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Small-scale fuel cells for residential applications

N.M. Sammes *, R. Boersma

Department of Materials and Process Engineering, The University of Waikato, Private Bag 3105, Hamilton, New Zealand

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Abstract

The market and technical requirements for small-scale fuel cells in residential applications are investigated, focusing on the 1 to 10 kW range. In particular, the peculiar features of the New Zealand situation are explored, with its specific energy resources and demands. It is shown that various technologies could be applied, with PEM, SOFC, PAFC and AFC competing on almost equal terms, with cost targets of 500 to 700 EUR/kW. The attributes and disadvantages are discussed, with a number of technology gaps being identified, and some solutions proposed. Two new developments in the PEM and SOFC systems are compared in relation to their use in domestic applications. The obvious premium application of fuel cells in New Zealand exists where grid connection is expensive. Other priority markets are also studied. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Fuel cell; Forecast; Residential; Market

1. Introduction

Research efforts into fuel cell systems received a tremendous boost in about 1985. Many people envisaged that the electrical power generated with fuel cells would be in multi-megawatt plants. However, a worldwide trend developed towards a more market-orientated, deregulated electricity production regime. As a result, it became clear that electricity generation on a smaller scale made economic sense.

The challenge is for the generation of power in the range of 1–100 kW, which must be cheap, reliable and require little maintenance. Conventional small generators produce electricity at a cost that is three to five times higher than that from the grid, with added problems of vibration and pollution levels. Consequently, they are traditionally used for back-up power, or if used as stationary generators, require costly redundant capacity to obtain sufficient reliability.

With fuel cells, an alternative power supply could be offered with systems running from a reticulated network, bottled gas or liquid fuel. The advantage over existing generators should be the longevity, reliability, low maintenance cost and at an energy cost below or equal to that of the grid. Even though fuel cells can overcome many of these problems, the relatively high capital cost is reflected in a high-energy cost, and the reliability of the conventional power supply is difficult to compete with.

Applications for market entry will be those that, at present, require a premium, for instance, in remote areas and for applications requiring high power quality. In the case of remote areas, the cost of connection to the grid can be prohibitive, examples include farming, signalling (train, air), telephone exchanges, and forestry. Examples of applications requiring a high power quality include computers, data processors, and control systems which do not necessarily have a use for the process heat (however, the value of the heat can often be ignored because of the higher value of the electricity). Other application areas are in places with insufficient or unreliable power supply, for example, in developing countries and where problems have arisen such as those observed in Auckland, New Zealand in 1998, where due to a combination of factors the capacity of the distribution network was stretched to its limit. This resulted in failure of a number of main lines to the city centre, causing major outages followed by a period of

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Abbreviations: MCFC, Molten carbonate fuel cell; PAFC, Phosphoric acid fuel cell; SOFC, Solid oxide fuel cell; PEM, Polymer electrolyte membrane (fuel cell); AFC, Alkaline fuel cell

* Corresponding author. Fax: +64-7-838-4835; e-mail: n.sammes@waikato.ac.nz

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2 months of limited power. An interesting factor contributing to the problems was that the capacity of the network itself had been overestimated.

The application of small fuel cell systems is described, with particular reference to solid oxide fuel cell (SOFC) and polymer electrolyte membrane (PEM) systems. The design and fabrication of a number of such micro-generators is examined and their applications and siting requirements described. Finally, the economics involved in the fabrication, siting and running of these systems is compared to conventional electricity generators.

2. Fuel cells for residential power

Reticulated power in densely populated areas can be expected to be the cheapest alternative in the near future. For fuel cell systems to be competitive in these areas, the cost has to be extremely low. In addition, the reliability of the existing grid is very high, and CO_2 emissions are displaced; both of these issues for stand-alone systems will be difficult to compete with. The worldwide trend of deregulation and privatisation of the electricity industry puts a further disincentive on their application in densely populated areas. Here the price may be reduced even further, partly because of increased competition but also because of cross-subsidisation of the more rural areas, which is ruled out in a business environment.

Thus, the rising cost of electricity in rural areas could well be the first large market niche for fuel cells for homes. As a result of the privatisation in New Zealand, the customer now has to pay for a new connection to the network. The cost of this can easily amount to several thousand Euros, and consequently, the alternative of using a fuel cell becomes economically viable. In the following sections, the existing technology will be reviewed and an assessment will be made of their applicability for domestic fuel cell power.

The molten carbonate fuel cell (MCFC) has not been included, as the technological difficulties have turned out to be far greater than expected. There is also a perception that this type cannot be used for small-scale applications, consequently, no small-scale developments have been undertaken.

2.1. Alkaline fuel cell (AFC)

For terrestrial applications, the alkaline fuel cell seems to have been superseded by the PEM. Where the PEM requires a somewhat elaborate water management system, the AFC requires an electrolyte circulation and pressure balancing system. In addition, the AFC's gas purity requirements are more stringent. It has to be recognised that the AFC may have better cold starting capabilities than the PEM; there is no water management system that can freeze. Therefore, once a better hydrogen infrastructure has been established the AFC may be expected back on the scene.

2.2. PEFC

The PEFC was first described by Grubb in 1959. Until today, the concept has remained relatively unchanged, though as a result of materials, design and operational improvements, the current density has increased from 30 mA/cm^2 on pure hydrogen and oxygen to over 1000 mA/cm^2 on reformate and air [1–3]. Ballard Power Systems of Vancouver can be considered the most successful company that manufactures this type of fuel cell. Another PEM manufacturer is Plug Power, who have a patented separator that consists of a metal plate with carbon strips attached to it, thus creating the gas channels. The novelty of their design is that there is no time-consuming machining of channels required; moreover, the metal sheet has allowed for a further reduction in separator plate thickness [4].

