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Electrochemical power sources: key agents for energy sustainability(Ⅰ)

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Abstract: There is mounting concern over the sustainability of global energy supplies. Among the key drivers are: (i) global warming, ocean surface acidification and air pollution, which imply the need to control and reduce anthropogenic emissions of greenhouse gases (especially carbon dioxide), nitrogen oxides, sulfur oxides, unburnt hydrocarbons and fine particles; (ii) the low estimated reserves of oil and natural gas; (iii) the need for energy security adapted to each country, such as decreasing the dependence on fossil-fuel imports (in particular, the vulnerability to volatile oil prices) from regions where there is political or economic instability; (iv) the expected growth in world population with the ever-increasing aspiration for an improved standard-of-living for all. Hydrogen is being promoted world-wide as a total panacea for energy problems. As a versatile carrier for storing and transporting energy from any one of a myriad of sources to an electricity generator, it is argued that hydrogen will eventually replace (or at least greatly reduce) the reliance on fossil fuels and thereby also avoid/ decrease emissions of carbon dioxide. Not unexpectedly, the building of a 'Hydrogen Economy' presents great scientific and technological challenges in the production, delivery, storage, conversion and end-use of this energy vector. In addition, there are many policy, regulatory, economic, financial, investment, environmental and safety questions to be addressed. Notwithstanding these obstacles, it is indeed plausible that hydrogen will become increasingly deployed and will compete with traditional systems of energy storage and supply. Future roles for electrochemical power sources ——batteries, supercapacitors, photoelectrochemical cells and fuel cells ——on the pathway to universal energy sustainability in stationary, mobile-power and road transportation applications are examined.

Key words: power sources; energy; sustainability; hydrogen

1 Society and energy in transition

The mastery of energy has always been the key to a better standard-of-living. The concept of energy is, however, difficult to understand ——it is an abstract quantity that manifests itself in many forms, namely, chemical, electrical, mechanical, radiant, nuclear and thermal energy. In an electrical power station, for example, fossil fuel (chemical energy) is converted via steam to mechanical energy and then, via an alternator, to electrical energy. In an electric vehicle, a battery is used to convert chemical energy into electrical energy, which is then converted to mechanical energy by a motor. Thomas Young (1773～1829), an Englsh physicist, has provided us with the most astute definition: 'energy is the ability to do work.' It is commonly understood that 'work' means the application of effort to accomplish a task and the rate at which work is performed is called 'power'. Thus, machines consume energy, perform work, and provide power. Further, the 'efficiency' of a machine is a measure of its performance obtained from the ratio of energy output to energy input. The efficiency must always be less than 100 % (which would imply perpetual motion).

The first major source of energy to be exploited by humankind was wood, which was burnt for heating and cooking. Power was derived mainly from human and animal muscle (horses, oxen, camels, etc.), from the wind (windmills and sailing ships), and from water (watermills). Even with these limited resources, however, some of the achievements were remarkable. Consider, for instance, the ancient pyramids of Egypt, the Great Wall of China, and the great cathedrals of Europe.

As populations expanded and became urbanized, wood was less readily accessible and coal assumed greater importance for heating

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purposes. Following the introduction of rotative steam engines in the 1780s that heralded the dawn of the Industrial Revolution, coal was used as the prime source of energy for the production of mechanical power. Steam engines propelled ships, railway locomotives and traction engines, and also provided a universal means for generating power in factories and on farms.

Late in the 19th century, the internal combustion engine was developed. Liquid petroleum was discovered ——first in USA and then across the world ——and was refined to provide fuels for both petrol and diesel engines. With its greater efficiency and convenience, this new technology soon replaced steam engines for most applications. Consequently, in many countries the use of coal declined (at least in percentage terms), while that of petroleum grew rapidly.

Since the mid 20th century, natural gas fields have been discovered in abundance. Some of the gas is associated with oil wells, but is found on its own in other places. Where oil wells are remote from centres of population, the gas was initially seen as a by-product that had no commercial value and was therefore flared. This situation changed with the development of technology for liquefying natural gas, and conveying it to market by road or by sea in cryogenic tankers. Thus, once considered to be a waste product associated with oil, natural gas is now regarded as a prime fuel.

In summary, starting with wood (a form of biomass), mankind has moved to fossil fuels ——first to coal, then to petroleum and latterly to natural gas ——to provide the energy needed by society. Electricity also is a useful form of energy, but this is a secondary fuel since it manufactured from primary energy sources. In the mid 1950s, commercial nuclear power was added to the range of primary energy sources.

