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Sustainable energy conversion: fuel cells — the competitive option?

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Abstract

The definition of sustainability is still under discussion, but it is becoming increasingly clear that present practices of energy supply and distribution are causing severe environmental pressures, and that they cannot be continued indefinitely. The fuel cell has been undergoing rapid development and is now at a stage immediately prior to commercialisation for a number of markets. It is expected to be economically competitive with many other energy conversion technologies within the next 5 years. However, introduction of the fuel cell may also speed the economic introduction of emissions-free energy carriers such as hydrogen, linking directly to renewably generated electricity. Hydrogen could be used as a form of energy storage in cases where electricity demand and supply were not matched. The fuel cell would then be complementary to, rather than competitive with, renewable generation technologies. Ultimately, the fuel cell, in both its high and low-temperature derivatives, could become one of the pillars of a future sustainable energy system. © 2000 Elsevier Science S.A. All rights reserved.

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1. Introduction

Sustainability is one of the buzzwords of the late 1990s, and seems set to remain popular into the new millennium, but it is not at all clear what 'sustainability' means. The Brundtland report [1] attempted to define it as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs', though there has been criticism of this perspective as failing to make clear the boundaries of the concept of development [2]. Schumacher, well before the present vogue, defined something very like sustainability as 'living off the interest and not the capital' of natural resources [3].

By that definition, energy generation has been largely and obviously unsustainable for many years, relying heavily on the capital of natural fossil reserves. Ultimately, sustainable energy conversion, therefore, is required not to use up natural resources, and must rely on renewable power provision.

The fuel cell is an energy conversion technology, not an energy resource, and thus its contribution to sustainability is dependent upon many other factors — in large part the process by which its fuel is procured. However, it fits into sustainable energy futures in many scenarios.

2. Energy provision: present and future

The vast majority (90.0%) of energy use reported worldwide is provided by fossil fuels [4] — and 28% of present energy use goes to transport [5]. Of course, there is significant indigenous use of fuels such as wood and dung that remain largely unquantified, but, in general, these do not have a major bearing on world energy consumption. However, the use of energy is grossly inequitable, with per capita consumption of energy in the 'rest of the world' less than one-third of the average in Europe and one-sixth that in North America [4]. This level is predicted to rise considerably into the next millennium, putting pressure on fossil fuel reserves and possibly opening new markets for technologies that can provide improved or alternative methods of energy provision [6].

In addition to this, a significant proportion of the predicted growth will be in demand for electricity, for the trappings of western civilisation that are associated with growth in per capita income such as fridges, televisions and other home appliances. Presently, that electricity is produced almost exclusively by the use of large power

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plants consuming fossil fuels, and is then delivered to the consumer over a complex and long distance network of wires. While the generating efficiency may be optimised because of the size of the plant, the delivery of electricity is anything but, and the inefficiencies introduced by poorly constructed markets may add to the problem. It appears that during the ice storm in Quebec in January 1998 there were power stations across the US border which were not prepared to sell power to back up the Canadian network unless the price was right. The price was never agreed and the grid collapsed, although it may have suffered regardless of that individual decision [7].

Nevertheless, the future of electricity provision is not constrained by the past, and the development of large grid systems occurred for many reasons, which were important at the time, not least the increased efficiency and reduced cost of power plant at multi-megawatt sizes. It is now being suggested that the logical path for the future is one of decentralised generation systems — power plants that can be as small as 5 kW to power individual homes, or as large as 50 MW for industrial cogeneration — which are sited near to their load [7]. Not only will this reduce the individual capital investment associated with each plant and, thus, the risk to the installer, it will also remove the requirement for expensive and increasingly controversial high-tension cabling to carry electricity over long distances. Transmission efficiency losses of 7–8% will also be reduced, and it may even be possible to move out of a world in which AC electricity is required and into one where DC can be produced and consumed. This would enable the reduction of reactive power requirements and harmonic distortion, for example, simplifying and reducing the cost of the electricity supply system, albeit at the expense of using thicker conductors.

