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The Bourner lecture
Power sources and the new energy economy

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Abstract

This paper focuses on the critical role of power sources in the future energy economy. It highlights the disruptive nature of the new energy technologies that will come into play, addressing the problems of greenhouse emissions and reduced availability of fossil fuel reserves. The importance of power sources such as fuel cells and batteries is discussed and their inter-relationship with the hydrogen economy explored. Overall it is clear that improved methods of energy storage are of critical importance and these must be optimised both in terms of cost and energy density. There are important challenges to be addressed; however, very positive outcomes can be anticipated.

Keywords: Future energy economy; Fossil fuels; Renewable energy sources; Electrochemical energy sources

1. The new energy economy

There are a number of key drivers to change our current fossil fuel dominated energy economy. Firstly, we are rapidly approaching the position where cheap oil and gas are no longer readily available. It is predicted [1], that the world crude oil supply will peak in 2015 and at this point cheap oil will cease to exist as demand will outstrip supply. It is suggested that this shortfall could be satisfied with unconventional oil produced from sources such as tar sands or oil shales; however, it is inconceivable that such unconventional oils can be economically produced at current oil price levels.

Similarly, natural gas is becoming less available with, for example, North Sea stocks now decreasing significantly and the UK starting to import significant amounts of natural gas from Siberia. There are still quite significant reserves of coal, most notably in China and the USA, and there are strong pressures to utilise this form of fossil energy. Secondly, there is the issue of security of energy supply. Partly, as a consequence of the demise of certain fossil fuel resources, but more especially due to perceived political problems, many of the developed nations wish to ensure security of energy supply and so are implementing major changes in the energy economy. Thirdly, and most importantly, concerns about greenhouse gas emissions especially from carbon dioxide (CO_2) strongly mitigate against utilisation of fossil fuel sources, unless there are significant improvements in conversion efficiency.

Further drivers for the restructuring of our energy economy, relate to environmental concerns in association with planning. There is a growing reluctance to accept large-scale generation systems and especially the associated high voltage transmission lines. Public objections at planning inquiries, mean that centralised large-scale electricity generation now faces considerable difficulties in establishing new facilities in terms of expense and even a lack of certainty that planning permissions may even be forthcoming. Obviously, these difficulties are magnified significantly with nuclear power generation due to the long-term uncertainties of nuclear waste storage and its acceptability.

2. Static generation

The result of these driving influences is that there are now intensive world-wide efforts towards implementing a new energy economy. This energy economy will be largely based on renewable generation from wind, wave, hydroelectric, tidal, biomass and photovoltaic systems. This generation will be necessarily distributed in nature. The electricity supply network will move from a central system distributing electricity out towards the periphery to a distributed system generating electricity ideally close to the point of use, but to quite a significant degree remote from both centre and point of use.

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A key character of many of these new renewable energy sources is intermittence of supply. Photovoltaic devices can only generate when the sun shines, which necessitates at least a diurnal cycle of supply. Wind and wave are wholly dependent upon climatic conditions with very large variations in output over very short periods of time. Tidal is more reliable, but again has a twice-diurnal cycle. In every case this means that in the absence of storage, these systems need to be designed grossly-over capacity with a peak capacity perhaps 5–10 times that which might be required as an average output.

With this background, energy storage becomes hugely important. Balancing of load by storing energy from high power generation periods to be later utilised as back up in low generation periods will be of considerable economic importance.

Similar considerations apply to other new clean technologies, such as power generation from fuel cells, and such technology is again likely to result in a highly distributed network. This is driven both in terms of security for local supply, and by the fact that there is no great advantage in having very large generation systems for fuel cell technology due to the excellent scalability of this technology. With fuel cell technology, it is quite likely that power will be locally generated on typically 1–5 MW scale [2] with each locality or conurbation having its own independent generation capacity, albeit with interlocality grid connection. Such technology will be much less dependent upon energy storage than renewables as output can be controlled to match demand, although fuel supply is of course an important constraint.

3. Transport applications

The consideration so far has been related to static systems for energy utilisation; however, mobile systems are extremely important. Transport is responsible for 30% of fossil fuel utilisation [3]. It is extremely difficult to utilise renewable energy sources for transport directly, with the exception of some older technologies such as sail power. Thus in a new energy economy that is largely based on renewable resources it is essential to store the renewable energy in some form and then distribute that energy before it can be utilised in a vehicle.