Increasing concern is being expressed over the heavily reliance of the world on fossil fuels (coal, oil, natural gas) as its major sources of energy for heating, mechanical power and electricity generation. There is overwhelming evidence that the unfettered use of such fuels will not deliver ‘energy sustainability’. That is, it will not maintain economic growth and cultural traditions whilst proving energy security and environmental protection.

1.1 Petroleum depletion

Most geologists and petroleum engineers are of the opinion that the Earth's ultimate reserves of economically-recoverable petroleum are in the region of 2000 billion barrels, of which over 40 % has been used already. Moreover, it is claimed that 94 % of all available oil has been discovered. Some major oil-producing regions (USA, North Sea) have passed their peak production rates and many studies predict a decline in the global production of crude oil by as early as 2010, the so-called ‘Big Rollover’ (Fig. 1). If this is not serious enough, an even more alarming fact is that much of the remaining ‘conventional’ oil (over 60 %) is concentrated in just five Middle Eastern countries: Saudi Arabia, Iraq, Kuwait, United Arab Emirates, and Iran. New oilfields will probably be discovered, for instance in the countries of the former USSR and/or off the coast of West Africa, but are unlikely to compare in size with those of the Middle East and will not significantly change the overall picture. It is true that Alberta (Canada) and Venezuela have, respectively, vast reserves of ‘oil tars’ and heavy oil (bitumen) that can be mined and refined to petroleum. In principle, both resources are sufficiently extensive to replace much of the conventional oil supply, although at a considerably higher cost ——not only economically but also in terms of environmental impact.

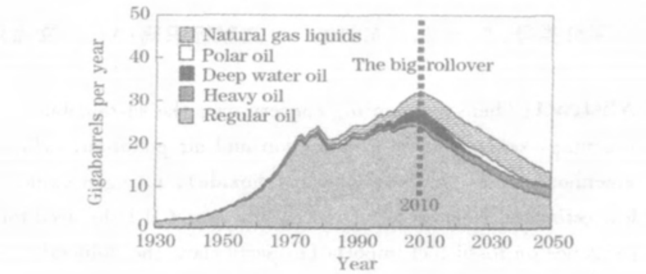

Fig. 1 Predicted life-cycles of oil production

Between 1973 and 2002, the world consumption of oil increased by 40 % compared with 54 % for energy as a whole. This was because natural gas and nuclear power took over many of the duties formerly assigned to oil (e.g., electricity generation, space heating of buildings). Accordingly, the lower growth rate in oil consumption has not reflected the much larger increase in demand (90 %) from the transportation sector over the same period. The demand for petroleum will doubtless intensify as the developing countries aspire to western-style mobility. Indeed, by 2030 there could be a shortfall that is equivalent in energy to 6 000 nuclear reactors, Fig. 2. To bring future demand back into line with the supplies available, a five-or ten-fold increase in the price of a barrel of oil is certainly possible. It is salutary to recall that at US $20, the price until quite recently, a barrel of oil costs about the same as a litre of whiskey ——and the latter did not take geological ages to mature! Clearly oil was, and still is, grossly undervalued in terms of its usefulness to mankind and its finite reserves.

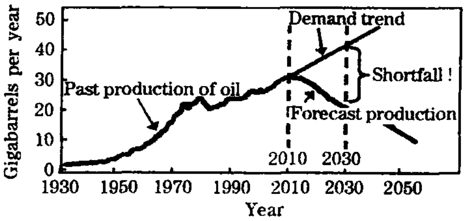

Fig. 2 Predicted global supply and demand for oil

1.2 Climate change

Of equal concern are the destructive effects of the growing levels of energy conversion and usage on the Earth's biosphere. Three facts seem incontrovertible: (i) the concentration of carbon dioxide in the atmosphere has risen steadily since the Industrial Revolution when fossil fuels started to be burnt in large quantities, Fig. 3a; (ii) carbon dioxide is a 'greenhouse gas' that absorbs infra-red radiation reflected from the ground and prevents its escape back into space; (iii) the Earth's climate is changing and generally warming, Fig. 3b. Most authorities link these three facts and conclude that carbon dioxide derived from fossil fuels is largely responsible for the observed change in climate. Moreover, small changes can have a huge impact. For example, the Arctic Ice Cap is rapidly disappearing (Fig. 4) and thereby exposing vast quantities of methane. Given that methane is more than twenty times as intense a greenhouse gas than carbon dioxide, its large-scale release to the atmosphere will exacerbate global warming. Is our Planet in danger of going into thermal runaway?