Combined with its self-starting capability, the low operating temperature and solid state design, the PEM fuel cell has become the favourite of the car manufacturing industry. There are still a number of operational issues to be resolved, which result mainly from the fact that an operation and start-up range from −20°C to +40°C is required. In addition, contamination in the reformate and air may have a deleterious effect on the performance [5–7].

Since the envelope for transportation applications seems to be more stringent than that for stationary production, and if, indeed, the car manufacturing industry succeeds in manufacturing fuel cell drive systems for under EUR 100/kW, this will also have very exciting implications for domestic power supply in general.

2.3. Phosphoric acid fuel cell (PAFC)

1992 saw the onset of the 200 kW PAFC generator developed by ONSI. Over 200 units have been sold and a wide variety of CHP applications have been demonstrated [8]. Toshiba, in a PAFC Research Association project, are developing 1000 and 5000 kW systems [9]. The target is for on-site power for large buildings or for industrial processes. For domestic applications, the scale of the present PAFC systems is clearly too large. From a theoretical point of view there is, however, no reason why the PAFC could not be used for domestic applications. It could well be a matter of mindset; the PAFC has the longest history of development for large-scale applications, which may hold people back from considering it for small-scale applications. In the end, the market will prove what is correct.

2.4. SOFC

Westinghouse, now Siemens-Westinghouse, has dominated the SOFC field for many years with its seal-less tubular design. The development of this system is aimed at generators with a capacity of up to 60 MW, which, in combination with a gas turbine, is projected to be 60% efficient [10]. The falling prices and increasing efficiencies of gas–steam turbine combined cycles have put tough goals on the cost targets of SOFC systems.

As a result, many developers have shied away from this competition and are now targeting distributed power generation. This has resulted, for instance, in the development of the 1.5 kW Sulzer stack [11].

The advantage of the SOFC is that because of its high operating temperature, it can reform gases internally, and can be placed in close thermal contact to a pre-reformer. This enables a high degree of integration and reduces the need for heat exchange systems.

The high operating temperature is also a major challenge for the SOFC. Next to the problem of structural stability of the materials, there is the problem of thermal matching of components, which is required to avoid thermal stresses during the start-up phase. Even with a perfect thermal match, thermal gradients, resulting in mechanical stresses, can occur during the start-up phase. Rapid start-up and transient behaviour is inevitably going to be a requirement for residential applications, and can be expected to be a materials and engineering challenge for SOFC developers.

2.5. Overview

For residential applications, the PEM and the SOFC appear to have the highest potential in terms of general developmental stage and developmental stage specific for this market. Both types are still facing a number of technical hurdles, which will be discussed later. The PAFC and AFC have, not so much for technical reasons, but rather from historical perceptions, not been developed for this market. Consequently, since these are unlikely to be first on the market, their potential for this market is diminished.

3. Trends

In this section, a trend analysis is carried out. The following trends are commonly distinguished [12]:

- Social Trends
- Political Trends
- Economic Trends
- Technological Trends

A trend analysis is carried out as part of a forecast in order to establish whether a new technology is in line with the trend of the time. If it can be detected that it is going against certain trends, then this may slow down and limit the uptake of the technology.

3.1. Social trends

- A growing awareness of the impact that people have on the environment; this has been an important driver for governments [13].
- Due to the different economies of scale of fuel cells, and the ability to develop an extensive local support infrastructure, there will be greater employment opportunities [14].
- Rural communities will obtain greater security and quality of power supply, and cheaper overall electricity prices, especially where the cost of supplying or maintaining distribution lines is high [14].
- Catastrophic failure of a domestic power generator due to natural hazards, such as earthquakes, is not likely to cause the same level of social disruption as that of a major thermal or hydro power station [14].

3.2. Political trends

- Many countries have become concerned about the growth in emissions of greenhouse gases, specifically carbon dioxide, methane and nitrogen oxides. The high costs, likely to be associated with reducing these emissions, have focused political attention on instruments that can achieve abatement as cheaply as possible; emission taxes are one of these instruments. It should be remembered that the most popular new tax among politicians would be a carbon tax. Several OECD countries have already implemented some form of carbon tax, others, such as New Zealand, are considering this possibility [15].
- Deregulation of the electricity market is presently causing uncertainty in the price as well as in the supply of electricity in New Zealand. Deregulation is a trend that takes place on a worldwide scale, and a situation can be expected to arise where inaccessible places will only be provided for at a high cost. The trend of deregulation of the electricity market has, in New Zealand, led to four government-owned electricity producers (one of which has recently been floated), and a number of line companies and retail companies. The reasoning is that companies are better able to compete than government organisations. Allowing for a number of companies will enhance competition, as a result of which power prices should drop. Gas is also a carrier of energy, which if converted into electricity rather than directly consumed, would enhance competition. This is in line with the intent of the new legislation.

3.3. Economic trends

- There is a growing awareness of the economic cost caused by pollution and energy inefficient technologies. Implementing the policies and legislation has resulted in a large variety of new businesses, focusing on, for instance, the use of environmentally friendly or recyclable materials, and exhaust gas clean-up from power plants, cars, etc. Different fuels have different impacts on the environment, as a result of which fuels are taxed differently to reflect their real cost. At present, although many OECD countries tax fuels on the basis of their carbon content, although exemptions are given. Considering the entire package of emissions, the real cost is better reflected by an emission tax, which can be expected to be implemented in the foreseeable future. Fuel cells can be expected to flourish under such a regime.