Demand for energy in transport is predicted to rise as fast as that for other uses, and in transport there has traditionally been almost no use of alternatives to fossil fuels. Even the majority of ‘‘alternative’’ fuels are merely fossil derived — such as LPG or CNG.

3. Impacts of energy

The environmental impacts of energy production and use are often graphically visible and have been well documented. Extraction, transport and use of fossil fuels cause landscape degradation and produce emissions. Whatever the definition of sustainability, it is clear that energy use in the past has never come within its remit. Local and regional pollution problems, however, are gradually being resolved. This has been achieved largely by the use of post-combustion gas clean-up, to ensure that emissions of dioxins, ozone precursors, acid rain precursors and other regulated emissions are severely reduced. It is projected that urban air quality will be well within World Health Organisation requirements in the majority of the developed world within 10 years.

However, the spectre of climate change is becoming increasingly ominous, and it is now substantially the reduction of greenhouse gas emissions that drives research into cleaner, more efficient technology and fuel combinations. It is clear that there are many avenues that can be explored with this in mind, from increased energy efficiency to better design of manufacturing facilities and the deployment of renewable energy technologies [8]. In addition, nuclear energy may be reconsidered, as it emits no CO_2 during electricity generation, though adverse local economics, its long-term legacy and public opinion may prove too strong to overcome. Below are several issues that cannot easily be resolved.

- Renewable energy generation is almost invariably intermittent. How is the link between supply and demand controlled to ensure electricity provision when it is required?
- Increased energy efficiency often leads to no reduction in demand. Instead, the cash saving is redirected into using more energy and increasing levels of comfort [9].
- Transport energy has been traditionally almost exclusively fossil derived. How can this be modified in the future?
- As the population expands and the demand for energy inexorably rises, there *must* be some point at which it is impossible to rely on fossil resources. It has already been suggested that the peak of oil production will be reached in the next few years [10] while demand continues to increase.

The only solution to these problems in the long term lies in embracing the concept of sustainability and making it practical and achievable.

4. Fuel cells and their place

The fuel cell is one of the oldest energy technologies known to man, yet its development has lagged behind that of its less elegant and often less efficient cousins, such as the internal combustion engine and the gas turbine. The fuel cell produces DC electricity from chemical energy, without transforming it first into heat and then into kinetic energy. It can, directly or indirectly, do so from a whole variety of fuels, often in a very efficient manner. It is also a modular technology, a fundamental attraction amongst suggested developments for energy conversion technologies and markets, and one which suggests that the fuel cell will be very successful in the future. Present demand is moving towards technologies that can provide high efficiencies with low emissions at low prices, producing high quality power and other energy services. The fuel cell appears capable of fulfilling those criteria. In addition, the fuel cell can serve equally well as a replacement for the internal combustion engine, since it is quiet, efficient, and clean. While capable of running on reformed fossil fuels, it is also capable of efficiently using renewably generated hydrogen.

5. Competitiveness

The fuel cell is currently economically competitive only in certain specialised circumstances. Innovative technological development and production engineering are required for the different types of fuel cells to fulfil their promise; it is possible that some may fall by the wayside. However, detailed engineering studies have suggested that the cost of the fuel cell system can be brought down, without the requirement of technical breakthroughs, to a level where it is fully competitive with the internal combustion engine for automotive applications [11,12]. In stationary power generation scenarios, the projections are similar, with detailed cost modelling leading to power plant prices that can begin to undercut conventional technologies, while maintaining flexibility [13]. Thus, competitiveness in the economic sense is achievable.

However, the fuel cell is not *competitive* in every sense. It is important to remember that the fuel cell is an energy conversion technology — not a primary energy source. It requires a fuel from which to generate power and heat, and that fuel has to be produced in some way, be it from fossil resources or from renewably generated electricity. And, in the long term, it is only fuels produced from renewable resources that are truly sustainable as energy carriers.