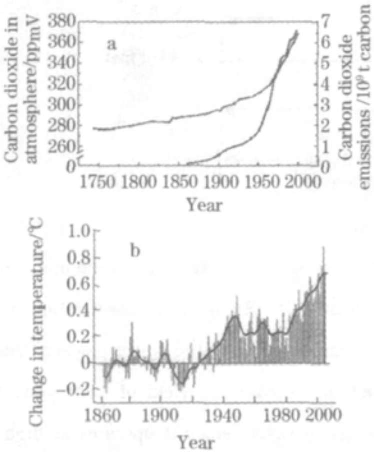

Fig. 3 (a) Atmospheric concentration of carbon dioxide from 1750 to 2000 (left axis) and global annual emissions of carbon (right axis); (b) global near-surface temperature averaged over land and ocean, 1860～2000

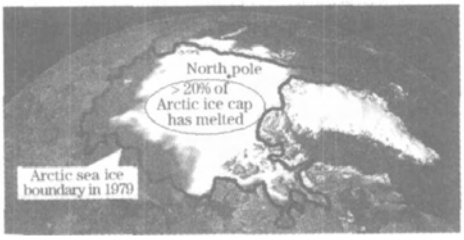

Fig. 4 Shrinkage of summer Arctic ice cap since 1979

1.3 Hydrogen: a new and sustainable energy vector?

Fossil fuels are laid down over geological time and once used, cannot be replaced on any realistic timescale. These fuels represent the world's energy capital. By contrast, many renewable (sustainable) forms of energy, i.e., those derived from wind, solar or marine (tidal, wave, ocean) sources, must be used as they are produced; otherwise, they are wasted. Other 'renewables' may have some storage element associated with them: biomass can be stored for short periods, while hydro energy is contained in lakes in mountainous regions or in reservoirs held back by dams. Geothermal energy, like fossil fuels, is retained underground until it is required. Renewables, which comprise the world's current account in energy, are widely available. Nevertheless, the world faces major problems in harnessing the resource ——many of the forms of this energy are small-scale, diffuse and, as yet, simply not cost-competitive with fossil fuels. Moreover, those that generate electricity directly have no storage component. Thus, there is growing support for the introduction of hydrogen as new and universal vector for storing and conveying both non-renewable and renewable types of energy and also as the ultimate non-polluting fuel. This proposition is commonly known as the 'Hydrogen Economy', Fig. 5. The counter proposition of increasing the deployment of nuclear power, which is not usually regarded as renewable energy but at least is carbon-free, is unpopular in many quarters because of concerns over radioactive waste. Some countries do, however, rely on nuclear power to provide an appreciable percentage of their domestic electricity requirements, e.g., France (78 %), Sweden (46 %), Ukraine (45 %), and Korea (36 %).

Hydrogen and electricity, which is also a secondary form of energy, are complementary: electricity is used for a myriad of applications for which hydrogen is not suitable, whereas hydrogen, unlike electricity, has the attributes of being a fuel and an energy store. These two energy vectors are, in principle, inter-convertible; electricity may be used to generate hydrogen by the electrolysis of water, while hydrogen may be converted to electricity by means of a fuel cell. It should be noted, however, that this electrochemical device is less than 100 % efficient so that there is a significant loss of useful energy in the inter-conversion.

While the 'Hydrogen Economy' represents a visionary strategy for our future energy security, its successful implementation is subject to two major requirements: (i) the individual technical steps must be connected by an infrastructure that provides seamless, safe and environmentally-acceptable transitions from production, to distribution and storage and then to use; (ii) hydrogen as an energy carrier must be economically competitive.

The present status of the functional areas that would facilitate such a radical change in global energy supply and use is reviewed briefly here and in a following (Dianchi, No. 2, 2006, April issue) paper.