The most obvious solution for this is hydrogen and the hydrogen economy certainly looks a very promising way forward for transport in particular. The likelihood is that the hydrogen will be produced electrochemically from renewable resources, distributed perhaps in compressed form, and utilised on-board with a fuel cell. Unfortunately, whilst this is clearly a pollution-free energy vector there are a number of complications that render its clean credentials somewhat suspect, at least in the short-term. First of all the cheapest and most direct early source for hydrogen production seems certain to be the reforming of hydrocarbons with significant CO_2 emissions. Barring sequestration, such emissions would be no less and quite possibly more than could be achieved if the fossil fuel was used directly, especially in a fuel cell. Secondly, the compression and storage of hydrogen is fairly energy-intensive with losses of perhaps 10% in compressing hydrogen or 30% in liquefying hydrogen [4]. Considerable research has been embarked on to find alternative solid state means of storing hydrogen, unfortunately the storage density of hydrogen is still very low, typically in the order of a few percent mass density of hydrogen. If hydrogen is generated renewably there are significant losses in hydrogen production. For example, the efficiency of generation of hydrogen by electrolysis is at the very most 80% energy-efficient using the best currently available processes. Alternative vectors such as ammonia, ethanol or methanol must seriously be looked at, especially in view of their much superior volumetric/mass density when compared to hydrogen. Although hydrogen is a very clean fuel in itself, its physical properties do not render it particularly amenable to utilisation. It is extremely likely that hydrogen or a related energy vector will be developed for utilisation in the transport industry in the foreseeable future, although this is perhaps not that likely to achieve dominant implementation before 2050. All things being equal, one would never wish to transform one energy vector into another if one could utilise that energy vector directly in the first place; however, it seems unlikely that electricity can be directly utilised in transport applications and indeed there are considerable advantages in load levelling—thus some sort of conversion of electrical energy will be required to produce a vector that can be transported in a different manner to electricity, as is gasoline for example.

4. Energy storage

There are probably two dominant types of energy storage systems required for the new energy economy, one related to static load levelling of renewables and the other to transport. For both, cost and reliability are extremely important, energy and power density are also important although to differing degrees. The energy densities available from different chemical fuels and energy storage devices are presented in Fig. 1.

Note that 10% by mass for hydrogen storage density has been assumed, a figure that should be viewed as a target rather than a currently available figure.

Although fuels do require an additional conversion device such as a fuel cell or internal combustion engine to be comparable as a power source to a battery, it is still very clear that batteries are more than an order of magnitude less in energy density. It is thus not surprising that electric vehicle development has now largely moved from battery-powered vehicles to hybrids with internal combustion or even fuel cell drives. Here it is power density rather than energy density that is all-important. Of particular interest to these applications are nickel/metal hydride, lithium [5] and high

