Available online at www.sciencedirect.com

Journal of Power Sources 118 (2003) 358–366

www.elsevier.com/locate/jpowsour

Technical design and economic evaluation of a stand-alone PEFC system for buildings in Sweden

Cecilia Wallmark*, Per Alvfors

Royal Institute of Technology, Chemical Engineering and Technology, Energy Processes, Teknikringen 50, SE-100 44 Stockholm, Sweden

Abstract

This paper deals with the prerequisites for a stand-alone fuel cell system installed to avoid replacing or upgrading an ageing, distant power grid connection which only supplies a few buildings with their power demands. The importance of sizing the included components in the energy system is presented in economic terms. The size of the fuel cell system and the energy storage system (battery, hot-water storage and hydrogen storage) are discussed in relation to the yearly distribution of the buildings' power demand. The main design idea is to decrease the size of the fuel cell system without making the battery too expensive and that the power requirements are fulfilled over test periods with decided length and power output.

The fuel cell system installation is not economically viable for the presented conditions, but in the paper future feasible scenarios are presented. The calculated incomes are shown as a function of the size of the fuel cell system and energy storage, the electricity costs, the fuel costs including transportation, the prices of electricity and heat, and the fuel cell system costs and efficiencies. The main factor in the system's economic performance is the fuel price, which contributes more than half the costs for the fuel cell system-based energy system. The cost of the power grid is also determining for the result, where the distance to the main power grid is the important factor. The evaluation is performed from the utility company's point of view.

Keywords: PEFC; Stationary fuel cell system; Stand-alone; Heat and power

1. Introduction

Economically viable stationary fuel cell system installations are still a futuristic concept in Sweden. Applicable fuel cell systems are not available and current fuel prices are too high compared to power prices to make such installations feasible. It is shown that small-scale fuel cell systems are not viable in near-term installations in Sweden [1], although the same kind of installations would be viable in other countries [2,3]. However, it is important for companies in Sweden to follow the feasibility of fuel cells and be prepared for a fast response to possible changes.

One early application for fuel cell systems often discussed internationally is in a stand-alone setting [4–6]. This paper deals with the prerequisites for a stand-alone fuel cell system installed to avoid replacing or upgrading an ageing, distant power grid connection which only supplies a few buildings with their power demands. The technical prerequisites of such a fuel cell system are explained in the paper and an economic analysis is performed. The economic investigation aims to show the viability of fuel cell systems in future scenarios in Sweden. The calculated incomes are shown as a function of the size of the fuel cell system and energy storage, the electricity costs, the fuel costs including transportation, the prices of electricity and heat, and the fuel cell system costs and efficiencies.

2. Background

In Sweden the utility companies have been legally bound to supply all domiciled buildings with electricity, resulting in a remarkable extensive power grid today. When the technologies of distributed generation are developing it is interesting and important for the energy companies to survey the market to ensure that the most economically viable alternative is chosen when the existing power grid is to be exchanged.

To analyse the present situation, an actual case study is examined. The example concerns a utility company that has to exchange a power grid connecting three residential buildings located far from the main power grid in a part of south Sweden called Småland. The three residential buildings are

---

* Corresponding author. Tel.: +46-8-790-6000; fax: +46-8-723-0858.
E-mail address: cecilia.wallmark@ket.kth.se (C. Wallmark).

0378-7753/03/$ – see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0378-7753(03)00101-0

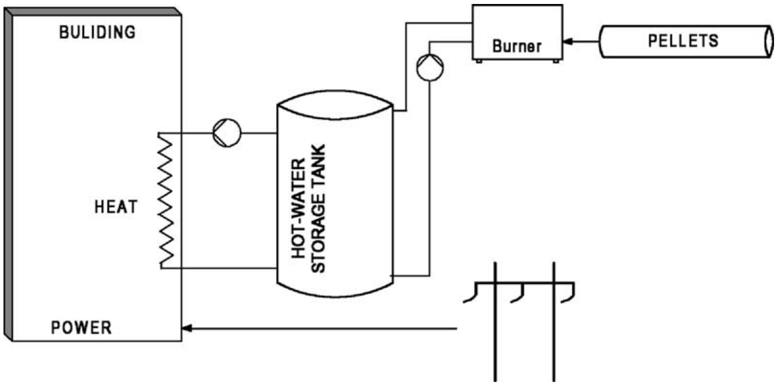

Fig. 1. The conventional installation. The three buildings are today connected to the power grid for electricity and assumed to cover their heat demand by burning pellets.

situated close to each other, 2.1 km from the main power grid. Fig. 1 shows how the buildings presently cover their heat and power demands; power from the old power grid, and heat from a pellet burner are assumed for the comparison.