3.4. Technological trends

- Examples of companies that are actively marketing fuel cells for the residential market are Plug Power and Sulzer. Both have demonstration projects to provide a home with fuel cell power.
- From user perspective, there is presently a greater awareness of power quality. Fluctuations in voltage, frequency and phase have already created a market for UPS systems (Uninterruptible Power Supply), that protect computers and other sensitive equipment from power surges.
- Combining heat and power has, for industrial purposes, allowed efficiency improvements for many processes. Moreover, being largely independent of the grid rules out effects of variations in electricity prices. The trend from centralised production to local production by industry to small-scale generation is evident.
- The trend of improvement in the technology itself is illustrated by an increase in power density of the stacks produced by Ballard [16]. Fig. 1 shows the volumetric power density of PEM fuel cell stacks from 1983 onwards. By plotting the log of the power density vs. time a straight line is found, which, according to forecasting literature, should happen and does indeed appear to happen. On a linear scale, it would result in an S-curve, which is related to product life cycles [12]. Because of physical limitations, one can assume that the trend will not continue forever. By assuming that the area power density is limited to 2000 mA/cm^2, and each cell with separator can be made 2.5 mm thick, then a limiting power density of approximately 7 kw/l is found; according to Fig. 1 this could happen by 2003.

4. Technology gap for residential applications

The gap between the existing technology and the requirements for domestic power are now considered. Information is required on the precise operational requirements for a fuel cell system for domestic applications.

In urban areas in New Zealand, reticulated gas is available, however, much of the water heating is performed using electricity. Historically, low electricity prices have allowed for this, but recent price increases have put pressure on many household budgets, especially in those cases where the house is also heated electrically.

In rural areas, water heating and cooking is generally performed with electricity and electricity supplemented with wood is used to heat the house.

4.1. Energy consumption behaviour

Evidently, the present design of the energy management of New Zealand houses needs to be reconsidered in order to allow a fuel cell generator to be used as efficiently as possible. Since fuel cells require a liquid or gaseous energy

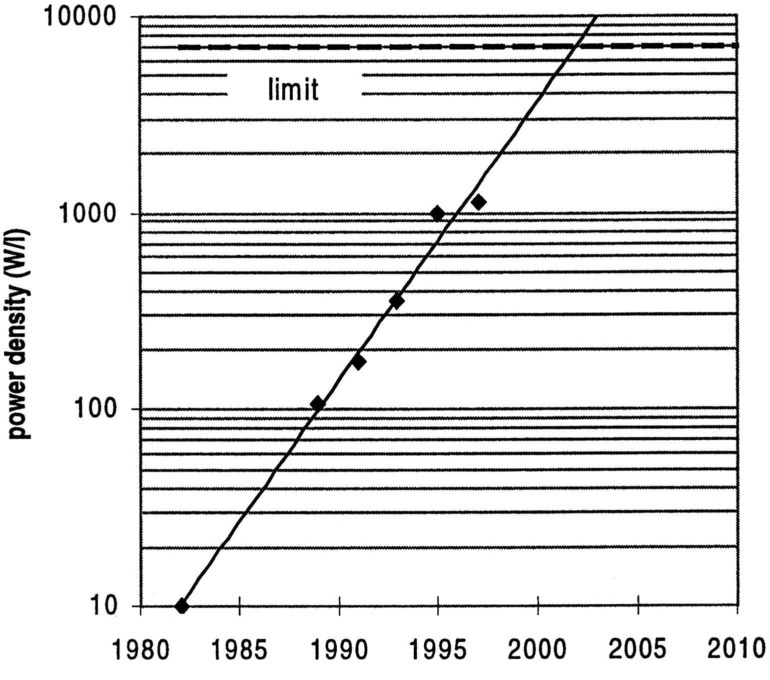

Fig. 1. PEM power density vs. time, extrapolated into the future. Due to assumed limitations in cell output and geometrical constraints, a level of 7000 W/l was found to be the maximum achievable.

carrier, the basis for the design should be to use the energy carrier for as many heating purposes as practically possible.

To obtain insight, the electricity consumption pattern of a number of houses in New Zealand has been investigated. Fig. 2 shows the power consumption during a 1-day period from the house of one of the authors. Electricity is used for cooking, house heating is partially derived from electricity. Water heating is metered separately and is not shown here. Because of the practical difficulties of distinguishing the amount of electricity used for heating purposes and for other purposes, a number of people have been interviewed. The respondents were requested to list the electrical appliances in the household and the time of day the appliances were switched on and off. From these data, a consumption profile was constructed; a typical one is presented in Fig. 3.

From both Figs. 2 and 3, it can be seen that a maximum energy flow of approximately 4 kW is required, while an average requirement of 500 W is found; the base load is 100–200 W. Switching between the base load and maximum is unlikely to take place within seconds; it is more likely that steps in demand of up to 1 kW can be expected. Levels are then maintained for a few minutes up to several hours.

4.2. Load following

With the current PEM technology, a quick response to the changes in demand is difficult to achieve. This is mainly attributable to the slow response of the gas-reforming unit. Provided that the gas supply responds fast enough, then load following for the fuel cell itself is not a problem. Traditionally, this problem has been resolved by using batteries to deal with the load changes. The fuel cell system then effectively becomes a battery charger. Batteries are expensive and have a limited lifespan, the excellent load following capabilities of the fuel cell are not fully exploited. Improving the sluggish response of reformers seems to be the way to tackle the problem. Companies