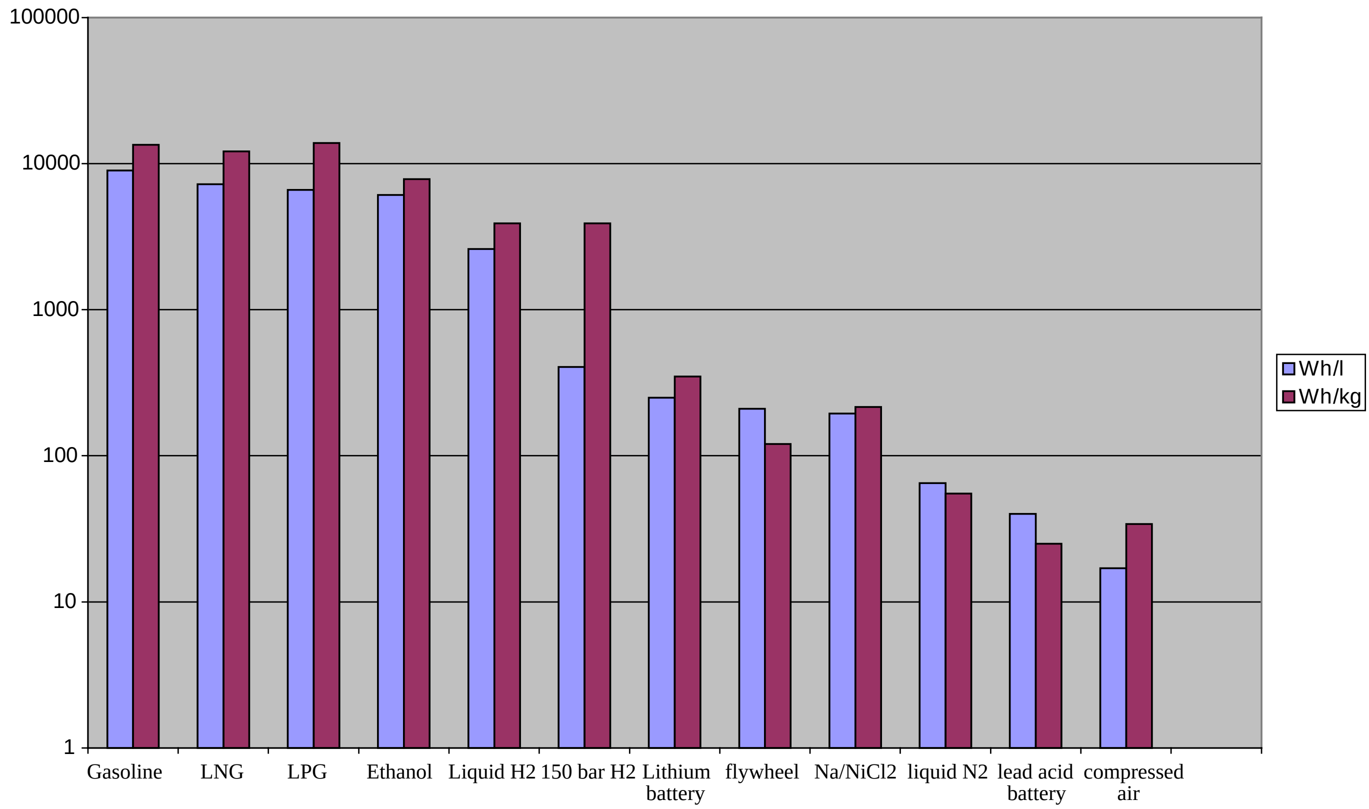

Fig. 1. Comparison between volumetric and gravimetric energy densities of different fuels and energy storage devices.

temperature sodium/nickel chloride systems. Future work will seek to optimise power and especially rate capabilities.

The options for static energy storage are much less clear. Pumped water is certainly historically of great importance and continues to offer a useful solution. Similar mechanical methods such as flywheels and compressed or liquefied gas also offer promising solutions, however electrochemical solutions hold considerable promise. At the upper limit expected for most renewable systems, regenerative fuel cells are already in demonstration, being targeted at the 5–500 MW range. Regenerative fuel cells convert electrical energy into chemical potential energy with two electrolyte solutions typically, sodium bromide and sodium polysulphide, separated by an ion-exchange membrane. Such systems may well be able to be modified for the smaller scale expected for renewable generation; however, there will be cost implications as e.g. the pump system may not be scaleable. Challenging for this important niche are the same rechargeable battery systems as targeted for vehicle research (Li, Ni/MH, $Na/NiCl_2$), but with different performance goals. A further possibility is a reversible fuel cell system that produces, stores and converts hydrogen back to electricity. One typical aspect of renewable generation systems is the presence of an unused dead space, such as a windmill pole. This aspect at least offers an appropriate housing for the energy storage device and development engineering should seek to exploit this opportunity.

5. Fuel cell technology

Fuel cell technology has been much heralded in recent years as a keystone of the future energy economy. In association with the hydrogen economy, it has been strongly promoted by the governments of most of the world's leading industrialised nations. There is now a phenomenal commercial interest in fuel cell technology with new start-up companies being established and major players in the energy market turning their attention to this technology. In the long term they are an essential component of any hydrogen or similar clean energy economy, in the short-term they promise greatly enhanced conversion efficiencies of more conventional fuels and so large reductions in CO_2 emissions. It is unlikely that a single technology alone will meet all requirements, there are distinct advantages for different electrolyte systems and temperatures of operation.

5.1. Solid oxide fuel cells

Solid oxide, i.e. high temperature fuel cells, have a particularly wide range of applications ranging from distributed megawatt scale generation through to local domestic generation at the 10 kW scale. There is also a wide range of other applications where cleaner energy is required, such as corrosion protection, uninterruptible power supplies, remote generation and domestic appliances. The most publicised examples are in the automobile sector where companies such as Ford and Renault are looking at high temperature fuel cells for auxiliary power generation and other companies such as Daimler Chrysler are looking at lower temperature polymer based fuel cells for complete electrical generation. The market scale is certainly in the billions of euros per annum. The degree and extent of market penetration and establishment really only depend on the ability to reduce the cost of these devices whilst ensuring their long-term stability. The technology is certain to be applied; its scale will depend on the success of researchers in improving performance and cost. It is quite likely that the fuel cell's impact upon society will be revolutionary.