2 Hydrogen production

2.1 Hydrogen from fossil fuels

The gasification of coal is the oldest means of obtaining hydrogen from fossil fuels. When heated in a restricted supply of air, coal undergoes pyrolysis to a mixture of hydrogen, methane and carbon monoxide (typically, 50 %, 35 % and 8 %, respectively), together with coal tar and coke. Alternatively, when heated coal is reacted with steam the 'water-gas reaction' occurs, i.e.,

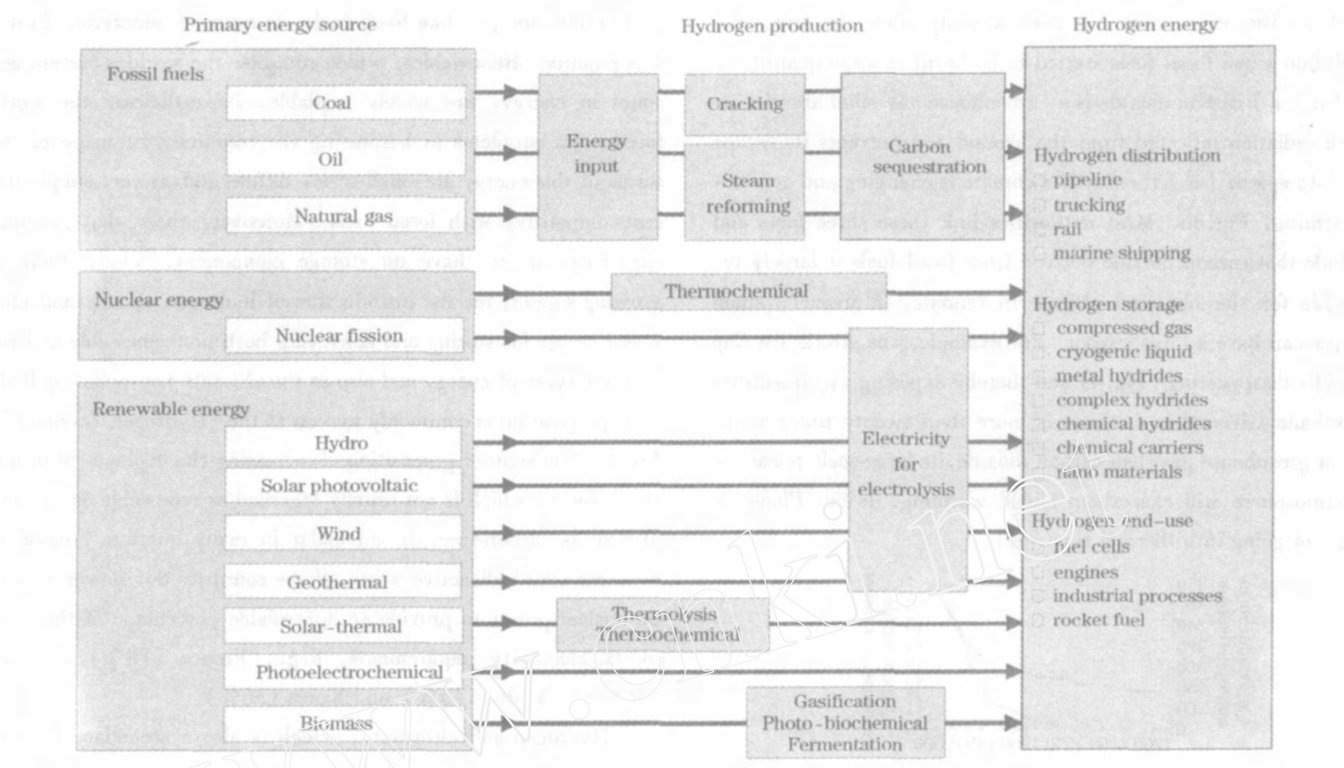

Fig. 5 A sustainable ‘Hydrogen Economy’

$$C + H_2O \xlongequal{} CO + H_2 \qquad (1)$$

The water-gas reaction is highly endothermic (heat absorbing) and thus soon ceases unless heat is supplied. Conversely, the combustion of coal or coke in air is highly exothermic (heat evolving). It is therefore usual to pair off the two reactions so as to balance the heat evolved with that absorbed. The two reactions may be conducted consecutively in short bursts or, more usually, simultaneously by feeding a mixture of air and steam to the heated bed. The resulting gas is a mixture of carbon monoxide, hydrogen, carbon dioxide, and nitrogen. This may be upgraded in terms of hydrogen content by the ‘water-gas shift reaction’. The gas is reacted with steam over a catalyst that converts carbon monoxide to carbon dioxide and increases the amount of hydrogen, i. e.,

$$CO + H_2O \xlongequal{} CO_2 + H_2 \qquad (2)$$

The carbon dioxide can be removed by a variety of gas-scrubbing techniques. The process engineering of coal gasification is quite complex. Nevertheless, several large-scale gasifierd have been developed. Research is also being conducted on similar technology for the processing of biomass and organic waste.

