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Energy storage — a key technology for global energy sustainability

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Abstract

The quality of life today is dependent upon access to a bountiful supply of cheap energy. For a sustainable future, the energy should be derived from non-fossil sources; ideally, it should also be reliable and safe, flexible in use, affordable, and limitless. This paper examines the present global use of energy in its various forms, and considers projections for the year 2020 with particular attention to the harnessing of 'clean' and renewable forms of energy for electricity generation and road transportation. The incorporation of renewables is constrained in many instances by the variable and intermittent nature of their output. This calls for the practical application of energy-storage systems. An evaluation is made of the prospects of the candidate storage technologies — pumped-hydro, flywheels, hydrogen (for use in fuel cells), batteries — for application in centralized and distributed electricity supplies, and in electric and hybrid electric vehicles. The discussion concludes with the developments foreseen over the next 20 years. © 2001 Elsevier Science B.V. All rights reserved.

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1. The challenge of global energy sustainability

It is now accepted that the present production and use of energy pose a serious threat to the global environment, particularly in relation to emissions of greenhouse gases (principally, carbon dioxide, CO_2) and consequent climate change. Accordingly, industrialized countries are examining a whole range of new policies and technology issues to make their energy futures 'sustainable'. That is, to maintain economic growth whilst providing energy security and environmental protection. Clearly, the world is set to make major changes to its energy supply and utilization systems. This paper examines how batteries and fuel cells may play a significant role in helping such changes secure global energy sustainability, and hence sets the theme for this 100th edition of the *Journal of Power Sources*.

1.1. World energy usage

The extent of the challenge in moving towards global energy sustainability and the reduction of CO_2 emissions can be assessed by consideration of the trends in the usage of fuels for primary energy supplies. Such information for 1973 and 1998 is provided in Table 1 for both the world and the Organization for Economic Co-operation and Development (OECD countries — a consortium of 29 countries). The data is published by the International Energy Agency (IEA) [1] and is the latest information available to the authors. In summary, the total primary energy supply (in megatonnes oil equivalent, Mtoe) in the world and in OECD nations was, respectively, 6043 and 3742 Mtoe in 1973, and 9491 and 5096 Mtoe in 1998. What may we deduce from this data?

- The total energy supply of the world has increased by 57% in 25 years, while that of OECD nations has increased by 36%. The difference represents the faster growth of many less-developed nations which start from a lower energy base.
- While the production of oil has increased everywhere, the expansion in activity has been fairly modest with the result that oil now provides a significantly smaller share of the total energy supply.
- Coal is used mainly to generate electricity and despite the fact that the industry is using more gas, the overall increase in electricity consumption has resulted in little change to the percentage contribution made by coal.
- The production of natural gas has risen appreciably following the discovery and opening up of new fields. Nevertheless, again because of the overall increase in energy demand, the percentage contribution of natural gas has increased only modestly (since 1998, there has been a 'dash for gas' in electricity production, using combined-cycle gas turbine technology, and it is likely that the energy statistics for 2000, when published, will show a greater swing to gas).

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Table 1
Total primary energy supply by fuel (in % terms) in 1973 and 1998 [1]

Energy supply	The world[a]		OECD[b]	
	1973[c]	1998[c]	1973	1998
Oil	44.9	35.7	53.2	41.9
Coal	24.9	23.3	22.3	20.5
Gas	16.3	20.3	18.8	20.6
Combustible renewables (biomass) and waste	11.2	11.2	2.1	3.3
Nuclear	0.9	6.7	1.3	10.9
Hydro	1.8	2.3	2.1	2.2
Other[d]	0.1	0.4	0.2	0.6

[a] Excludes international marine bunkers and electricity trade.
[b] Excludes international electricity trade.
[c] IEA data have rounding errors of 0.1%.
[d] Includes geothermal, solar, wind and heat.

- Although the use of combustibles and waste to generate heat has increased slightly in OECD countries, it is still far lower than in the rest of the world. The latter reflects the shortage and cost of fossil fuels in many non-OECD countries.
- Over the period under consideration, the nuclear generation of electricity has increased seven- to eight-fold. For the present, this growth has largely stopped, and may well be in decline.
- Hydroelectric-power (‘hydro power’) makes only a small contribution to the world energy supply, but its significance for electricity production is considerable. This source of power is limited mainly to regions with mountainous terrain. In some countries, however, it may be the dominant means of generating electricity (in Iceland and Norway, for example).
- The contribution of all the non-combustible forms of renewable energy (‘other’ in Table 1) is exceedingly modest.

The goal of global energy sustainability implies the replacement of all fossil fuels (oil, coal, natural gas) by renewable energy sources. This is indeed a monumental challenge. For example, in 1998, total non-fossil energy was only 20.6% (including nuclear) throughout the world, and was even less (17.0%) in OECD countries. Furthermore, there are limited hydro sites left to be exploited, and if the nuclear program contracts, as seems likely, and the total world demand for energy rises, as is virtually certain, the proportion of energy provided by non-fossil sources will fall below its present low level.

The IEA’s forecast of the world demand for primary energy in 2010 and 2020 is shown in Table 2. Compared with the situation in 1998, the IEA predicts a 21% increase in 2010 (11 500 Mtoe) and a 44% increase in 2020 (13 700 Mtoe), with nuclear playing a diminishing role. Fossil fuels (oil, coal, natural gas) will continue to provide about 90% of this demand. Oil in the form of petroleum will be the dominant fuel and will meet 40% of world energy needs. This reflects a substantial increase in the demand for transportation fuels. Shell International, for example, has predicted that oil consumption by road vehicles in 2020 will be 40% higher than today.

Table 2
Forecast of total primary energy supply by fuel (in % terms) for the world in 2010 and 2020 [1]

Energy supply	Year	
	2010[a]	2020
Oil	38.8	38.3
Coal, combustible renewables (biomass) and waste	28.4	28.7
Gas	23.6	25.2
Nuclear	5.8	4.4
Hydro	2.6	2.6
Other	0.7	0.8

[a] IEA data have a rounding error of 0.1%.

Of course, all predictions over extended periods are subject to large uncertainties and depend upon the growth assumptions used in the model. In the case of energy, however, these uncertainties may be less than in other fields. This is because reasonable guesses may be made for both the demand side (population growth, effects of globalization, and the aspirations of less-developed countries) and the supply side (known and likely reserves of fossil fuels). Even major swings in the price of fuels do not seem to impact their consumption greatly. This is because people value highly their comfort (heating, air-conditioning), their leisure (transportation) and their employment (industry and commercial use of fuel) and, within reason, are prepared to pay for these ‘essentials’ at the expense of other purchases. Thus, a radical reduction in consumption and a total change to renewable sources, as is implied by energy sustainability, seem barely feasible.

1.2. Greenhouse gas emissions

A further complication arises from the second important goal in the drive towards true global sustainability, namely, that of reducing greenhouse gas emissions, especially those of CO_2. In December 1997, representatives of 160 countries gathered in Kyoto at the United Nations Framework Convention on climate change to discuss targets for reductions in greenhouse gas emissions. The resulting ‘Kyoto protocol’ has called for the industrialized nations (so-called ‘Annex I countries’) to reduce the average of their individual emissions by at least 5% below 1990 levels in the period 2008–2012. The specific targets proposed for the key industrial powers of the European Union, Japan and USA are 7, 6 and 8%, respectively. Not only does this initiative imply a marked reduction in the use of fossil fuels, particularly coal, but also such emission targets cannot be achieved by burning biomass and waste, two of the most promising renewables in the short-term. Whereas it is true that the substitution of coal by natural gas could result in a significant reduction in CO_2 emissions, the extent to which this is possible is dictated by considerations of resource availability, politics and economics. Nevertheless, the increasing use of combined-cycle gas turbines for electricity generation (as part or complete replacements for coal-fired stations) is likely to make a useful contribution. A further problem is that many less-developed nations foresee substantial *increases* in CO_2 emissions as their economies develop. For instance, without major changes in its present policies, China expects to be emitting three times as much CO_2 in 2020 as in 1995. This would be more than that produced in United States, the world's largest consumer of energy today.

The implementation of revolutionary energy policies will not be easy in any country, and the IEA estimates that global CO_2 emissions will grow by 60% between 1997 and 2020 [2]. Emissions from less-developed countries will increase at a rapid rate as they become industrialized, and there is a danger that the present industrialized countries will be disillusioned about adopting costly strategies to reduce their own emissions. It is not surprising, therefore, that the dynamics between industrialized and developing countries have been at the forefront of climate negotiations and are one of the major reasons why the Kyoto protocol has experienced difficulties and has still to come into force. At a meeting held in Bonn in July 2001, the rules governing the 1997 Kyoto protocol were put in place. The next stage in the process will be a new round of talks in Marrakesh in October 2001 to discuss technical details of the Kyoto and Bonn agreements.