A technical and economic analysis is performed to evaluate the possibilities to replace the worn-out power grid with a local fuel cell system. The evaluated alternative is to install an ethanol-based fuel cell system in connection to the buildings, supplying power, but also heat to the buildings, as illustrated in Fig. 2. A lead-acid battery will be installed together with the fuel cell system. The main tasks for the battery will be to manage the short-term changes in the power demand, and to help the start-up of the system. The existing pellet burners will be utilised further on as well, as the heat demand will exceed the generated heat from the fuel cell system. The burner has the best performance when run continuously—giving higher efficiency and lower emissions [7]—which affects the optimal control strategy for the whole energy system. Furthermore, the existing hot-water storage tank is utilised in the new system.

The installation of a fuel cell system will decrease the emissions for the energy supply to the three buildings. Important decreases in emissions of NO_x and particulate matter will be seen, and partly decreased emissions of, for example, CO_2 [8].

3. Assumptions

The buildings in this study are situated far from the fuel infrastructure, such as pipelines for natural gas. Due to this fact a fuel transportable by truck is assumed to supply the energy system. The availability today is higher for ethanol than methanol in Sweden, hence ethanol is chosen as the fuel for the residential fuel cell system. Ethanol is produced in Sweden in a few locations, but methanol is imported [1]. The ethanol price is high, but a gaseous fuel would not be possible to transport by trucks to the building, as too much gas is needed. The assumed ethanol price, 0.70 SEK/kWh [9] is presented as a reasonable price, but lower than available in Sweden today. The required area to grow the grains needed for the three buildings would be approximately 17 ha, and the processing plant would not be likely on site. For local production, biogas production could be an alternative, such as for the demonstration plant with a SOFC system in Switzerland [10]. But it would most probably be

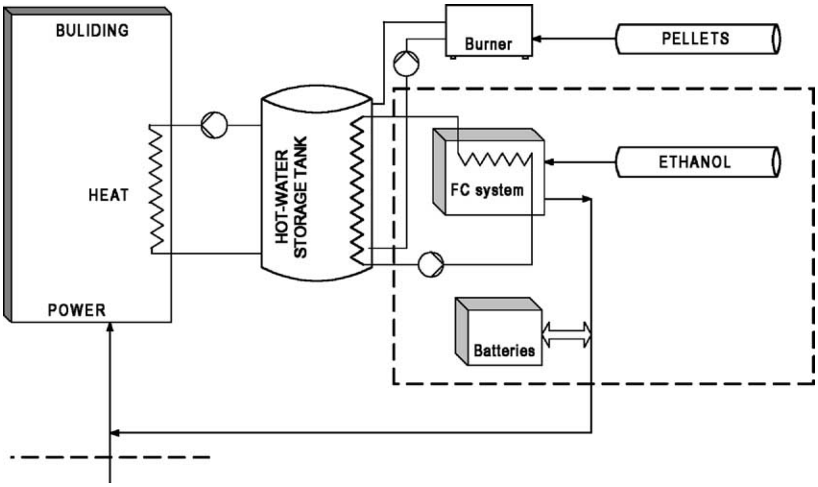

Fig. 2. The fuel cell system installation. The dashed lines show the changes compared to the conventional system.

even more expensive. Future fuel options could be LPG, petroleum or diesel, which already have an infrastructure and are transported all over the country by trucks. However, the fuel processing of these conventional fuels are in the fuel cell system more complicated, and therefore not demonstrated to the same extent as more easily reformed fuels. Furthermore, the mentioned fuels are taxed, in contrast to ethanol.

The assumed installation costs, efficiencies, life times and economic factors are displayed in Table 3.

3.1. The fuel cell system

The main parts of the fuel cell system simulated in this study are a polymer electrolyte fuel cell (PEFC) stack and a fuel processor for ethanol. This combination is experimentally shown to give a net electrical efficiency of >25% [11], but discussed for a various of efficiencies as function of the power densities of the reformer by [12]. The main reactors in the fuel processing are the steam reformer working at approximately 700 °C, a water gas shift reactor working at approximately 200 °C and a preferential oxidation working at approximately 120 °C. A power conditioner is included in the fuel cell system, built for stand-alone applications with automatic control of the power quality.

Fig. 3 shows the dependency of a fuel cell system thermal efficiency on the return temperature of the cooling media, but for a fuel cell system with lower working temperature than the system analysed in this study. The heat difference must be cooled of, e.g. with a fan. In this study the fuel cell system average electrical efficiency is assumed to be 35%, and the total efficiency to be 85%. Both efficiencies have the potential to increase in future products. The installation cost for the fuel cell system is assumed to 15,000 SEK/kWh$_{el}$, which is lower than available at present, but believed to be within reach in a couple of years.

