great challenges lie in making the substantial improvements in materials that are needed to increase efficiency in the generation, conversion, transmission and use of energy. For example, the most effective way to increase fuel economy in automobiles is to lower their weight, and we are starting to see more vehicle components being made of lightweight, tough and strong composite materials. One reason for optimism is that physics, chemistry, biology and engineering research are now converging at the nanoscale. Many of the sub-cellular components that nature uses to make fuels and composite materials (wood, bone and shell, for instance) are at the nanoscale, including vital proteins, such as enzymes, photosynthetic units, molecular motors and cell membranes. For their part, physicists and chemists have developed many wonderful techniques to image, manipulate and interact with nanoscale objects in real time, and much progress is being made in developing theoretical tools for studying assemblies of atoms on these scales.

In addition to advancing alternative energy technologies, research is also needed to manage fossil fuel resources better. Even though locating oil reservoirs using seismic techniques is highly developed, more effective oil extraction will require finer resolution and more accurate three-dimensional reconstruction of an image of an underground formation from the scattered wave. In exploiting any reservoir, mine or energy technology, we need to take environmental effects and waste disposal processes into consideration. Much more needs to be done to understand how various species flow and react in heterogeneous soils and formations. Complex chemical reactions in solution, reactions and ion exchange with soils, combined with flows through porous rocks in the presence of microorganisms, make this research very difficult.

These difficult scientific and technological problems in energy involve not only all of the sciences, but also science policy. Energy policy will differ among nations according to circumstance and national objectives, but many of the issues require international cooperation. All nations share the atmosphere of our planet, and all benefit from reduced emissions of pollutants. A healthy global economy benefits both producers and consumers of energy. International cooperation is especially important in basic research, and such cooperation should continue to be strongly encouraged. As energy plays such a vital role in society, it is important that policy, science and technology work together harmoniously; global energy security problems cannot be solved if the three components work in isolation. Policy determines what is acceptable, science shows what may be possible, and technology demonstrates what, within acceptable constraints, is practicable. □

1. Grätzel, M. Photoelectrochemical cells. *Nature* **414,** 338–344 (2001).
2. Steele, B. C. H. & Heinzel, A. Materials for fuel-cell technologies. *Nature* **414,** 345–352 (2001).
3. Tarascon, J.-M. & Armand, M. Issues and challenges facing rechargeable lithium batteries. *Nature* **414,** 359–367 (2001).
4. Schlapbach, L. & Züttel, A. Hydrogen-storage materials for mobile applications. *Nature* **414,** 353–358 (2001).
5. Larbalestier, D. High-T_c superconducting materials for electric power applications. *Nature* **414,** 368–377 (2001).
6. Bernard, J. E., Wei, S. H., Wood, D. M. & Zunger, A. Ordering-induced changes in the optical spectra of semiconductor alloys. *Appl. Phys. Lett.* **52,** 311–313 (1988).
7. Wei, S. H. & Zunger, A. Band-gap narrowing in ordered and disordered semiconductor alloys. *Appl. Phys. Lett.* **56,** 662–664 (1990).
8. Energy Information Administration Office of Energy Markets and End Use. *Annual Energy Review 1999* <http://www.eia.doe.gov/aer> (US Department of Energy, Washington DC, 2000); *International Energy Annual 1999* <http://www.eia.doe.gov/aer> (US Department of Energy, Washington DC, 2001).
9. Mamontov, E. & Egami, T. Structural defects in a nano-scale powder of CeO_2 studied by pulsed neutron diffraction. *J. Phys. Chem. Solids* **61,** 1345–1356 (2000).
10. Grätzel, M. in *CATTECH: the Magazine of Catalysis Sciences, Technology and Innovation* Issue 5 Vol. 3 No. 1, 4–17 (Baltzer Science Publishers, 1999).
11. International Energy Agency. *IEA Agreement on the Production and Utilization of Hydrogen*. 1999 Annual Report IEA/H2/AR-99 (ed. Elam, C. C.) p. 37 <http://www.osti.gov/servlets/purl/774832-xO3oJD/webviewable/774832.pdf> (1999).

Acknowledgements

We acknowledge fruitful discussions with many colleagues; G. Dresselhaus and P. Dehmer in particular have offered valuable suggestions.