The conclusion to be drawn from this brief review of the overall energy scene is fairly gloomy, at least in the short-to-medium term. Unless dramatic new energy technologies emerge and/or there are major changes in the relative economics of different energy sources, it is difficult to see how a substantial movement towards global energy sustainability is likely in the next 20 years. Even though the renewable energies may well grow rapidly, their contribution to the overall world energy scene and to a reduction in CO_2 emissions will still be minimal. The IEA takes a somewhat more optimistic outlook and points to lower emissions which may result from the trading of CO_2 emissions permits, improved fuel efficiency and the use of new fuels in the transportation sector, as well as the switching of power generation from coal to gas and nuclear. The IEA admits, however, that economic and political obstacles will not allow such changes to be put in place rapidly and they mostly relate to the post-2020 era.

2. The prospects for renewable energy

Fortunately, nature has bestowed upon us bountiful supplies of benevolent renewable energy which, in principle, should be capable of being harvested to meet the world's energy needs in a sustainable and non-polluting fashion. The various renewable sources of energy are listed in Table 3, together with their method of utilization and the likely timescale of early commercial use.

Combustible materials ('biomass') are used principally for direct heating applications and for cooking; a minor amount is used to raise steam to generate electricity. At present, the extent of biomass combustion is limited largely by the supply available. There is considerable scope for growing more energy crops. Nevertheless, any exploitation of biomass will be principally a matter of economics. Similarly, if the economic conditions were favorable, the solar heating of water and of buildings could be increased substantially and, thereby, savings in fossil fuels could be achieved. In particular, hot water in lagged containers may be stored for a considerable time, as may the passive heat in a well-insulated building. These are areas where architectural design and building methods have a key role to play.

Table 3
Renewable energy sources and means of utilization

Energy source[a]	Energy utilization	Availability
Agriculture and forestry waste	Combustion process	Now
Energy crops	Combustion process	Now
Landfill and sewage gas	Combustion process	Now
Municipal solid waste	Combustion process	Now
Direct solar (active and passive)	Heating	Now
Geothermal	Heating/electricity	Now/limited scope
Hydro power	Electricity	Now
Wind power	Electricity	Now and developing
Hydrogen/fuel cells[b]	Electricity	Now and developing
Solar photovoltaic	Electricity	Now and developing
Tidal power	Electricity	Now/limited scope
Wave power	Electricity	Medium-/long-term
Solar-thermal	Electricity	Medium-/long-term

[a] Although the distinction between 'energy' and 'power' is scientifically rigorous, in general discussion of renewable energy sources there is a tendency to use the terms interchangeably. We prefer to use 'energy' where stored energy is implied (e.g. geothermal, biomass, hydrogen, batteries), and 'power' where a machine or device is rated in power output (e.g. hydro power, wind power, fuel cells).

[b] Hydrogen is essentially a secondary form of energy but should be included as it is widely considered to be the ultimate conduit (the so-called 'hydrogen economy') between the primary renewable source and its conversion to electricity, ideally via a fuel cell.

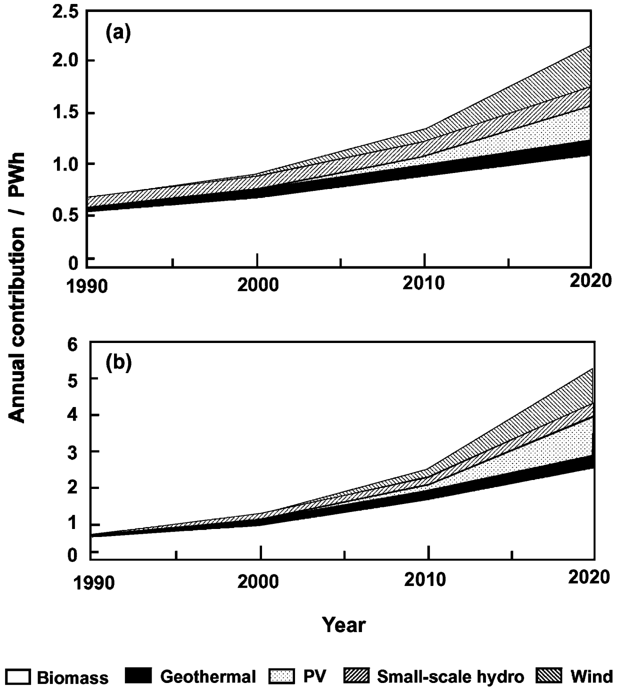

Fig. 1. Growth in electricity output from renewables: (a) WEC current policies scenario; (b) WEC ecologically driven scenario [3].

Several major studies of the global scope for renewables in the years ahead have been recently undertaken by IEA, World Energy Council (WEC), United Nations (UN), and Shell International. Inevitably, these studies are based on various prediction models and energy scenarios. By way of illustration, the WEC projections [3] for the contribution of individual renewables to electricity generation (measured in PWh; note the different scales) are shown in Fig. 1(a) and (b) for the following two scenarios.

1. The 'current policies scenario' (Fig. 1(a)) assumes continuation of existing trends, i.e. small increases in the price of fossil fuels, steady increases in energy efficiency, modest penetration of renewables, etc. On this basis, 'new' renewables (i.e. excluding traditional large-scale hydro) are predicted to contribute 2.1 PWh per year to electricity production in 2020 (1 PWh = 10^9 MWh). When the expected contribution of traditional large-scale hydro is included (4.4 PWh), the output rises to 6.5 PWh (hydro production in 1998 was 2.6 PWh [1]).
2. The 'ecologically driven scenario' (Fig. 1(b)) assumes faster and more extensive penetration of renewables which may arise from a range of measures, e.g. greater cost reduction, enhanced environmental concerns, and higher costs of fossil fuels. Under these assumptions, the new renewables are expected to grow at an increasing annual rate and lead to a global output of 5.2 PWh in 2020. Adding in large-scale hydro, which will not increase so rapidly in this scenario, the total renewable electricity production predicted for 2020 is 9.2 PWh (total electricity demand in 2020 is predicted to be 20 PWh). The 'renewables intensive scenario' proposed by UN gives 11.0 PWh by 2020 (for comparative purposes, the total world production of electricity in 1998 was 14.33 PWh with the following percentage breakdown: coal 38.4%, hydro 17.9%, nuclear 17.1%, gas 16.1%, oil 8.9%, other renewables 1.6%. Electricity represented 15.2% of the world's energy consumption [1]).

The predicted world demand for electricity in 2020 is around 20 PWh [3], i.e. a 40% increase above the 1998 level. According to which scenario is adopted, total renewables (including traditional large-scale hydro) will contribute between one-third and one-half of all electricity generated in 2020. If only new renewables are considered, the data given in Fig. 1 show that roughly one-half of the electricity of this type will come from burning biomass in power stations, either directly or via intermediate gasification. Whilst this helps to compensate for the declining nuclear power program, it does not lower CO_2 emissions and, it could be argued, places far too much emphasis on biomass at the expense of non-polluting renewables. Moreover, traditional uses for biomass for domestic heating and cooking are also expected to grow.

The portfolio of renewables is well diversified geographically to an extent which depends upon the resources available, the state of development of the various technologies, local preferences and politics, and the level and structure of energy demand. It is not anticipated that the various renewables will diffuse uniformly throughout the world. To cite an obvious example, tropical countries will tend to favor solar power, while high-latitude countries will prefer wind power. Countries with excess hydro power will favor exploiting this for non-traditional uses, e.g. electric road vehicles, space heating. Some of the technologies, for instance, photovoltaics, are likely to be introduced via a series of niche applications, and will grow and diffuse gradually as experience develops and costs fall. Even intervention at government level to encourage new technologies may have comparatively little impact on the rate of their implementation and the breadth of their distribution. This is because good operating practice generally develops gradually and it is also necessary to establish a strong manufacturing base. Other factors which may delay the uptake of renewables are the failure of governments to have an overall policy for dealing with siting decisions, considerations of environmental impact, delays in granting planning permission, local public opposition, non-availability of risk capital, and public reluctance to provide financial support in the early years until the technology is fully commercialized.

With these introductory remarks to provide an overall perspective, we may now consider the role of energy storage in the electricity sector with particular reference to electricity generated from renewable energy sources. It should be remembered, however, that the contribution made by renewable electricity to the overall supply of world energy is still comparatively small.