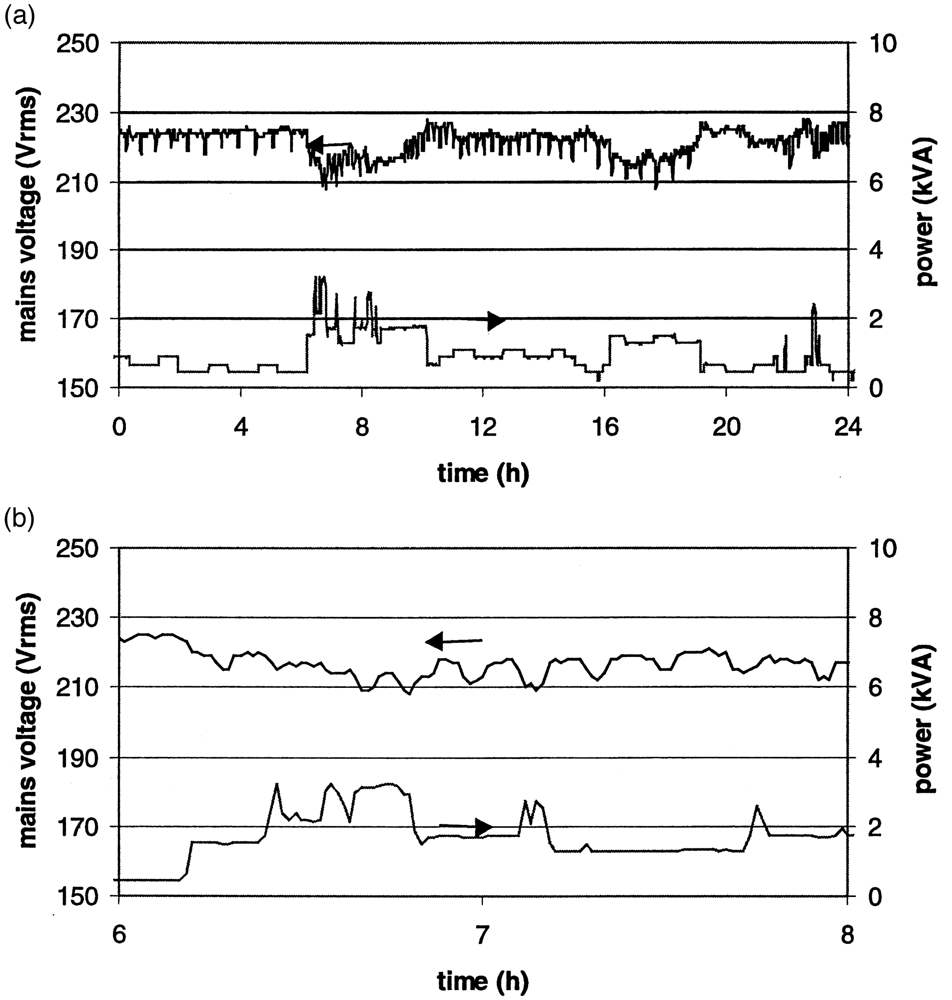

Fig. 2. (a) Electronically logged data plot of electricity consumption over a 24-h period of the house of one of the authors; (b) the period from 0600 to 0800 h is magnified. Samples were taken every 5 s and averaged per minute. Read-out accuracy of the current was 1 A, therefore the resolution of the power consumption was approximately 200 W.

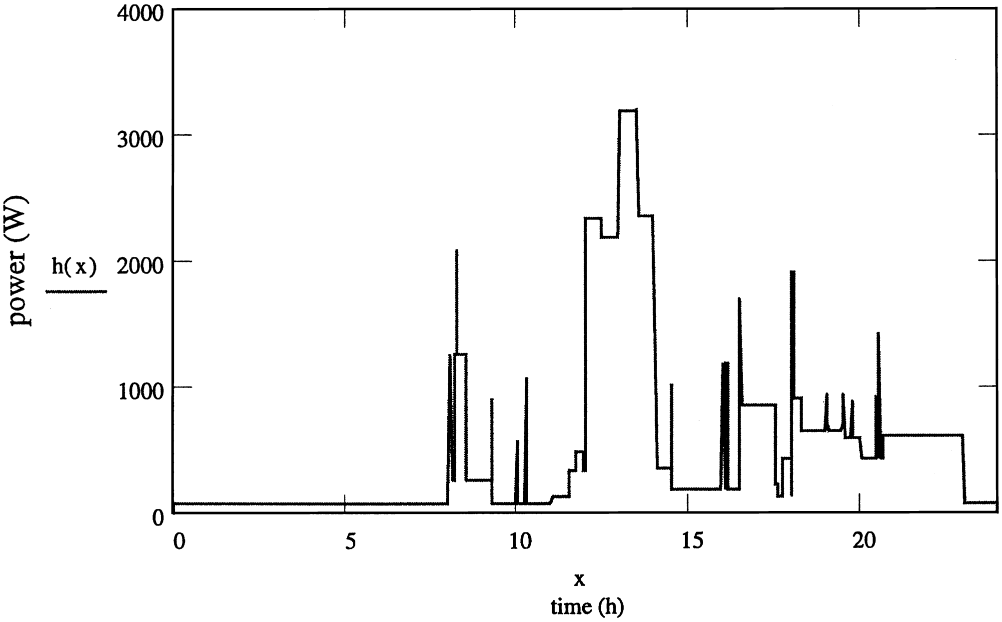

Fig. 3. Electricity use by interviewing, over a 24-h period. Users were asked to list the time of use and the ratings of electrical appliances. The technique can be used to discriminate between electrical water heating that might be better run on gas and other electricity users.

such as Ballard of Canada have been very successful at improving the response of the methanol reforming process by employing a heat-exchanger type reformer [17]. Haldor Topsoe of Denmark has reported similar successes for natural gas reforming [18].

Improved response can also be created by using a reformate buffer in the system. For instance, 1 kW of electricity for 5 min at 40% fuel cell efficiency requires some 70 l of hydrogen, which at 4 bar (a) would require no more than 20 l of space in the system, roughly the size of an expansion tank in water heating systems.