The steam reforming of natural gas is the most efficient and widely used process for making hydrogen. At present, it is also the cheapest route. The methane is reacted with steam and air over a nickel-based catalyst, i. e.,

$$CH_4 + H_2O \xrightarrow[\text{Ni catalyst}]{900\ ^\circ C} CO + 3H_2 \qquad (3)$$

The resulting product is known as ‘synthesis gas’ (or ‘syngas’) because it may be used for the preparation of a range of commercial products that include hydrogen, ammonia, methanol, and various organic chemicals. As with the gasification of coal, steam reforming can be combined with the water-gas shift reaction [reaction (2), above] to increase the yield of hydrogen. Steam reforming is very energy-intensive since it operates at high temperature (850～950 ℃) and high pressure (3.5 MPa). The thermal efficiency can reach 60 %～70 %.

The third method for producing hydrogen is ‘partial oxidation’ in which fuel and oxygen are combined in proportions such that the fuel is converted into a mixture of hydrogen and carbon monoxide. The amount of hydrogen is only about 75 % of that produced by steam reforming (but of course, the content can be increased via the water-gas shift reaction). Depending on the composition of the fuel and the required processing rate, the partial oxidation process is carried out either catalytically or non-catalytically. The drawback to partial oxidation is that it requires the use of expensive oxygen (rather than air, which would dilute the product hydrogen with nitrogen). In ‘autothermal reforming’, the exothermic reaction of partial oxidation is combined with endothermic steam reforming so that the gasification process requires virtually no input of external energy.

In Australia, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) is investigating the possible use of solar energy, in the form of a solar furnace, to provide the heat required for the steam reforming of natural gas and other methane-containing gases, e. g., landfill and coal-bed methane. As the resulting syngas would contain a substantial amount of embodied solar energy (up to 25 %), solar-thermal reforming offers the prospects of high thermal efficiencies and greatly reduced emissions of carbon dioxide. Moreover, the emissions would be in concentrated form and thus would be more amenable to gas separation.

There are three basic designs of solar furnace: (i) a simple parabolic dish that focuses the sun's rays on to a thermal receiver that is mounted above the dish at its focal point; (ii) parabolic trough mirrors that track the sun as it crosses the sky and have receivers located at their foci; (iii) an array of thousands of individual mirrors ('heliostats') around a central receiver set on top of a tall tower. To demonstrate the feasibility of solar-thermal reforming, CSIRO erected a solar dish of 48 curved mirrors (Fig. 6) but is now exploring decentralized generation through the development of more practical 'mini' versions of the solar-tower approach [design (iii)] coupled to a small steam reformer. Apart from the benefit of permitting the generation of hydrogen close to where it is needed, this modular technology is less expensive than a dish and is more flexible in that it allows easier integration of additional units to meet any growth in demand. Obviously, the solar furnace cannot function at night or during periods in the day when there is no sunshine. Therefore, to maintain continuity of hydrogen supply to the customer, this calls for an adequate storage system or back-up from a conventional steam reformer.

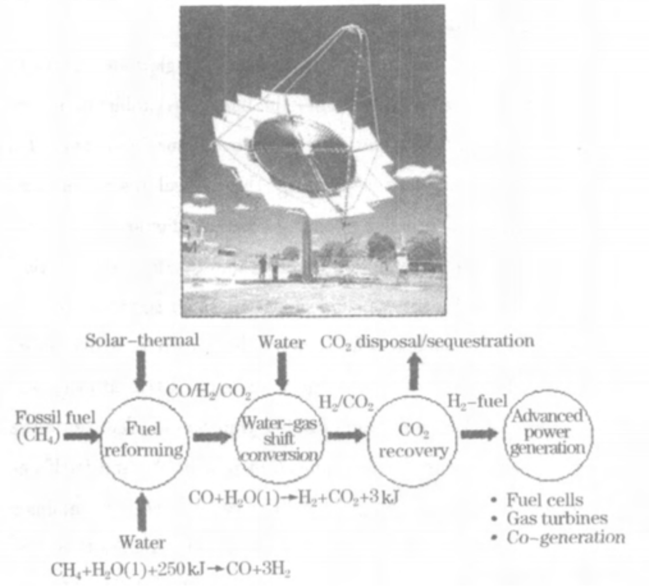

Fig. 6 CSIRO solar collector that, on a clear day, can concentrate 91 kW_{th} of thermal energy for the reforming of natural gas

Whereas it is likely that natural gas will provide the earliest affordable feedstock for hydrogen, today's costs are prohibitively high for applications such as transportation while petrol is still comparatively cheap. Moreover, the fact that processes based on the use of fossil fuels produce carbon dioxide in addition to hydrogen appears to be self-defeating on environmental grounds. Clearly, their future will depend on developing efficient means to separate this greenhouse gas and then sequester it, possibly in underground chambers or by chemical loops. Therefore, efforts are underway to develop technology that will reduce both costs and emissions.