3. The role of energy storage in the electricity supply network

Fossil fuels have two important characteristics in addition to being concentrated sources of energy. They are *energy stores* and they are *readily transportable*. This means that the fuels may be stored until such time as they are required and may be transported by rail, road or pipeline to where they are to be used. By contrast, most of the renewables (except for biomass and hydro) cannot be stored and cannot be transported to the place of use, except by first converting them to electricity. Electricity is the most versatile and preferred form of energy for many applications and therefore it is not surprising that renewable energies and electricity generation are so intimately bound together. Electricity is readily transmitted over long distances and distributed to consumers by cable, but there is often the problem of matching the supply to meet the demand. This calls for the development and application of systems for the efficient storage of electricity.

There are several distinct applications for energy storage within the conventional electricity supply system, as follows.

- System regulation
  Energy storage can serve to meet short-term, random fluctuations in demand and so avoid the need for frequency regulation by the main plant. It can also provide 'ride through' for momentary power outages, reduce harmonic distortions, and eliminate voltage sags and surges.
- Spinning reserve
  Energy storage eliminates the need for part-loaded main plant which is held in readiness to meet sudden and unpredicted demands, as well as power emergencies which arise from the failure of generating units and/or transmission lines.
- Peak shaving
  Energy storage accommodates the minute–hour peaks in the daily demand curve.
- Load leveling
  Storage of surplus electricity generated overnight (i.e. during off-peak hours) to meet increased demand during the day.
- Renewable energy
  Storage of electricity generated by renewables so as to match the fluctuating supply to the changing demand.

Through such applications, it is considered that energy storage can be multi-beneficial to both utilities and their customers in terms of: (i) improved power quality and reliability; (ii) reduced transmission/power losses; (iii) cost savings (e.g. deferral of new generation units and sub-station upgrades, and of new transmission lines and transformers); (iv) decreased environmental impact (lower emissions, diminished electric/magnetic field effects, integration of renewables); (v) strategic advantages (greater siting and fuel flexibility).

Countries which have a fully interconnected network, such as France and UK, tend to have surplus generating capacity. Low-cost generating plant is used for base-load and higher-cost plant is brought on line to meet peaks in demand. Storage capacity is strictly limited to a few pumped-hydro facilities in mountainous regions, sometimes supplemented at a local level by limited battery storage. Many utilities world-wide would welcome the introduction of more extensive battery storage and large lead–acid systems (MWh) have been field-tested in Germany, Japan, Puerto Rico, and USA. The economic targets to be met are, however, exceedingly stringent and, to date, battery energy storage has not proved to be economically viable.

With the advent of renewable energy, a new demand for storage opens up. Generally, renewable energy sources will be smaller than conventional power stations and will range in size from wind farms of a few megawatts capacity down to solar photovoltaic panels of a kilowatt or less. Moreover, the sources will be widely distributed. The larger wind farms will feed into the electricity grid, but small wind turbines or photovoltaic installations will supply communities such as farms, individual buildings, offices, or shopping complexes. Battery storage for these distributed small units will be simpler than in the case of the massive, megawatt-sized batteries required at power stations. Mains supplied electricity may also be stored locally, near the point of use, in medium-sized batteries. Storing *distributed* electricity (see Section 4) has the advantage of load leveling the supply network as well as the generating plant. This is particularly advantageous in cities where the cost of installing additional cabling is high.

The largest form of electricity storage practiced today is pumped-hydro. This requires two water reservoirs, in the form of lakes, separated by a substantial difference in vertical distance (i.e. a 'head'). During the night, when surplus generating capacity is available, water is pumped from the lower lake to the upper. During the day, when extra electricity is required, the process is reversed and the falling water passes through a turbine to generate electricity. This process is cost-effective, with a round-trip efficiency of around 70%, but its use is limited by the availability of suitably mountainous terrain together with land to build the twin lakes. Pumped-hydro is particularly appropriate for a network which has a large nuclear component since, for both technical and economic reasons, nuclear reactors are best operated on base-load. As the response time of pumped-hydro is rapid, it may contribute to all of the network applications mentioned above. A typical pumped-hydro plant, as operated by a utility, is capable of generating many megawatts of electricity. To date, this is the most practical and economic means of storing electricity on the megawatt–hour scale.

There are many small hydro schemes of less than a megawatt, and often just a few kilowatts, which are operated by private owners or developers. Sometimes these are based on historic water mills. Modern schemes are of the 'run-of-the-river' type in which a shallow weir (perhaps a meter or so high) is constructed to create the necessary pool for intake to a turbine via a pipeline or canal. Some small pumped systems have also been constructed to store surplus energy from wind turbines in isolated communities with a local grid. Such small-scale ('mini') hydro capacity is likely to increase as research on computerized control systems and improved turbines lowers the costs of producing such power.

Reviewing briefly the renewable forms of energy which lead to electricity generation (Table 3), tidal and geothermal sources are restricted to very few sites in the world and so may be discounted from this global discussion. Wave and solar-thermal generation are practical, and may eventually prove economic, but at present are still in the developmental stage. Fuel cells do not require a storage facility as they are switched on and off at will; the fuel acts as the storage role. Thus, given these considerations, wind and solar photovoltaic have emerged as the two dynamic and growing sources of renewable electricity which require a storage component, and which are presently cost-effective in certain situations. Referring back to the two WEC energy scenarios illustrated in Fig. 1, it is predicted that wind and photovoltaic sources together will contribute between 0.7 and 2.1 PWh of electricity to the world supply in 2020; some unknown fraction of this will need to be stored (to set this prediction in perspective, UK, a developed country of ~58 million people, generated 0.354 PWh of electricity in 1998 [4], while the total world generation that year was almost 14.33 PWh [1]).

3.1. Wind power

Wind power differs from solar power in that it is available, in principle, for 24 h per day, but in practice its intensity is highly variable. Large wind turbines are capable of generating 1–2 MW of electricity in a strong breeze, but in light air the output falls off dramatically. Wind farms in Europe generally employ wind turbines with peak outputs in the range 500–1500 kW(p) and consist of around 20 turbines spread over 3–4 km^2 of land (the power output is rated in peak-watts, W(p)). A typical 600 kW(p) machine would generate between 1.6 and 2.75 GWh per year on sites with annual mean wind speeds of 7.0 and 10.0 $m\ s^{-1}$, respectively [3]. Thus, several thousand such turbines would be required to replace the electricity generated by one large fossil-fuelled or nuclear plant. Even then, there would be long periods of low or zero generation which would necessitate the provision of back-up conventional plant. Because of this requirement, the utilities will normally only give credit for the electricity actually supplied (kWh) and not for the power capability of the turbine (kW). This is a financial penalty which is common to most renewable forms of energy where the supply is not totally reliable. Generally, in a grid-connected system, electricity produced by wind turbines or photovoltaic arrays would not be stored, as economics would dictate that all such electricity be used at once, and that conventional plant be shut down to compensate. This argument does not apply to stand-alone generators where storage is essential.

The visual impact of present-day wind farms, together with the land they occupy (often on headlands or other scenic coastal sites), cause concern to local residents and environmentalists. Other problems are the noise from the turbines, interference with television when using steel blades, and bird kills. Some of these objections may be overcome by siting the wind turbines off-shore, on the continental shelf, where the wind is often stronger. Here, the problems are higher capital costs of installation and cabling to bring the electricity ashore, higher maintenance costs, and the hazard to navigation. Both on- and off-shore wind farms are being built in various countries and are already making small contributions to national energy supplies. For example, UK government has recently announced a major expansion of off-shore wind power in the North Sea, the windiest region of Europe. UK plans to build 18 off-shore wind farms, with over 500 turbines, over the next decade. There is now more than 8 GW(p) of wind power installed world-wide [3], which is equivalent in terms of power (but not energy output) to four to eight conventional power stations. The electricity supplied by wind power in 1997 was less than 0.5% of total world consumption of electricity, possibly as low as 0.2%.

3.2. Solar photovoltaic

The science and technology of solar photovoltaic electricity is advancing rapidly [5]. In recent years, the efficiency of silicon solar cells has improved steadily and the cost of photovoltaic modules has fallen as the manufacturing base has developed. The principal applications for solar-generated electricity to date have been in situations where mains electricity is not available — such a facility is known as a 'remote-area power supply' (RAPS). One such area is in marine operations, where solar modules are employed to power navigation buoys, on drilling platforms, for the cathodic protection of structures, and as independent electricity supplies for small boats. In terrestrial applications, RAPS systems now operate microwave relay stations, telecommunications networks, railway signaling, street lighting, irrigation equipment, and pipeline monitoring and cathodic protection; and provide power to remote communities, homesteads, and holiday caravans. In the space field, solar electricity is used to power all satellites — a minor use by market volume, but vital for modern telecommunications. Most of the RAPS applications are small, i.e. in 0.1–10 kW power range, but require a sizeable back-up battery with a storage capacity of 1–100 kWh. Collectively, however, RAPS systems represent a huge potential market, world-wide, for solar installations and battery manufacturers.