For the internal reforming SOFC the problem is actually eliminated. The fuel gas flow needs to be increased in accordance with the power requirement, as more gas passes through, more hydrogen is produced at the electrodes. Changes in conversion requirements can be followed almost instantaneously.

4.3. Cold start capability

For the PEM, insufficient activity of the catalyst at low temperature, and the presence of high purity water which is required to humidify the membrane, may hamper start-up capability at low temperatures. This water is also used to remove process heat, but freezes below 0°C.

In concept, solutions to overcome the latter problem would be to use a cooling circuit, which is separate from the humidifying circuit. Thus, process heat removal can take place with a coolant containing anti-freeze. Of course, the requirement for humidifying the membrane still remains. Drainage of the water in the humidifying circuit would then be required to prevent frost damage, which could be done automatically. At present, much work is being undertaken on membranes that do not require humidifying.

In case the activity of the catalyst is too low at low temperatures, then the coolant can be heated, to heat the fuel cell stack. Thus, highly active catalysts at low temperature would not be required.

For the SOFC, the aspect of freezing of process water is unlikely to be a problem when the system is unoperational for prolonged periods of time. What is more likely to be a problem is whether the system can start from cold to the operating temperature within minutes. Based on the heat capacity of the materials, it can be calculated that heating to the operating temperature within 5 min should be possible, certainly if the fuel flow can be set to 5 to 10 times the flow used for nominal operation. As indicated earlier, the thermomechanical problems associated with this are not insignificant, although tubular systems proposed by Kendall and Prica [19] seem to be able to deal with the problem.

5. Significance in terms of market volume

The presently perceived application fields for fuel cells are shown in Table 1; perceptions of 10 years ago are shown in Table 2. The difference in perception illustrates that the move towards localised power is not solely restricted to the domestic market, but comes in a broader perspective, namely that of a diversified market for distributed electricity generation.

An important question is whether there will be a market for domestic power generators; the applications of Table 1 could well be perceptions from technologists, and may not be based on sufficient market research. For New Zealand, it seems appropriate to make a distinction between the following segments in the domestic power market.

5.1. Residential, urban

The cost of buying and running a fuel cell system would have to be balanced against the cost of using the grid. At an annual energy cost of EUR 450 of electricity from the grid vs. an operating cost of EUR 300 for reticulated natural gas for the fuel cell system, EUR 150 remains to cover the cost of the fuel cell system. Assuming that people will accept a payback time of 5 years then the fuel cell system can cost EUR 150/kW. Considering the present state of the art, this is too low for a system of approximately 5 kW. However, with the goals set for automotive applications it is not impossible, but it is obviously not the first market to aim at.

5.2. Residential, rural

As with urban applications, the incentive to install a fuel cell system is small when a connection is already present. When a new connection has to be established then the cost of this can be considered in competition with a fuel cell system. Table 3 shows entry levels assuming different lengths of cable, costing EUR 50/m to install. At full load, an electrical efficiency of 40% is assumed, however, at part load, higher efficiencies will be obtained, as can be expected from a fuel cell. Thus, the value of 60% can be thought to represent an average efficiency during an extended period. It can be seen from Table 3 that for the longer cable, the fuel cell becomes the cheapest alternative when its cost drops below 500 EUR/kW, at an efficiency of 40%. At 60% efficiency, it becomes cheaper when the price of the fuel cell system is below 700 EUR/kW.

Depending on the precise circumstances, it becomes evident that a domestic fuel cell generator rated at 5 kW may cost from EUR 2500 to EUR 3500. In the calculations it was assumed that the gas, which is bottled propane, delivered at a cost of 0.05 EUR/kW h, a fairly high cost in comparison with the electricity cost. At a substantially lower gas cost (EUR 0.02/kW h), such as from reticulated natural gas, the specific cost of the system could be allowed to increase to EUR 1100/kW. For New Zealand, this is, however, not an alternative, since normally there is no reticulated gas in rural areas. Cheap gas can also be derived from manure from farming; however, the cost of a digester for this process would involve a price for the gas.

Table 1
Present development targets and perceived markets

1999 Fuel cell applications	Power output range
Portable	1–100 W
Residential	1–10 kW
Stationary — on site	0.1–1 MW
Stationary — conventional	10–100 MW
Land transport — low speed (golf cart, wheel chair)	1 kW
Land transport — passenger car	10–100 kW
Land transport — bus	100–200 kW
Land transport — auxiliary power	1–10 kW
Maritime	
Cold conditions	100 W
Remote power (relaying, signalling)	1 W–1 kW
Main stream fuel cell types	PEM, PAFC, SOFC

Table 2
Development targets and perceived markets for fuel cells 10 years ago

1989 Fuel cell applications	Power range
Stationary power	10–100 MW
Co-generation	10–100 MW
Transport	10–100 kW
Main stream fuel cell types	PAFC, MCFC, SOFC, PEM, AFC

5.3. New Zealand market size

In New Zealand, the competition of fuel cells and other alternative power generating systems has been especially tough because of the low energy prices. The electricity reorganization, which has been imposed to increase competition, was intended to reduce these even further. Opinions vary widely on whether this will actually happen; so far, the cost has gone up. Assuming that the cost levels will stay at the present level, then the market prospect for fuel cells is limited to the planned rural residential market, with possible extensions into farming, since these may be able to source gas cheaply from biogas.

Presently, approximately 25,000 new residential dwellings are being built in New Zealand per year [20]. The majority of these are built on designated development areas near cities. It proved difficult to find an estimate of the rural residential dwellings in this total. However, based on information from Regional Councils and Statistics New Zealand, it was estimated that this could be up to 5%, which is 1250 units per year.