Hydrogen can also be produced by the direct thermocatalytic decomposition ('cracking') of methane or other hydrocarbons. The energy requirement per mole of methane is in fact less than that for steam reforming, although only half as much hydrogen is produced, and the process is simpler. In addition, a valuable by-product ——clean solid carbon ——is produced, which obviously can be captured and stored more easily than gaseous carbon dioxide. There is, however, the problem of progressive catalyst deactivation through carbon build-up; reactivation would result in unwanted carbon dioxide emissions.

2.2 **Hydrogen from water**

Water is the other huge storeroom of hydrogen. Breaking-down water to hydrogen also requires energy ——electrical, chemical, heat or light or can be employed.

2.2.1 Electrolysis

Although electrolysis is a mature technology, only a few percent of world hydrogen is obtained by this method, and mostly as a by-product of the chlor-alkali process for the manufacture of chlorine and sodium hydroxide. Electrolysis is extremely energy-intensive ——the faster the generation of hydrogen, the greater is the power required per kilogram produced. The practical operating voltage exceeds the theoretical or 'reversible' value of 1.229 V due to ohmic losses in the electrodes and electrolyte, and to electrochemical kinetics ('overpotential') losses at the electrodes, Fig. 7. Thus, electrolyzers are most effective when operating at low current densities, i.e., at low production rates. Large-scale units using alkaline electrolyte typically run at 70 % to 75 % efficiency, while smaller systems with polymer electrolytes reach 80 % to 85 %. Steam electrolyzers, in which some of the energy required to split water is supplied by heat, can achieve very high efficiencies (over 90 %) but are presently not commercially feasible.

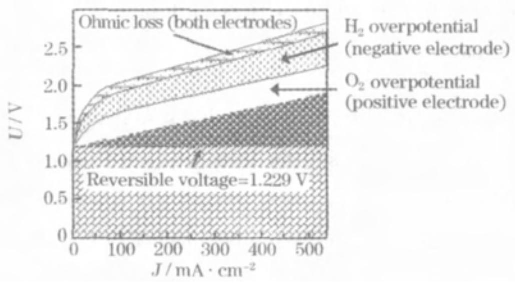

Fig. 7 Performance (U-J) of a basic (unactivated), unipolar electrolyzer operating at 90 ℃

Consideration has also been given to operating fuel cells in reverse as electrolyzers. The dual-function system is termed a 'regenerative fuel cell'. Such technology would save on weight and costs compared with a power system that employs a separate fuel cell and electrolyzer. It would also offer the prospect of using renewable energy (e. g. , solar, wind, geothermal) to generate hydrogen that would be stored in the same unit for subsequent production of electricity. To date, however, reliability problems with bifunctional electrodes and efficiency limitations of the 'charge-discharge' process (ways have to be found to optimize the catalyst for both processes) have delayed progress on these devices. In summary, more efficient electrolyzers and practical regenerative fuel cells should be considered as key electrochemical agents for energy sustainability.

It should be noted for that many scientists now argue that the most energetically favourable and economic approach to the electrolytic production of hydrogen is to use electricity derived from nuclear fission. After all, there would be no fugitive pollution (as would be the case with electricity generated in fossil-fuelled power plants) ——the radioactive waste is easily held captive. Clearly, the time has come to rethink our relationship with the awesome power of the atom. Further into the future, there is every hope that initiatives such as the International Thermonuclear Experimental Reactor (ITER) programme will hasten the practical realization of nuclear fusion, which is widely acknowledged to be the ultimate provider of sustainable energy.

2.2.2 Thermochemical production

It is also possible to decompose water to form hydrogen without generating electricity first. This would remove the need for an electrolyzer and avoid the problem of emissions. For example, thermal energy can be used via 'thermochemical cycles'. In each of the leading processes, heat is used to decompose sulfuric acid to oxygen and sulfur dioxide. There are then several possible cycles. The most promising employs iodine to produce hydrogen iodide exothermically, which in turn dissociates endothermically to hydrogen and iodine and the cycle is then repeated, e. g.

$$H_2SO_4 \xrightarrow{800\ ^\circ C} O_2 + SO_2 + H_2O \quad (4)$$

$$SO_2 + I_2 + 2H_2O \overline{} 2HI + H_2SO_4 + heat \quad (5)$$

$$2HI \xrightarrow{450\ ^\circ C} I_2 + H_2 \quad (6)$$

Efficiencies of around 40 % have been demonstrated in the laboratory, but the processes are still far from practical realization. Thermochemical cycles are, however, obvious candidates for coupling with the waste heat from nuclear power plants.