By definition, RAPS systems do not act as substitutes for mains electricity and so do not directly reduce the consumption of fossil fuels in power stations. Nevertheless, in the absence of a photovoltaic facility, if the alternative is to use a small petrol or diesel generator to charge batteries, the reduction in the consumption of fossil fuel and the concomitant lower emissions of CO_2 start to become significant. Obviously, these benefits will increase as the price of solar modules falls further and the modules are ever more widely used in RAPS applications. In some locations, it may be desirable to employ a diesel generator and/or a wind turbine in conjunction with a photovoltaic array, either because the insolation is inadequate or because an array of the required size is too expensive. To a degree, solar power and wind power are complementary in high latitudes, since winds tend to be stronger in winter when sunlight is at a premium.

Much larger solar arrays have been developed for supplying the electrical load of buildings such as office blocks. These installations are generally grid-connected and supply only part of the electricity requirements of the building. Because of this grid connection, there is no requirement for energy storage. Several grid-connected demonstration plants of MW-size have already been built. A futuristic concept which has been mooted is that of massive solar arrays in tropical, desert regions of the world. These could be linked to new electricity grids, or used to manufacture non-fossil fuels or chemicals in dedicated ‘solar chemical plants’.

Optimizing the output from a photovoltaic array is quite a sophisticated procedure. Much is dependent upon the latitude, which determines the angle of the array to the sun, as well as upon whether the loads are seasonal or constant throughout the year and whether the peak demand is during the week (as with a rural school or workplace) or at the weekend (holiday cottages, caravans, etc.). Another critical factor is whether the array is fixed in position, or steerable to follow the sun during the day. A steerable array is more expensive to construct but, for a given electrical output, can be smaller than a fixed array.

The back-up battery to a solar installation performs three roles: (i) to store electricity from daytime, when it is generated, to evening or night when it is required; (ii) to meet power surges during the day (‘peak shaving’); (iii) to smooth fluctuations in the current and voltage output from the array (for instance, as the day progresses or as the sun disappears behind clouds). Thus, the system is one in which both the electrical output of the array and the electrical demand for the application are quite variable, and in which the battery has to be sized to smooth these fluctuations over a period of, typically, up to a week. Optimization of the size and the cost of both the solar array and the battery, working together, is quite a complex exercise and much effort has gone into the development of system designs and associated control algorithms.

4. Storage options for small-scale, distributed generation of electricity

From the foregoing discussion, it will be clear that the local, small-scale storage of electricity is likely to assume greater importance in the future, whether the electricity be mains-generated and distributed, or produced locally by wind turbines, photovoltaic arrays or fuel cells. This is perhaps fortunate, as the storage of hundreds or thousands of megawatt–hours, which is desirable for large central generation plants, can presently be achieved only with pumped-hydro and this method is limited in terms of availability. All other storage technologies are on a smaller scale. What, then, are the options for energy storage on a small scale, as would be needed for local or district schemes, so-called ‘distributed electricity networks’.

Electricity cannot be stored directly, except in very small amounts in various types of capacitor or in electromagnetic superconducting coils — both of these technologies are costly, and the latter is still at the development stage. Rather, electricity has first to be converted to an alternative energy form for storage. There are four possibilities: (i) potential energy (pumped-hydro, compressed-air); (ii) kinetic energy (usually in the form of flywheels); (iii) thermal energy (hot water, fused salts); and (iv) chemical energy (generally as hydrogen, methanol, or as chemicals in batteries). Thermal storage is used in UK for the space heating of buildings, but is quite unsuitable for reconversion to electricity as this would involve going through the Carnot cycle twice, with associated loss of efficiency. Thus, potential, kinetic or chemical energy storage are the only realistic options.

The interconversion of one form of energy to another inevitably involves inefficiencies. The storage of electricity as another energy form, followed by reconversion to electricity, involves a two-stage, cyclic process with cumulative losses. The overall electrical efficiency is expressed as the ratio of electrical output of the system to the electrical input (Wh_{out}/Wh_{in}). When both the input to the system and the desired output are high-voltage ac and the storage medium utilizes low-voltage dc (as with batteries, electrolysers, and fuel cells), the electrical losses include those in the transformers and rectifiers as well as those inherently associated with the storage devices themselves. In the specific case of dc electrochemical storage, the losses may be subdivided into ‘coulombic losses’, which arise from side-reactions (e.g. the ‘gassing’ of lead–acid batteries during charge), and from ‘voltaic losses’, which are due to shifts in the electrode potentials from the equilibrium (thermodynamically ideal) values during the passage of current. Overall electrical efficiencies (ac back to ac) for electrochemical processes generally lie in the range 50–75%.

4.1. Kinetic energy storage in flywheels

Simple steel flywheels are employed in reciprocating engines to smooth out power pulses from the pistons.

Flywheels store electricity by converting it to kinetic energy: electricity to be stored powers an electric motor which increases the speed of the flywheel, while electricity is recovered by running the motor as a generator which causes the flywheel to slow down. The amount of energy stored is proportional to the mass of the flywheel and to the square of its angular velocity. Thus, the rotational speed is much more important than the mass in determining the amount of energy stored. The maximum energy which can be stored is dependent upon the tensile strength of the material from which the flywheel is constructed. The circumferential tensile stress in the rim is also proportional to the square of the angular velocity. It follows that the maximum stored energy is to be found in a flywheel of high tensile strength rotating at the maximum safe speed. The highest tensile flywheels are not made of steel, but of fiber-reinforced composites such as carbon-fiber/epoxy or Kevlar/epoxy. As well as rotating faster and storing more energy than steel flywheels, these composite wheels are much safer if the maximum safe speed is exceeded, since they tend to delaminate and disintegrate gradually from the outer circumference, to produce fine fibers, rather than explode catastrophically.

High-speed flywheels are generally mounted in vacuum enclosures, to eliminate air drag, and on low-friction bearings or magnetic suspension systems. They have a number of attractive features for energy storage, namely, flywheels:

- act as high-power devices, which absorb and release energy at a high rate;
- do not have the electrical inefficiencies associated with electrochemical devices;
- have a long life, which is unaffected either by the frequency of cycling (charge–discharge) or by the rates of uptake and release of energy;
- have flexibility in design and unit size;
- require no maintenance (unlike many batteries);
- are constructed from readily available materials;
- in principle, can be mass-produced at reasonable cost (especially when expressed on a per kW, rather than a per kWh, basis); and
- create no environmental impact in use or in recycling.

The most significant limitation of flywheels lies in their relatively modest capability for energy storage. They are essentially surge-power devices rather than energy-storage devices, and are best suited to applications which involve the frequent charge and discharge of modest quantities of energy at high-power ratings. In this respect, flywheels are complementary to batteries. A typical advanced flywheel will store $\sim$1 kWh of electricity, but may be charged–discharged at a rate of 25–50 kW. Most interest in flywheels has arisen from their possible application to electric and hybrid electric vehicles (HEVs), so individual units have tended to be of 0.5–1 kWh size. This work has followed through to units considered for stationary applications. In an ambitious research program, the New Energy Development Organization (NEDO) in Japan is attempting to develop a 10 MWh commercial flywheel system for load levelling at electricity substations.

Flywheels are of potential interest for the localized storage of electricity generated by wind turbines and photovoltaic arrays. Since these two technologies may exhibit large, frequent and rapid fluctuations in power output, a flywheel-based buffer store could remove the need for downstream power electronics to track such fluctuations and so improve the overall electrical efficiency. In many situations, rechargeable batteries would seem to be a more appropriate storage medium and these are widely used today, but a battery–flywheel combination is worthy of consideration.

4.2. Chemical energy storage: hydrogen fuel cells

Fuel cells, like batteries, are electrochemical devices for the direct production of low-voltage, dc electricity. A suitable fuel, generally hydrogen, is fed to the negative electrode of the cell and air or oxygen to the positive. The resulting electrochemical reaction produces water and electricity. Fuel cells are more akin to primary batteries than to secondary batteries in that they do not store electricity by recharging and the fuel has to be produced externally.

Commercial hydrogen is manufactured in large quantities by catalytic steam-reforming of natural gas or naphtha, or by the partial oxidation of heavy oils. Less than 5% of the world's hydrogen is made by electrolysis, predominantly as a by-product in the manufacture of chlorine and caustic soda. In regions of cheap hydro power, large electrolysers have been considered, and some built, specifically for hydrogen production. These are rather special cases and, in general, it has not been economic to manufacture hydrogen in bulk by electrolysis. In Australia, CSIRO is exploring the possibility of using a 'solar dish' of mirrors to concentrate sunlight on to a central receiver to produce heat for combining methane-containing gases (e.g. natural gas, landfill and coal-bed methane, methane derived from coal) with water to generate synthesis gas (hydrogen and carbon monoxide), which is further converted, via the water–gas shift reaction, to a mixture of hydrogen and CO_2. To date, most hydrogen has been used in chemical plants adjacent to where it is produced, e.g. for the synthesis of ammonia or for oil refinery use.