6. Developers of fuel cell systems for residential applications

- *Analytic Power Corporation* is a privately owned corporation based in Boston. Analytic Power manufactures small portable systems of up to 200 W and has developed

Table 3

Entry level estimates for a 5 kW fuel cell system for domestic power in New Zealand in competition with the cost of establishing a connection with the electricity grid. The calculation was performed using a conventional technique for evaluating capital investments (e.g., Ref. [27]). A discount rate of 12% was applied, and an annual electricity requirement of 5000 kW h was assumed. The lifetime of the fuel cell system was set at 10 years, that of the cable at 30 years. The fuel cell system runs on bottled propane and incurs a gas bottle rental fee of EUR 50 per year. The conventional system incurs line charges of EUR 90 per year. Heat recovery benefits are not included

Electricity cost (EUR/kW h)	Fuel cost (EUR/kW h)	Connection fee (EUR)	Fuel cell system efficiency (%)	Fuel cell entry level (EUR/kW)
0.07	0.05	5000	40	500
0.07	0.05	2500	40	130
0.07	0.05	5000	60	700
0.07	0.05	2500	60	360

a 3 kW residential power supply system based on two PEM fuel cell stacks rated 1750 W each (see Fig. 4). The stack, along with a diesel fuel processor and an electrochemical compressor, are being developed to power meteorological stations and supply hydrogen for weather balloons for the Marine Corps. It will also be used in a residential power generator. The FC-3000 cell stack, a 1.75 kW fuel cell which operates on hydrogen or reformed gas, is cooled with a two-phase dielectric fluid. It has advanced composite bipolar plates, which allows for 68 cells and coolers in a stack of 250 mm long. Analytic Power estimates that their fuel cell system can be produced for 3000–4000 EUR per unit, a number which concords with the numbers presented earlier [21].

- *Energy Partners* of West Palm Beach, FL, was formed in 1990 to develop PEM fuel cell stack and system technology. Units rated up to 20 kW have been demonstrated. The company aims at various markets for fuel cells, including the domestic market with a system rated 10 kW running on natural gas. Energy Partners have successfully produced composite graphite bi-polar plates, offering a low cost, high volume manufacturing process, and consequently eliminating many of the problems associated with the conventional machined graphite plates [22] (see Fig. 5).
- *Plug Power* of New York has developed and demonstrated a 7 kW PEM system for residential power supply, running on natural gas (see Fig. 6). The systems are planned for commercial sale in the near future. Plug Power

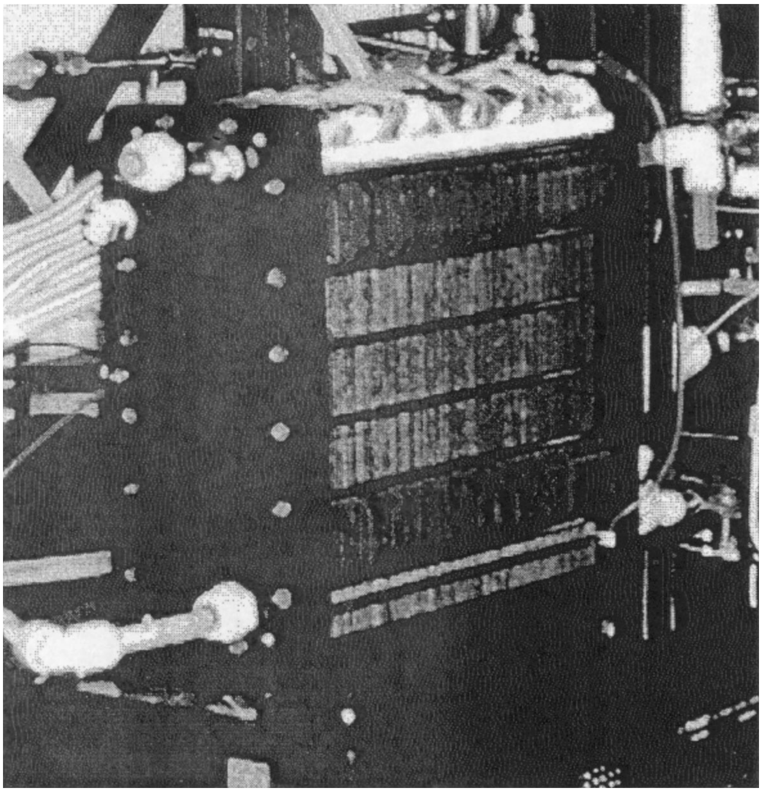

Fig. 4. Analytic Power FC3000; a 1.75 kW PEM fuel cell stack.

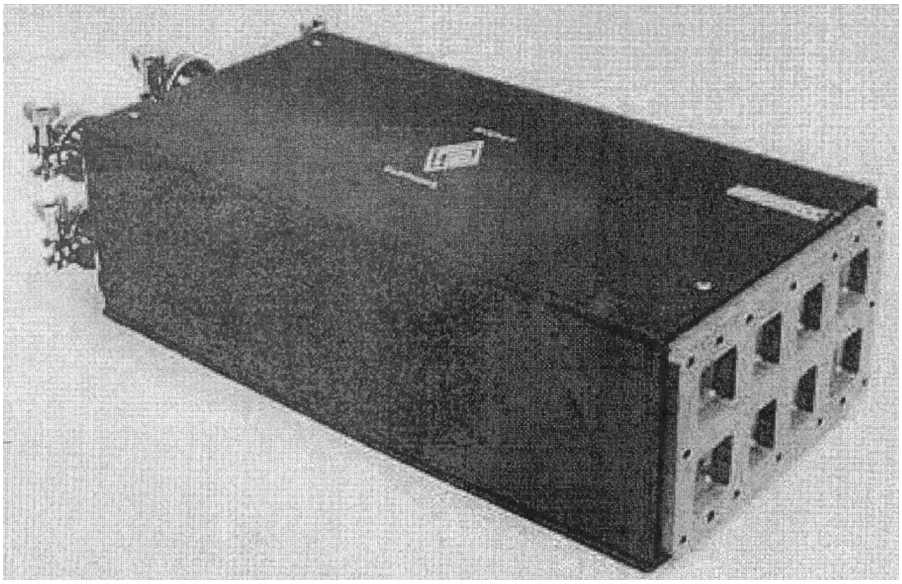

Fig. 5. Energy Partners 110 cell PEM fuel cell stack.