2.2.3 Photoelectrolysis

Photoelectrolysis is one of three possible methods (v. i.) for the direct production of hydrogen via the harnessing of solar radiation. Light is converted to electrical and chemical energy by using a semiconducting oxide, such as titanium dioxide (TiO_2), to absorb photons, Fig. 8. Those photons with energies that exceed the band-gap generate electron (e^-)-hole (h^+) pairs that become separated by the electric field. The holes are driven to the surface where they oxidize water to oxygen, whilst the electrons travel round the external circuit to reduce water to hydrogen at a metal counter electrode such as platinum. By virtue of its relatively low cost, titanium dioxide is most attractive as a photovoltaic material. It does, however, have a somewhat high band-gap energy (～3.2 eV) and therefore absorbs light energy in the ultraviolet rather than in the optical part of the spectrum. Accordingly, present efficiencies are only 1 %～2 %, i. e. , well below the commercial target of 10 %. To achieve improvements in performance, research efforts are being directed principally towards finding a means to shift the spectral response of titanium dioxide into the optical region through modification of band-gap and light-absorption properties, or to find suitable alternative oxides.

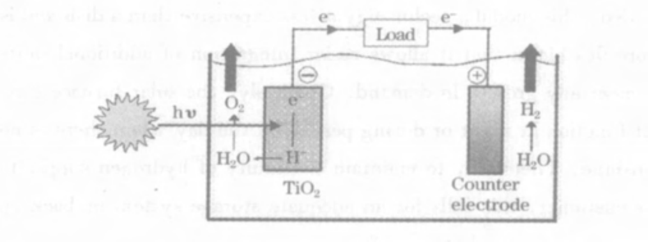

Fig. 8 Operating principles of a photoelectrochemical cell for hydrogen production

Unfortunately, materials with smaller band-gaps are subject to photocorrosion. To a certain extent, the band-gap problem encountered with photovoltaic materials can be overcome by means of a subterfuge. This involves separating the optical-absorption and charge-generating functions by coating titanium dioxide, for example, with a dye that is capable of being photo-excited in the optical spectrum and thereby acts as an electron-transfer reagent. The operating principles of such a cell - commonly known as a dye-sensitized solar cell ——are shown in Fig. 9. The dye (D), after having been excited (D^*) by a photon of light, transfers an electron to the conduction band of the titania ('injection process'), and itself becomes oxidized (D^+) in the process. The cell electrolyte contains a 'redox mediator', i. e. , a substance that can be oxidized and reduced electrochemically. Positive charge is transferred from the dye to the mediator (M_{red}) and the dye is returned to the reduced state ('interception process'). The oxidized mediator (M_{ox}) diffuses to the positive counter-electrode, where it is reduced again by the electrons travelling around the external circuit. The theoretical maximum voltage that such a cell can deliver is the difference between the redox potential of the mediator and the Fermi level of the semiconductor. Such redox cells have demonstrated sunlight-to-electricity efficiencies of 10 % in the laboratory, but only 5 % in the field.

The possible benefits to be gained by using a photoelectrochemical cell in tandem with a dye-sensitized solar cell, to absorb complementary parts of the solar spectrum, are also being explored. A schematic of a tandem cell is shown in Fig. 10. The front cell absorbs high-energy ultraviolet and blue light in sunlight, while longer wavelength light in the green-to-red region of the spectrum passes to, and is absorbed by, the dye-sensitized solar cell. This boosts the energy of the electrons that are then fed back to a hydrogen electrode in the front cell. With such an arrangement, overall efficiencies of up to 12 % have been reported. There are, in fact, many different possibilities for photoelectrochemical cells and these electrochemical devices are attracting much scientific interest as key agents for energy sustainability.