One of the problems with hydrogen, being a gas, is that it is not readily transported in bulk, except by dedicated pipeline. The conveyance of hydrogen in cylinders is both inconvenient and cumbersome, while liquid hydrogen is very expensive to manufacture and transport. If an interest is to develop in the local generation of electricity using fuel cells, then it will be necessary to have a source of hydrogen for each generation site. Three possibilities exist for the supply of hydrogen to stationary fuel cells, namely: (i) a gas grid; (ii) a dedicated water-electrolysis or solar-thermal plant; (iii) the central manufacture of liquid fuel (probably methanol), conveyance of this fuel by road tanker to the fuel-cell facility, and conversion back to hydrogen in a reformer.

It may be noted, in passing, that methanol has been described — accurately as regards the empirical formula, viz. CH_4O, but in terms abhorrent to a chemist — as: 'two molecules of hydrogen made liquid by one of carbon monoxide'. Thus, it is a very suitable means of conveying hydrogen as a liquid. Furthermore, in recent years, methanol reformers have been developed specifically to provide hydrogen for fuel cells. These will be particularly important for electric vehicles powered by fuel cells, where considerations of mass and volume make the use of 'cylinder hydrogen' impractical in small vehicles.

Looking ahead, then, we foresee several possible applications for fuel cells, as follows.

- In association with an electrolyser and a hydrogen store, fuel cells provide a means for the storage and regeneration of locally produced electricity, i.e.

  $$\text{Electricity} \rightarrow \text{Electrolyser} \rightarrow \text{Hydrogen store} \rightarrow \text{Fuel cell} \rightarrow \text{Electricity}$$

  The electrolyser would be sized to take all the electricity provided by the renewable resource, and the hydrogen would then be the storage medium. This is seen as a possible alternative to the storage of electricity in batteries. A problem to be resolved is: how is the hydrogen to be stored to smooth the fluctuating supply and demand? Possibilities are as compressed gas, as liquid hydrogen, or as a solid hydride. At present, a solid hydride appears to be the preferred solution, but this technology is still at the research stage.
- Using methanol as fuel (via a reformer to produce hydrogen), fuel cells might be used for the local, district generation of electricity. This route does not capture renewable energy and so does not contribute to sustainable energy development unless the methanol is produced from biomass rather than from fossil fuel.
- Finally, fuel cells might find application as power sources for electric and HEVs (see Section 5).

From this discussion, it appears that although fuel cells may well become important for the local generation of electricity and/or for electric road vehicles, they will contribute nothing to sustainable energy unless the fuel is derived from renewable energy sources rather than from fossil fuels.

4.3. Chemical energy storage: batteries

Batteries are the most likely medium for the storage of renewable electricity and, indeed, are already used in conjunction with wind turbines and photovoltaic installations. In this discussion, we consider the five classes of battery which have received wide attention as possible candidates for the storage of renewable electricity.

4.3.1. Lead–acid batteries

An overwhelming preponderance of large secondary batteries in use today are of the lead–acid variety. Although this battery was invented in the 19th century, it has undergone steady development during the intervening period. The basic electrochemistry of the cell has remained essentially unchanged and most of the developments have been in the areas of materials science and engineering design. Major advances have been made in the lead alloys used for the plate grids, in the processing of the plates themselves, in the materials and design of the separators, in the methods of cell/battery construction, and in the packaging (polypropylene containers rather than glass or hard rubber/pitch). All these changes have led to batteries of improved performance, lower mass, and lower cost.

Several different types of lead–acid battery are manufactured. Automotive batteries are widely used in cars, trucks, boats, aircraft, etc. for engine starting and other duties. They are not often subject to deep discharge and under these conditions have a life of several years. Leisure batteries, as used in caravans, boats, etc. to supply the 'house electrics', are an upmarket form of flat-plate battery which may experience regular discharges of moderate depth. Industrial (stationary) batteries are employed in uninterruptible power supplies in many different situations where a loss of mains power would be serious. Tubular-plate traction batteries are used to power electric vehicles, e.g. tugs, tractors, fork-lift trucks, and some road vehicles. Finally, 'valve-regulated' (or 'sealed') lead–acid batteries are assuming increasing importance as they do not require water additions and may be used in any orientation.

Lead–acid batteries have invariably been chosen for wind- or solar-powered installations on account of their wide availability in a range of sizes and their acceptable cost. For the storage of renewable energy, the chief disadvantages of these batteries are the need for periodic water maintenance (water 'top-up', except with valve-regulated cells), relatively poor performance at low and high ambient temperatures, and a variable but limited charge–discharge cycle-life (typically, $\sim$500 deep-discharge cycles). It should be pointed out, however, that research on valve-regulated batteries, particularly of the 'gel' type, has resulted in major improvements in life [6], especially under the partial state-of-charge conditions which are typically experienced with wind- or solar-based power supplies. The importance of the different limitations of lead–acid batteries will depend upon the application, and it is necessary to weigh them carefully against the performance and cost of competitive batteries.

4.3.2. Alkaline batteries

"Nickel–iron" and "nickel–cadmium" batteries, which employ an electrolyte of potassium hydroxide and positive electrodes of nickel oxide, were invented around 1900 and are therefore almost as old as the lead–acid battery. These alkaline batteries have never, however, enjoyed the same degree of commercial success, mainly because of their considerably higher cost.

The ''nickel–iron battery'' suffers from major defects. The iron negative electrode is subject to appreciable corrosion and self-discharge on standing, and its low overpotential for hydrogen evolution gives rise to excessive gassing during recharge. These effects result in a low overall electrical efficiency (Wh_{out}/Wh_{in}) and a high water-maintenance requirement, neither of which is acceptable for the storage of electricity from renewable sources. Despite considerable research on this battery, the problems have not been resolved.

By contrast, ''nickel–cadmium batteries'' are widely-used to a moderate extent in both mobile and stationary applications. The high-rate and low-temperature performances of the battery are better than those of lead–acid. Other beneficial features are a flat discharge voltage, long life (~2000 cycles), continuous overcharge capability, low water maintenance, and high reliability. On the debit side, the battery has a high cost (up to 10 times that of lead–acid) and a low-voltage (1.2 V), and there are environmental concerns associated with the disposal of toxic cadmium in spent batteries. The higher cost may be acceptable for sites which are remote, unmanned and difficult to access. The long life of the battery and its freedom from maintenance will then present cost savings to be weighed against the higher capital outlay.

A third, nickel-based, alkaline battery — the ''nickel–metal-hydride system'' — has recently been commercialized and now finds widespread application in portable telephones and other electronic devices. Large versions of the battery have been produced and used to power prototype electric and HEVs. Nickel–metal-hydride is, however, even more expensive than nickel–cadmium. Thus, unless and until the cost falls substantially, the technology is unlikely to be a strong candidate for the storage of renewable electricity.

4.3.3. *Flow batteries/regenerative fuel cells*

A flow battery is, essentially, a hybrid between a fuel cell and a secondary battery. The system resembles a fuel cell in that the reactive chemicals are stored in tanks which are external to the electrochemical unit. The capacity of the battery (in Wh) is therefore determined only by the size of the tanks, while the power output is determined by the size of the electrochemical cell stack. This separation of energy and power is not possible in a conventional battery, but is similar to that of a fuel cell. On the other hand, unlike a fuel cell, a flow battery is electrically rechargeable. Thus, the battery has also been termed a 'regenerative fuel cell'.

The basic concept of a flow cell is shown in Fig. 2. There are two separate electrolyte-circulation loops, one for the catholyte (positive electrode) and one for the anolyte (negative electrode), with separate storage tanks for each. The two halves of the electrochemical cell are separated by a membrane which allows the passage of one species of ion only. In order to develop a useful voltage, the cells are series-connected in a stack which is similar to the assembly of a fuel cell. Indeed, the technology of cell and module design is much more akin to that of a fuel-cell stack than to that of a battery, with the stack being constructed on the 'plate-and-frame' principle. Sometimes, the external storage tanks are divided into two, i.e. one half for the reactant and the other half for the discharge product, or even two separate tanks are employed in each loop.