One of the most important areas to be addressed in the development of solid oxide fuel cell technology is the fuel electrode. A major objective for its short-term implementation is the development of SOFC anodes capable of operating in natural gas without suffering from carbon build-up due to catalytic cracking. Nickel based electrodes are widely used at present and work well with hydrogen or steam-reformed fuels. There are major improvements in efficiency to be achieved if reforming can be fully achieved internally, or better still, if oxidation can be achieved with minimal steam additions. For many applications it is essential to heat up and cool down the fuel cell and there are major risks of failure from oxidation of the nickel. The key development issues are to achieve new anodes that are much more redox-tolerant, more resistant to coking problems and also more tolerant of sulphur. This would allow a much wider range of hydrocarbon fuels to be utilised in simpler systems and certainly facilitate the implementation of biofuels. Most importantly it would facilitate the implementation of this energy-efficient technology into the current infrastructure.

There are many advantages to reducing the operating temperature of high temperature fuel cells, in particular ease of sealing, improved long-term stability and the ability to use lower cost steel interconnected cells. At low operating temperatures the major performance limitations are high overpotential losses at the cathode. There is, therefore considerable interest and activity in improving the efficiency of the present cathode material-based on (La, Sr)MnO_3-with new materials that show much better electrocatalytic activity especially through improved mixed ionic and electronic conductivity.

Most current SOFC designs are based on yttria stabilised zirconia, which can only operate effectively at very high temperatures due to its non-ideal ionic conductivity. There is significant effort directed at developing new thin film technologies that reduce the resistance of this and related materials. In addition, there is also a great deal of interest in finding new, alternative oxide ion conducting electrolytes such as ceria or lanthanum gallate that can be used at lower temperatures, e.g. 600 °C, but with improved stability.

Historically, lanthanum chromate interconnects have been widely considered, however there are a number of problems, mainly associated with cost and corrosion. Interest is therefore now turning towards finding new interconnects based upon steel. The search is focused largely on corrosion resistance and avoidance of chromium contamination of electrodes arising from degradation of the interconnect.

An important area, especially for hydrocarbon based fuels, is the processing of fuels through steam reforming or partial oxidation reforming to allow hydrocarbons to be used more effectively in the fuel cell. Other important approaches in fuel processing relate to sulphur scrubbing, deliberate cracking to provide hydrogen for the fuel cell with carbon sequestration, and cogeneration, systems to generate useful feedstocks as well as electricity.

5.2. Proton conducting membrane fuel cells

Polymer electrolyte membrane, PEM fuel cells are the other leading edge fuel cell systems. The technology is essentially hydrogen-based and is more mature than SOFCs. There are still important areas of materials development especially relating to electrolyte and catalysts for electrodes and reformers that will further advance the technology. An important new development relates to proton conducting solid oxide fuel cells (PCFC) that operate at temperatures higher than polymer membrane systems, e.g. 750 versus 900 °C. These have recently been shown to operate successfully using dry hydrocarbon feedstocks.

6. Electrolysis

Fuel cell technology may be also used in reverse for electrolysis of water or steam to produce hydrogen and oxygen. This provides one of the most promising routes for generation of hydrogen from renewable electricity and so providing much needed clean hydrogen. A related process is combined electrolysis of steam and carbon dioxide to produce synthesis gas. From synthesis gas several valuable compounds, e.g. methanol or dimethyl ether, may be produced. This technology could also be developed for transportation of renewable energy from remote areas or for better distribution of energy from gasfields to urban areas. Although not a major application in the short-term, electrolysis of steam or carbon dioxide has also been frequently proposed to produce oxygen for manned space stations, e.g. on Mars.

7. Conclusion

Electrochemical energy conversion and storage devices undoubtedly have a major role to play in the new clean energy economy. In energy conversion the key technology is based on fuel cells, with several different application scales being envisaged and different variants of the technology expected to be utilised in these. For energy storage related to transport, high power batteries are being developed for hybrid vehicles. For energy storage related to static renewable generation systems batteries, regenerative fuel cells, reversible fuel cells and electrolysis of water are all competing to fill the very important niche for load levelling of relatively unstable supplies.

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