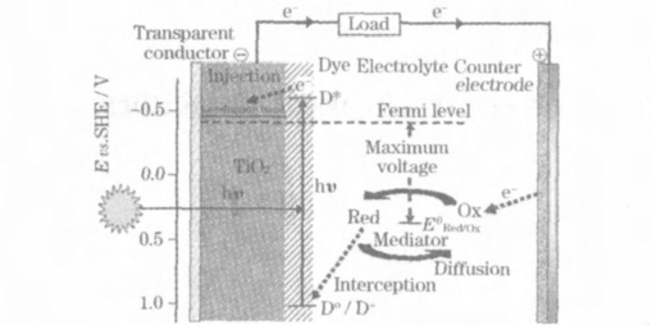

Fig. 9 Operating principles of a dye-sensitized titania solar cell

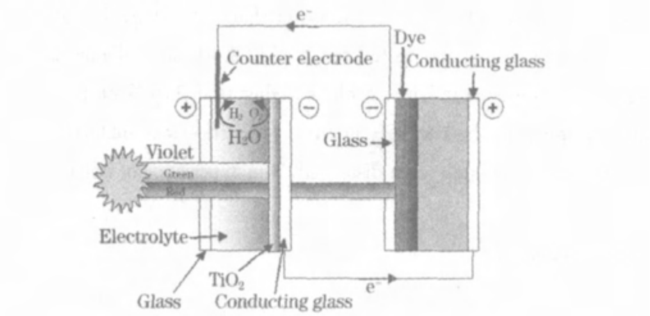

Fig. 10 Operating principles of a tandem photolectrochemical cell for enhanced hydrogen production

2.2.4 Biophotolysis

Photosynthesis is the basis for almost all life on earth. The first step involves splitting water into oxygen and hydrogen, and then hydrogen is mixed with carbon dioxide and turned into carbohydrates. There are, however, some groups of micro-algae that are capable of releasing hydrogen. For example, green algae contain an enzyme, hydrogenase, that manages the dark-to-light transition which the micro-organism face daily; it catalyzes the reduction of protons by electrons to form hydrogen. Biologically, however, the system is not designed for continuous operation. This is because the enzyme is very sensitive to oxygen and is only synthesized after several hours of dark pre-incubation under anaerobic conditions. Thus, with the production of oxygen by the algae after a short period in sunlight, the rate of hydrogen evolution decreases. To overcome this, two-stage 'indirect biophotolysis' processes are being investigated in which a photosynthetic carbon dioxide fixing stage that generates oxygen is followed by a dark anaerobic fermenting stage that produces hydrogen, Fig. 11. Clearly, fundamental molecular research into genetically-engineered micro-organisms, together with the technological development of efficient and inexpensive photobioreactor designs, has to be undertaken before such light harvesting can become a practical proposition.

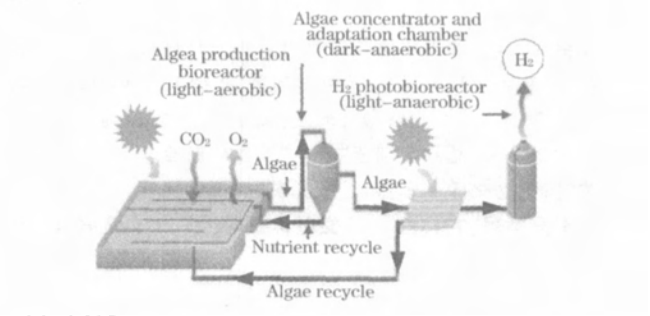

Fig. 11 Schematic of a two-stage biophotolytic cell for hydrogen production

2.2.5 Thermolysis

The temperature required for breaking down water directly into hydrogen and oxygen can be achieved by focusing the sun's rays from a large number (up to thousands) of individual mirrors on to a thermal receiver mounted on top of a central, tall 'solar tower'. The key scientific challenges are to find catalysts that will reduce the dissociation temperature, and to provide an improved means for separating the gases so as to prevent recombination. Large-scale production in areas with poor road or rail links is not practical —— the hydrogen should be generated close to where it is needed.

It has also been suggested that solar-thermal radiation could facilitate and improve the photoelectrochemical decomposition of water by enabling the process to be conducted at high temperatures and pressures. Much of solar radiation lies in the infra-red part of the spectrum and is of too low energy to be utilized in photoelectrochemical reactions so that it is wasted. Radiation received by the solar tower would therefore be separated into an infra-red component to heat pressurized water to at least 300 ℃, and into optical/ultraviolet radiation to effect the water-splitting reaction. Thermodynamic calculations suggest that the required energy is substantially reduced at high temperature and pressure and that it should be possible to reach overall efficiencies approaching 20 % for the conversion of solar energy to hydrogen. There is, however, a drawback in that regions of the world where insolation is both high and persistent are often those where water is in short supply.

(To be continued)

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