Several flow batteries are at various stages of development. The best known of these is the ''zinc–bromine battery'' in which an electrolyte of zinc bromide is employed in both the electrolyte loops. The overall cell reaction is simply

$$\mathrm{Zn} + \mathrm{Br_2} \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftarrows}} \mathrm{ZnBr_2} \qquad (1)$$

The open-circuit voltage is 1.83 V at 25°C, and the cell voltage is 1.3 V at an operating current density of 100 mA cm^{-2}. On

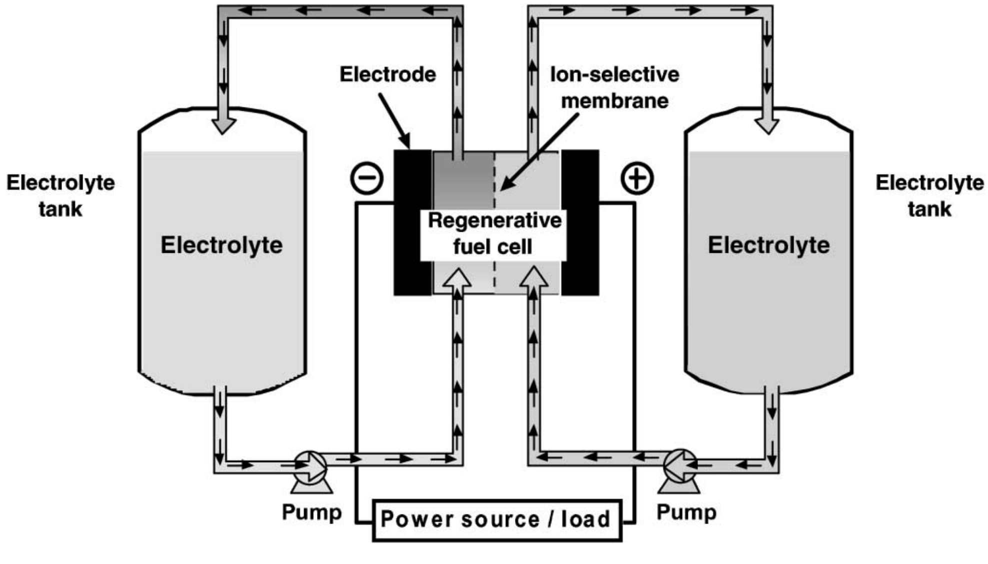

Fig. 2. Schematic of a flow cell which shows the electrolyte and electrical connections.

charge, some of the bromine formed in the positive-electrode loop dissolves in the electrolyte, while the majority is stored in the external tank as an insoluble polybromide complex. Zinc–bromine batteries have been demonstrated successfully in electric vehicles and in stationary applications. A principal problem is the corrosiveness of bromine, both from a materials compatibility and a safety standpoint.

A second flow battery is the ‘‘vanadium redox battery’’. The two electrolyte loops of this battery both contain vanadium in sulfuric acid medium, but in different valence states which may be oxidized/reduced at the electrodes. The half-cell reactions are the following.

At the positive electrode

$$V^{5+} + e^- \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftarrows}} V^{4+} \qquad (2)$$

At the negative electrode

$$V^{2+} \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftarrows}} V^{3+} + e^- \qquad (3)$$

The open-circuit voltage is 1.6 V. The battery has four external storage tanks: two for the reactants in the charged state and two for those in the discharged state. Some years ago, a 12 kWh battery was constructed for use in a demonstration solar house. More recently, the battery has been further developed by Kansai Electric Power and Sumitomo Electric in Japan.

By far the largest flow battery described to date is the ‘‘Regenesys^{TM} regenerative fuel cell’’ which is being developed in UK by Innogy plc. This is based on the oxidation/reduction of non-metals rather than cations. During discharge, the reaction of the negative electrode involves the oxidation of S^{2-} anions in Na_2S solution to sulfur, while at the positive electrode Br_2 dissolved in NaBr solution is reduced to Br^- anions. The open-circuit voltage of the cell is 1.57 V, i.e. lower than that of a zinc–bromine cell. The Regenesys^{TM} battery is being considered for load levelling in the electrical supply industry. Individual modules (cell stacks) are shown in Fig. 3. Prototype storage plants in 15–30 MWh range are under construction, and larger units of 100 MWh are envisaged. This does appear to be a promising approach to electricity storage on a large scale, provided the performance and the costs of the battery prove to be acceptable.

Fig. 3. Regenesys^{TM} regenerative fuel cell modules.

4.3.4. High-temperature batteries

High-temperature batteries are based upon molten sodium as the negative-electrode reactant and make use of a solid electrolyte, beta-alumna, in the form of a ceramic tube. Beta-alumna is an electronic insulator, but has a high conductivity for sodium ions at elevated temperatures. The positive-electrode reactant is either molten sulfur or solid nickel chloride. Large batteries, made up of several hundred cells, are contained within a double-walled, steel, vacuum enclosure so as to minimize the heat loss.

The ‘‘sodium–sulfur battery’’ operates at 300–400°C. The discharge reaction, which produces various sodium sulfides, takes place in two stages. During the first stage, the open-circuit voltage remains steady at 2.076 V, but then declines progressively to 1.78 V during the second stage. This battery was the subject of intense research and development for almost 30 years in various countries, e.g. Canada, Germany, Japan, UK, and USA. Except in Japan, all attention was directed towards electric-vehicle applications, and all the programs were abandoned in the mid-1990s for a combination of technical, commercial and safety reasons, even though the battery had been demonstrated in numerous electric vehicles. In Japan, the focus was on stationary energy-storage applications and, so far as the authors are aware, this program is still continuing. At present, there seems little prospect of the work being restarted in the other countries.

A major concern of sodium–sulfur batteries is the safety hazard of having molten sodium in close proximity to molten sulfur and separated only by a brittle ceramic tube. Should a tube crack or fracture, there will be a runaway thermal reaction and associated fire and this can extend beyond the cell and propagate throughout the battery. To avoid such a situation, numerous safety features are incorporated in the cell and these serve to limit the uncontrolled reaction. Nevertheless, a concern remains. Other problems with the sodium–sulfur battery are materials' compatibility and corrosion, and the inability of cells to pass current when fully charged. Since these problems all stem from the sulfur electrode, it was concluded that liquid sulfur was not a satisfactory material for the positive electrode and needed to be replaced by a non-volatile solid. In summary, whether or not the sodium–sulfur battery becomes commercially successful is a question of reliability, safety, and cost.

The development of the "sodium–nickel-chloride ('ZEBRA') battery" grew out of the sodium–sulfur program. The battery has a lower mean temperature than its sulfur-based counterpart (i.e. 300 versus 350°C) and may be operated over a wider temperature range (200–400°C). The overall cell reaction is

$$\mathrm{NiCl_2} + 2\mathrm{Na} \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftarrows}} \mathrm{Ni} + 2\mathrm{NaCl} \tag{4}$$

and the open-circuit voltage is 2.59 V. Early studies showed that the cell was best assembled in the discharged state using a mixture of nickel metal and sodium chloride. Liquid sodium chloraluminate, $NaAlCl_4$, is added to the mix as a second electrolyte so as to make good electrical contact between the surface of the beta-alumna tube and the positive reactant mix. The assembly of the cell in the discharged state has the added advantage that the sodium, when formed, is ultra-pure as only sodium ions diffuse through the beta-alumna lattice.

Work on the ZEBRA battery has been in progress for about 20 years and is now in an advanced state. The battery has many advantages over sodium–sulfur, namely, no corrosion problems, no volatile constituents (making for a much safer cell), and tolerance of overcharge and overdischarge. Thousands of cells have been assembled on a pilot production line and many vehicle-sized traction batteries have been built. The performance of both the batteries and the electric vehicles they power has been excellent. The present position is that a prototype production plant is under construction in Switzerland. As well as vehicle traction batteries, the ZEBRA system is suitable for building stationary storage batteries, although stringent cost targets need to be addressed. The battery is unlikely to meet the cost targets for bulk electricity storage, but may be suitable for some RAPS applications.

4.3.5. Lithium batteries

Finally, mention should be made of rechargeable lithium batteries. The lithium-ion battery employs 'intercalation' materials for the positive and negative electrodes, together with an electrolyte composed of a lithium salt dissolved in an organic liquid. The intercalation electrodes act as host structures which can reversibly accommodate lithium ions and electrons. Accordingly, during charge and discharge, the lithium ions shuttle back and forth between the two electrodes. The cell contains no metallic lithium and is therefore much safer on recharge than the earlier lithium-metal designs of cell. The latter were prone to thermal runaway and fire due to reaction of the lithium with the electrolyte. Small, lithium-ion batteries are now widely employed in portable electronic devices. A few large lithium-ion battery modules have been made as prototypes for electric-vehicle power sources, but as yet these have technical problems and are costly.

Considerable research is being directed towards the development of all-solid, rechargeable lithium batteries which use solid polymer electrolytes. Although good progress is being made on three classes of solid electrolyte, namely, dry solid polymers, polymer gels and polymer composites, it is too early to make reasonable predictions of the future prospects of lithium–polymer batteries.