employs a separator plate consisting of narrow composite graphite strips that are glued onto a stainless steel backing. The strips are positioned in such a manner that gas channels are provided. Plug Power found that the presence of stainless steel did not adversely affect the performance of the cells, as reported with all steel separators. The company aims ultimately at systems of 30 to 40 kW for transport applications [23].

- *H-Power* of Belleville, NJ, has devoted a large proportion of its development effort to compact power sources for portable, mobile and remote missions with power ratings of 50 W. These systems operate at atmo-

Fig. 6. Plug Power Natural Gas fired residential power generator (7 kW).

spheric pressure and do not require an external humidification source. Because of the small size of the stacks, forced convection with air is used to remove the heat. H-Power has also built a 2 kW prototype PEM generator running on propane, which is intended for the residential power market (see Fig. 7) [4].

- *Northwest Power Systems* have integrated their patented fuel processor and a PEM fuel cell stack (De Nora) to produce systems rated at 2.5 to 5 kW; see Fig. 8 which shows a fully-integrated 5 kW fuel cell system using a De Nora PEM stack. On July 31 1999, in Post Falls, ID, USA, the company demonstrated a PEM fuel cell system in the ‘‘NeXt House’’; a showcase home built by the Bonneville Power Administration in partnership with Kootenai Electric cooperative. Interestingly, another niche market, the remote arctic village, is being studied as a possible application for 3–5 kW PEM fuel cells by a consortium which includes Northwest Power, LLC, Energy

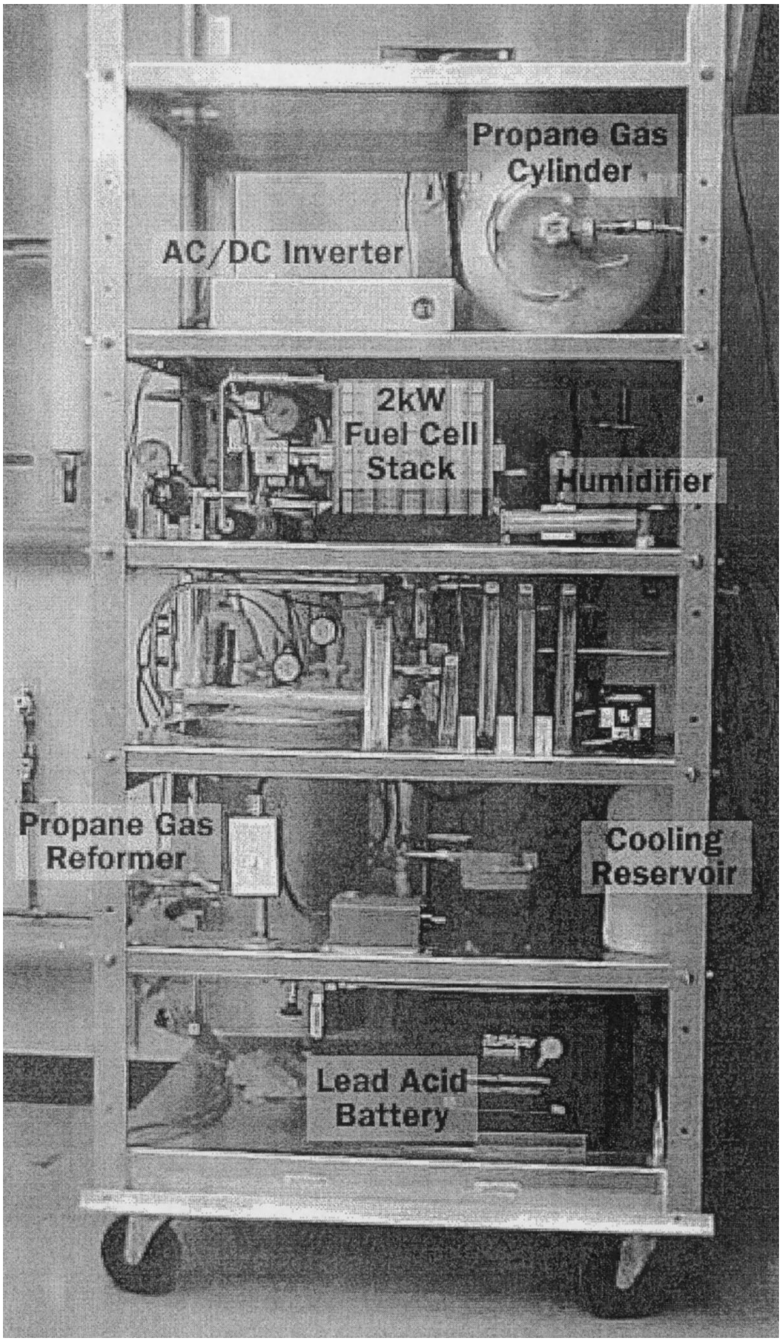

Fig. 7. H-Power 2 kW PEM fuel cell system, utilising a propane reformer to generate hydrogen.

Fig. 8. Northwest Power Systems fuel cell processor integrated with a PEM fuel cell stack (De Nora).