The intermittent nature of the renewable generating options that exist favour the use of energy storage for power provision; hence, when demand is high but resources are not available, night-time television for example, cannot be powered by daytime photovoltaic panels without energy storage in some form. Energy storage can be achieved with battery technologies, but in the long-term it is a requirement that mobility is also sustainable; batteries have not so far been shown to be an ideal option for motor vehicles. It seems plausible to suggest that the production of hydrogen from excess electricity for energy storage is one option that will be carefully considered, with hydrogen and electricity two of the primary energy carriers. The elegance of the hydrogen option lies in its production from water with only accompanying emissions of oxygen. The hydrogen can then be recombined with oxygen from the air to form water once again, while generating electricity on demand. In this case, the fuel cell is not *competing* with the renewable generation technology; rather it is complementary to it, and this synergy may help to drive the market for each type of technology forward. Inefficiencies associated with multiple interconversions are affect by the benefits of energy storage.

6. The biomass dimension

As suggested above, the fuel cell may well be a fundamental part of a future sustainable energy chain. However, renewable hydrogen from electrolysis is not the only fuel option. Biomass, in forms as diverse as municipal solid waste, sewage sludge and forestry residues can all be converted to methane-rich gas streams or liquid fuels and then, if necessary, to hydrogen. However, energy requirements are driven by demand for services such as lighting, warmth, cooking facilities, mobility, and not by demand for electricity, or any other energy carrier, in itself. Heat, for example, is critical to human survival and to industrial processes, amongst many other things.

Hydrogen use in fuel cells is most efficient at low temperatures. This is a fundamental law following the relationship of the Gibbs free energy ($\Delta G°$) and the enthalpy ($\Delta H°$) of the hydrogen oxidation reaction that takes place [14], and is shown schematically in Fig. 1. Operating a fuel cell on hydrogen is, therefore, best performed at temperatures around 100°C, producing waste heat suitable for space heating and household use but little else. Nevertheless, future demand for heat will increase rather than diminish, and so this heat must be produced by some other process.

The direct oxidation of methane is much more efficient at high temperatures than that of hydrogen, as shown in Fig. 1, because the entropy component in the relevant equation is much smaller [15], methane can, therefore, be used effectively and directly in high-temperature fuel cells to produce waste heat for various requirements. This is significantly different from the process that presently takes place in most high-temperature fuel cells, which reform the methane internally to carbon dioxide and hydrogen, and then oxidise the hydrogen.

At present, methane is largely found in the form of natural gas, a fossil fuel, already dismissed in the far future as an unsustainable energy option. However, it can also be efficiently produced from many of the significant biomass

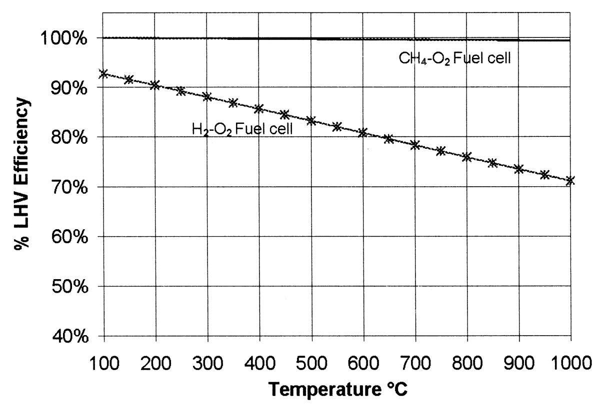

Fig. 1. Variation in theoretical efficiency between a hydrogen and methane oxidation reaction.

resources discussed above in a process that should be both CO_2-neutral and release only minimal levels of regulated pollutants.

This ability to use renewable hydrogen in low-temperature processes, renewable methane directly in high-temperature processes and renewably generated electricity in areas where it is both available and in demand, makes a coherent and sustainable long-term energy system both possible and plausible.

7. The confluence of drivers

Throughout, the existence and importance of a number of different drivers has been alluded to in the context of future fuel cell applications. It is important not to underestimate the possible synergies and strengths of these drivers in this context.