5. Electric and hybrid electric vehicles

The transportation sector accounts for over half of the world's consumption of oil, and much of this is used by road vehicles. In UK, for example, road transportation in 1999 accounted for 77% of the petroleum consumed by the transportation sector. In the aviation field, any possible reduction in business travel through electronic communications (video conferencing, etc.) will be offset by growth in tourism. There may be scope for further electrification of the world's railways and a move away from diesel locomotives. The real prize lies in reducing petroleum consumption in road transportation. Major improvements are being made in engine technology, and in Europe there is a trend towards smaller and more economical vehicles. Also, government policy on fuel taxation has a role to play. For the purposes of this paper, however, the focus is on electric and hybrid electric road vehicles (EVs and HEVs), and their associated energy-storage systems.

The widespread adoption of vehicles powered wholly or in part by batteries for commuting and for deliveries in cities would make a significant contribution to improving urban air quality. This is why California, for example, has set so much store by EVs and, more recently, by HEVs. To the extent, though, that the electricity is generated by fossil-fueled plant, the contribution towards energy sustainability and reduced emissions of CO_2 will be minimal. The overall efficiency (defined as traction energy at the wheels divided by the primary energy input of the fuel supplied to the oil refinery or electricity power station) is not very different for petroleum-driven vehicles and EVs, while with EVs, the emissions are merely transferred from the tailpipe to the power station. Therefore, the contribution which battery EVs might make to global energy sustainability is second-order, unless and until renewables become a prime source of electricity.

To focus international attention on the potential for road transportation powered by renewable energy, Australia introduced in 1987, a competitive race for small, solar-powered electric cars across 3000 km of the Australian 'outback' from Darwin to Adelaide — the World Solar Challenge. The rules of the race stipulate photovoltaic-generated electricity to be the sole source of power for the cars. Competitors from 19 countries have participated in the five races held to date; the winners are shown in Fig. 4. Although it is clearly recognized that exclusively solar-powered cars will never be practical, the races have provided a valuable test-bed for the development of electric and hybrid electric cars. For example, when General Motors

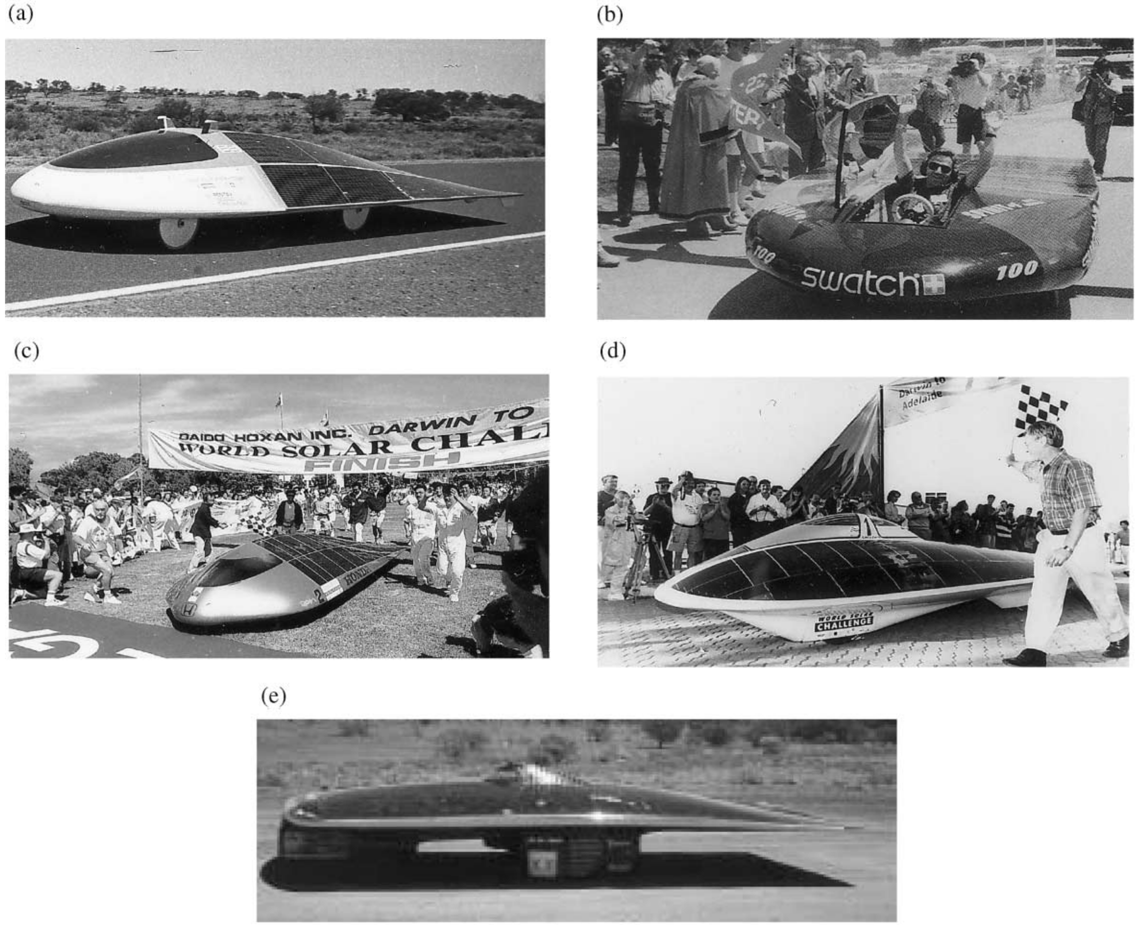

Fig. 4. Winners of the World Solar Challenge: (a) General Motors *Sunraycer* (USA) 1987; (b) *Sprit of Biel/Bienne II* (Switzerland) 1990; (c) Honda *Dream* (Japan) 1993; (d) Honda *Dream* (Japan) 1996; and (e) *Aurora* (Australia) 1999.

introduced the *Impact* electric car (later to become the *EV*1) in 1991, it was asserted that the vehicle capitalized on engineering and design principles first put into practice with the '*Sunraycer*', the winner of the first World Solar Challenge. It is also perfectly possible that photovoltaic panels on the roofs of small electric cars will make some contribution towards their energy supply.

Most of the world's major vehicle manufacturers are pursuing the development of battery-powered EVs [7,8]. Several companies have progressed beyond the prototype stage and have manufactured vehicles in small numbers for sale. These include: the Peugeot *106*, the Citroën *AX* and the Renault *Clio* (all French vehicles powered by alkaline batteries); the General Motors *EV*1 (lead–acid); the Toyota *RAV4-EV* (nickel–metal-hydride).

Considerable interest is also being shown in the concept of the HEV, which has two power sources [7–9]. This may be an all-electric vehicle, with a fuel cell to provide range and a high-power battery to boost acceleration. Alternatively, it may be a heat-engine–battery hybrid of which there are two basic types: (1) the 'series HEV'; and (2) the 'parallel HEV', see Fig. 5. In the series configuration, the output of a heat engine is converted to electrical energy through a generator which, either separately or jointly with a battery, powers a single drive-train. In one typical version, the series HEV would have a battery which is sufficiently large to meet the daily range and peak-power requirements for city driving, and a small heat engine (internal combustion engine or gas turbine) which is used to generate electricity purely as a 'range extender' for out-of-town driving. The battery is said to operate in the 'dual-power mode'. The series HEV is essentially an electric vehicle with an EV-sized battery and a small auxiliary engine.