Partners, Plug Power, Teledyne Brown Engineering, Energy Systems (TBE), Schatz Energy Research Center, and Hydrogen Burner Technology.

- *Sulzer Hexis* of Switzerland is developing a 1.5 kW SOFC system, primarily for residential applications (see Fig. 9). In this system, fuel and oxidant flow radially over the round planar cells. The oxidant makes a double pass through the channels in the interconnect. In the first pass, it is heated to the process temperature, while removing the process heat. The oxygen reacts during the second pass, while it flows radially outwards. The fuel makes a single pass over the anode, also radially outwards. Fuel and oxidant are combusted immediately on reaching the perimeter of the stack. The cells are made by the Netherlands Energy Research Foundation, and consist of a stabilised zirconia electrolyte [11].

A further selection of fuel cell developers that could possibly diversify the residential power market was made and is briefly discussed below.

- *Ballard* of Vancouver, Canada is marketing systems for automotive applications, stationary power, and portable applications.
- *BCS Technology* of Bryan, TX, specialises in portable PEM systems running on hydrogen and air. They produce stacks rated up to 500 W, insufficient for a house, but appear to have the fuel cell technology required to move into this market.
- *De Nora* from Italy can be considered the most successful European PEM manufacturer. Their experience with electrochemical systems has enabled them to take up an important position as a fuel cell manufacturer. With Ansaldo, they are developing a drive system for a fuel cell powered Renault. In the USA, De Nora is represented through E-Tek and CovalH2.
- *ECN* from The Netherlands is involved in an EC project on PEM for transport, with ECN developing the fuel cells. The main contractor of the project is Volkswagen. Apart from these PEM activities, ECN also supplies SOFC cells to Sulzer.
- *Global Thermoelectric* of Calgary, Canada has recently bought into the SOFC technology off Juelich, Germany. The technology has been demonstrated at a level of 1 kW. Global Thermoelectric intends to be active in the domestic power market.

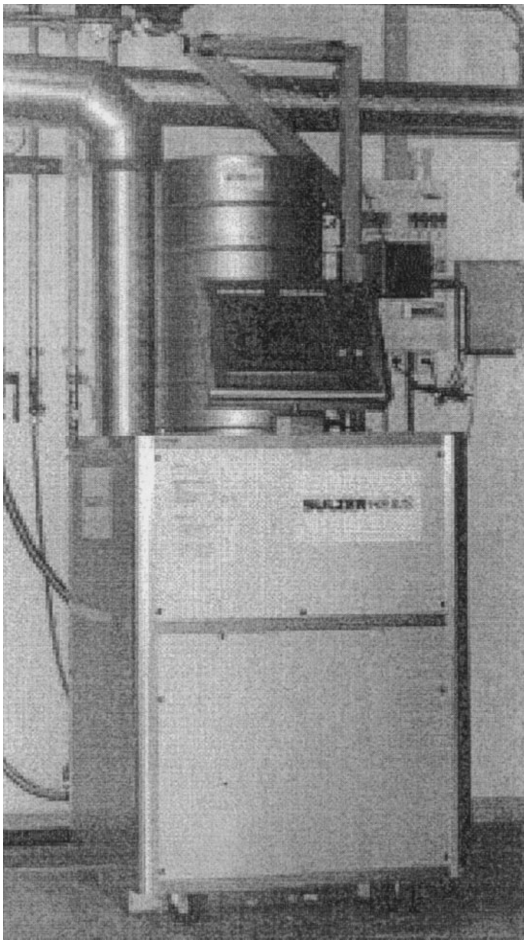

Fig. 9. Sulzer 1.5 kW natural gas fired residential power generator.

- *International Fuel Cells LLC* is a subsidiary of UTC (United Technologies), who developed the fuel cells for the Apollo missions. IFC has carried out research on all the different fuel cell types and systems, but recently has redirected its focus entirely towards the PEM and related systems [24].
- *Mitsubishi Heavy Industries* of Japan have developed a 10 kW SOFC system, based on stacked tubular cells. Each tube consists of a number of segments, while each segment is a fuel cell. The cells are placed in an array, which is part of a system, and appears to have a high degree of integration in regard to heat exchange and gas reformation.
- *Mitsubishi Electric* of Japan has, under a NEDO programme, developed a 10 kW PEM system [25].
- *Schatz Energy Research Center* is located at Humboldt State University in California. Various PEM fuel cell demonstration projects are carried out in fuel cell systems ranging from 200 W to 9 kW.
- *SOFCo* of Utah develops systems based on a planar SOFC design and is presently developing a 2 kW system running on natural gas. The aim is for systems ranging from 10 to 50 kW.
- *Toshiba* has developed a 5 kW PEM under a NEDO project, and is aiming at a 30 kW system for stationary applications. Independently, they have been working on a PEM for transport, portable power and residential power [26].
- *Toyota* has developed a proprietary PEM fuel cell, along with systems for transport applications [27].
- *ZSW* of Germany targets solar energy systems using PEM and has built a 200 W demonstration unit.

7. Conclusions

- Present social, political, economic and technological trends show that fuel cell technology is likely to be well-received and can be expected to be stimulated under a regime of pollution reducing policies and deregulation of the electricity market.
- The present state of the technology will need further development in order to meet all the user requirements. No major obstacles were identified that could prevent the technology from maturing.
- At present cost levels of up to 1000 EUR/kW, fuel cells are competitive in certain market niches as in the case where there is no readily available grid connection. Consequently, this market is worth exploring and should be considered as a first niche market. It was estimated that the market for fuel cell generators in New Zealand is approximately 1250 units per year.
- A number of companies have been identified that are presently targeting residential power systems, or could potentially move into this market.

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