- As deregulation of energy infrastructures is occurring, and seems set to continue, the demands of consumers are becoming more sophisticated. Small, decentralised, flexible and cost-effective systems can meet both consumer demands and industry expectations for quick economic return.
- Regulation of pollutant emissions is becoming increasingly strict, and the siting of cogeneration plant in the areas in which it is most efficient (e.g., urban centres) means that it must comply with stringent emissions and noise standards. In some areas emissions charging may also be introduced, in an attempt to internalise the externalities arising from polluting emissions.
- Urban centres are also restricting polluting transport modes. Hydrogen fuel cell buses, for example, are showing their worth at present in niche markets, and probably in the future in many traditional ones. Fuel cell cars may also offer both environmental and consumer benefits.
- Reductions in CO_2 emissions have been agreed by the majority of governments under the Kyoto Protocol [16]; this requires integrated solutions, including energy efficiency and use of alternative energy sources.
- Renewable energy is becoming increasingly competitive and must be integrated into both existing and renewable power grids, despite its intermittent nature. Production of hydrogen as an energy storage medium is under investigation in many areas.
- Hydrogen is being considered as a candidate for vehicle fuel and stationary power systems using fuel cells. It allows for a simple fuel cell system and very high energy conversion efficiencies, and can be produced from any hydrocarbon or from water.

The fuel cell fits neatly into solutions that include all of the above. It is also timely in that it offers the prospect for new opportunities in many markets, thus appealing to consumers. The possibility for exports appeals to government funders. Its low emissions profile may appeal to the environmental lobby. It represents high technology, appealing to scientists. In many more ways than may be obvious, the fuel cell is a competitive energy conversion option.

8. Transitions and timeframes

In the near future, it is clear that even the most progressive countries will be providing for the majority of their energy needs by the exploitation of fossil resources. Some of these countries, however, are aware that their Kyoto commitments will force them to re-think conventional energy strategies. These commitments have been made by the majority of industrialised countries, with most agreeing to reduce their CO_2 emissions in comparison with 1990 levels. In part because of this, significant work in CO_2 removal and sequestration is now taking place [17], with the aim of producing comparatively low-cost hydrogen from fossil fuels with minimal greenhouse gas emissions. While renewable energy generating capacity begins to be exploited, it may be that carbon sequestration can act as one plank of a bridge to a future renewable hydrogen economy. Importantly, fuel cells can be fuelled using hydrogen from any fossil fuel resource.

In some niche markets, such as remote areas, renewably generated hydrogen and fuel cell systems can already be economically competitive [18]. These systems can act as proofs of concept, allowing control strategies to be refined and costs to be reduced before they are integrated into the wider market. At the same time, fuel cell systems seem set to be introduced into domestic power generation markets, battery replacement markets, and vehicle engine markets. The synergies that will arise from developments in these areas will aid further market penetration.

The timeframe is, as with any major infrastructure and technology change, unclear. Shell has forecast that up to 50% of energy generation by 2050 could come from renewable sources, with hydrogen a significant component in the fuel mix. If the first fuel cell systems prove successful then the technology may actually drive replacement faster than has presently been suggested, and may also benefit renewable energy systems as providers of non-fossil hydrogen. Not only that, but markets in which renewables have hitherto been uncompetitive, due to the intermittent nature of their energy production, may be opened up. However, in the distant future, a sustainable energy system is likely to be decentralised, relying on local renewable resources and using hydrogen, methane and fuel cells to fulfil demand for energy services.

9. Conclusions

Although sustainability is difficult to define, it is clear that present energy provision does not fulfil whatever criteria are chosen to describe it. In the future, a confluence of drivers is likely to lead to sustainable energy systems based on renewably generated hydrogen, methane from biomass and renewably generated electricity. The fuel cell, while presently not economically competitive, except in a minority of niche markets, is likely to become so in the near future, and can be flexibly integrated into future energy systems using either hydrogen or methane as a fuel. However, as an energy conversion technology, it requires some form of fuel, produced from primary resources. Since both electricity and heat will be required in the future, and load curves are unlikely to be flatter than they are today, energy storage will be required for renewably generated electricity to manage peaks and troughs in demand. Hydrogen from renewables, coupled with fuel cell generation on demand, provides an elegant and *complementary* solution to this problem. It is, therefore, suggested that not only are fuel cells a future *economically competitive* option for sustainable energy conversion, they are also a *complementary* option in the sustainable energy system of the future.

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