By contrast, the parallel HEV has two distinct drive-trains such that the vehicle can be driven mechanically by a heat engine, or electrically by a battery–electric-motor, or by both. The heat engine is larger than that in a series HEV (but smaller than that in a conventional automobile) and is sized for steady highway driving. The independent battery system provides auxiliary power for acceleration and hill-climbing, accepts regenerative-braking energy, and restarts the engine in city traffic. In such duty, the battery has to furnish and absorb high, short bursts of current and is said to operate in the 'power-assist mode'. The parallel HEV corresponds to a

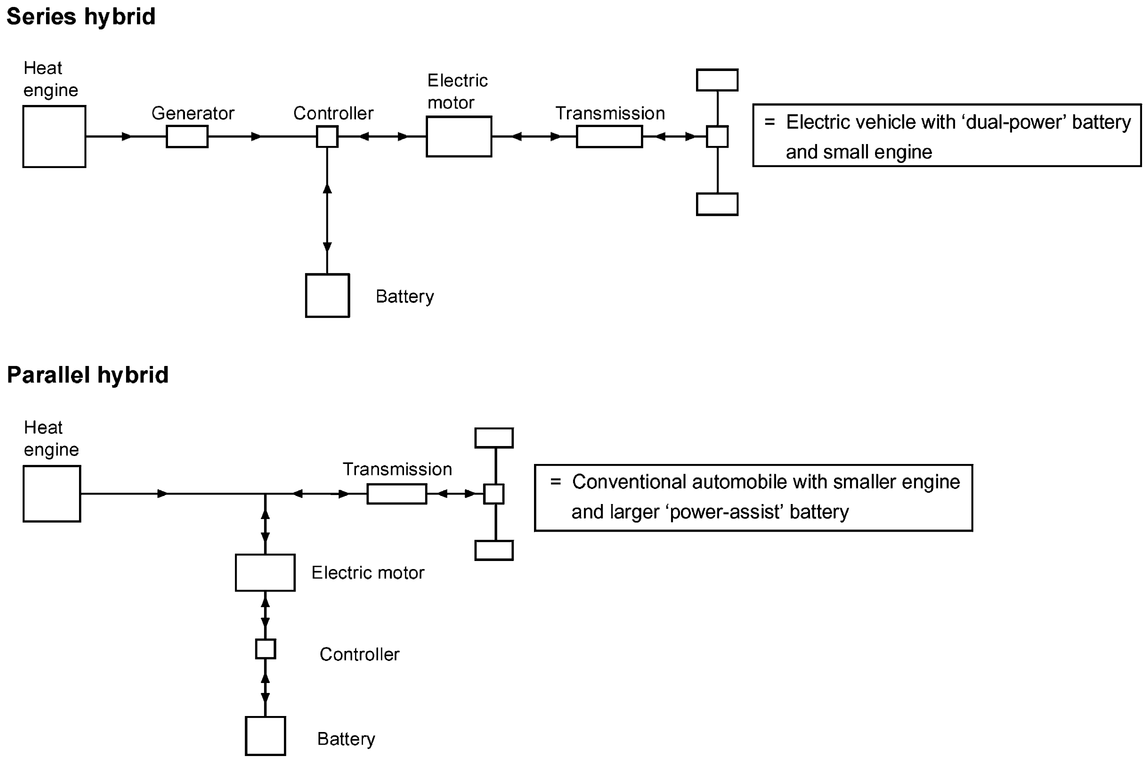

Fig. 5. Series and parallel configurations of HEVs.

conventional automobile with a smaller engine and a larger battery. The Toyota *Prius* and Honda *Insight* — both parallel designs which use nickel–metal-hydride batteries — have, to date, attracted the most attention. Many other automobile companies are developing hybrid cars and trucks as they are seen to be practical and to overcome the range limitations of pure-battery EVs.

The advancement of fuel cells for EVs is also attracting much attention. Electric vehicles powered by fuel cells are quite different from battery-driven counterparts. Not only are these vehicles less limited in range, a factor of prime interest to the user, but also the fuel (methanol or hydrogen) could, in principle, originate from renewable biomass. At present, there seems to be little serious endeavor to produce liquid fuels from crops, except in Brazil where ethanol motor fuel has been made by fermentation of biomass. Automotive companies which are active in the development of fuel-cell vehicles include General Motors, Ford, Honda, and DaimlerChrysler. There are several types of fuel cell, but the one which is considered to be most suitable for vehicle use is the proton exchange membrane (PEM) version. Power units are now available commercially that employ methanol reformers from Johnson Matthey (UK) coupled to PEM fuel cells from Ballard Technologies (Canada). Such power units are being used by DaimlerChrysler in its *NE-Car* (where *NE* stands for 'no emissions'). Almost certainly, fuel-cell vehicles will be hybrid systems in which a battery or supercapacitor will be used to provide surge power. Many of the major oil companies also now recognize the serious threat to the environment posed by the traditional fuels used by road transportation and are marketing cleaner fuels, e.g. low-sulfur diesel, liquefied petroleum gas (LPG), compressed natural gas (CNG), while working towards sustainable hydrogen fuel for the longer term, the so-called 'hydrogen economy'. (A detailed discussion of fuel-cell vehicles is to be found in an accompanying paper in this 100th volume of the *Journal of Power Sources* [10]).

If electric vehicles are to make significant inroads into the transportation sector, it will be necessary first to establish an appropriate infrastructure for 'refueling' the vehicles. In the case of battery-driven vehicles, this implies setting up public charging points at offices, car parks, shopping centers, etc. Studies in UK, for example, have shown that there should be plenty of electricity generating capacity available, particularly overnight, to support a national fleet of EVs. The cost of installing the network of charging points will, however, be substantial. The ability to recharge lead–acid batteries in a short period (e.g. 15 min) has been demonstrated successfully, but this would increase the power rating, size and cost of the charging equipment.

The infrastructure problems are different with fuel-cell EVs. No electrical recharging points are required. Instead, it is necessary to establish a new industry to supply hydrogen, or more likely a liquid fuel to be converted to hydrogen on board the vehicle. Methanol is the obvious choice but this, too, would require a new infrastructure for its manufacture on a large scale. A possible alternative is to develop a compact, on-board reformer which will convert petrol to hydrogen. Work is proceeding on this technology, but it has to be noted that this makes no contribution to sustainable energy as there is little possibility of producing petrol from non-fossil sources.

6. Conclusions

Predictions of the future course of events in the global management of energy resources are, as for any sphere of activity, notoriously difficult and unreliable and are made more so by rapid advances in science and technology. Who, for instance, would have predicted the world-wide web 20 years ago? Given this serious reservation, the conclusions we draw tentatively from this study are as follows.

1. Projections for the world consumption of energy in its various forms over the next 20 years are fairly well established and an overall growth of around 40% is expected. People value energy highly and, therefore, the amount consumed is not very price-sensitive. The projected breakdown of total energy among its various primary sources 20 years hence is also fairly certain, given no major political upsets.
2. Even though renewable forms of energy may grow rapidly on an annual percentage basis, their contribution to the overall world energy scene in 2020 will still be modest. In the specific field of electricity generation, renewables are predicted to contribute between 6.5 and 11.0 PWh globally in 2020, out of a total electricity generation of around 20.0 PWh. Much of this renewable electricity will still be derived from large-scale hydro power.
3. Given the above, and also the fact that, after hydro, the combustion of biomass and waste is the next largest contributor to renewable energy, it is unlikely that the world will reduce its overall emissions of CO_2 on a 20-year time-scale. Individual countries may possibly meet their Kyoto targets (if indeed these targets are enforced) in part by substituting efficient gas generation of electricity for coal, but growth in emissions from developing countries will more than nullify any savings made by the developed countries.
4. There is considerable scope for making savings in fossil-fuel consumption through energy conservation measures, and also by substituting the combustion of biomass derived from energy crops or from municipal waste. The latter is a matter of policy and economics.
5. Similarly, given the right economic conditions, there is much scope for using solar heat to heat water and buildings. Solar heat may be stored for many hours and has the added advantage that there is no emission of CO_2.
6. Wind and solar photovoltaic sources will make increasing contributions to electricity generation in the decades ahead. Wind power is erratic and is therefore unreliable. Moreover, the extent of wind generation may be limited by environmental considerations. The contribution of photovoltaics is tiny, the technology is still economically unfavorable. As the cost of photovoltaic modules and arrays falls, they will progressively be taken up in niche markets and diffuse world-wide, but by no means uniformly.
7. There is a very real need for a means of storing the electricity generated by most renewable forms of energy. Realistic options are pumped-hydro, kinetic energy in flywheels, or chemical energy in batteries. Where the terrain is suitable, pumped-hydro is the way to store large quantities of electricity. By contrast, flywheels and batteries are able to store only comparatively small amounts of electrical energy and are therefore better suited to locally generated or distributed electricity. Flywheels, in particular, have only a small energy-storage capacity but may be charged and discharged at very high rates. They are, in effect, surge-power devices and, as such, are complementary to batteries. Batteries are the best option available for storing small–medium quantities of electricity.
8. The most promising of the storage batteries are judged to be lead–acid, alkaline nickel oxide, flow batteries (also known as regenerative fuel cells), and sodium–nickel-chloride batteries. It may well be that some or all of these will be used for storing renewable electricity, both for stationary and traction applications. At present, however, only lead–acid batteries are likely to meet the most stringent of cost targets.
9. Battery electric vehicles and heat-energy-battery hybrid vehicles are likely to be introduced in increasing numbers, and in due course will make a significant contribution to improving urban air quality. In the case of electric vehicles, however, unless the electricity is generated from renewable sources, there will be little benefit in terms of energy sustainability.
10. Fuel cells are thought to have a promising future for both stationary and traction applications. They will, however, make little or no contribution to sustainable energy nor to reduction in emissions of CO_2 unless the fuel employed is a liquid (e.g. methanol) manufactured from biomass, or is hydrogen generated with solar, wind and/or hydro power.

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