The fuel cell system has a limited possibility to increase the power level immediately due to transport limitations in the fuel processor. The excess hydrogen that passes through the anode side of the fuel cell stack could be utilised in short periods of time. The excess hydrogen could maximum give 10–20% increase of power level, depending on the present hydrogen excess level. The dynamic is then decided by the flow time through the reformer reactors. In this paper it is assumed that the response time to reach a new power level is in the range of a few minutes for the fuel cell system, a factor that should be improved upon by new technology.

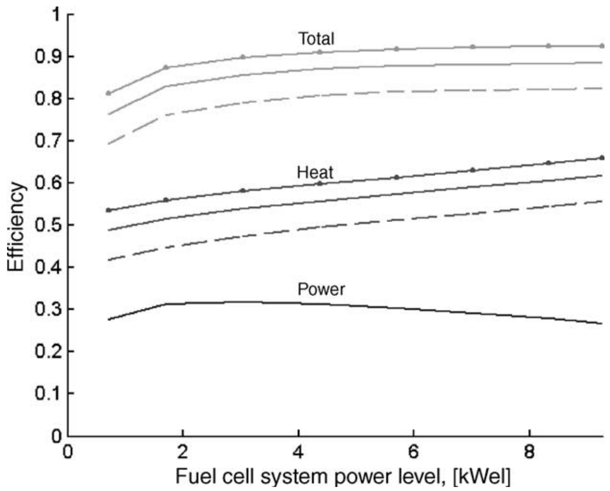

Fig. 3. Exemplified efficiencies of a fuel cell system. The three lines for heat and total efficiency respectively, are calculated for three different return temperatures of the cooling media, 60 °C (- - -), 50 °C (–) and 40 °C (-··-).

The working temperature of the fuel cell stack is assumed to be large enough to give a reasonably sized hot-water storage tank, without creating the situation where more than a few percent of the total amount of generated heat over the year must be dumped in the summer. It would in this case require the fuel cell stack working temperature exceeding 80 °C, for a combined hot-water storage tank containing tap water heating.

3.2. The power grid connection

The Swedish law requires that a power grid connection must be built up if requested and paid by the end-user. The power grid is at the present extensively built-up, but due to the high costs for connecting new buildings distant from the existing lines, new connections are seldomly requested. It is, however, required that an existing power grid must be maintained by its owner. In this situation a stand-alone installation could be an alternative for the utility company. The cost for the private connection to the power grid is surveyed centrally in Sweden as a function of the maximum power demand over large geographical areas, independent of the distance to the main power grid. This makes the rural power grid a conscious problem for the energy companies, to which they are searching for new solutions. Among the studied alternatives distributed generation is regarded as one of the more feasible.

The electricity bill for a private person is built up of four main parts: the fixed cost for the connection to the power grid, the variable cost for the transportation in the grid, the fixed cost for the electricity purchase and the variable cost for the used electricity. Normally, the two first parts are paid to the grid owner, and the two last mentioned parts to another utility company selling electricity. This study is performed from the first mentioned company's point of view, the grid owners. The earnings loss for the present power deliverer is neglected. The grid owner is mostly named 'the utility company' in the following text.

With the parameter values specified in Table 3, the yearly cost for the grid owner would be 48.5 kSEK/year to supply the three buildings with their power demands.

3.3. The energy demands

The total power demand from the three buildings is known to be around 27.3 MWh$_{el}$/year. This will, as adapted from another demand measurement, be assumed to correspond to a total heat demand on 116 MWh$_{th}$/year, [13]. Figs. 4–8

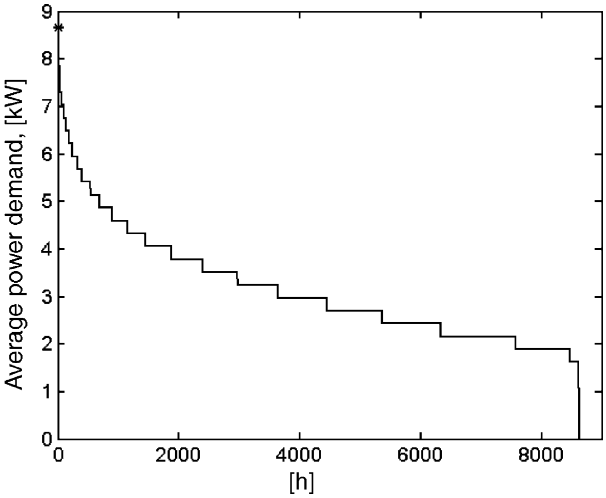

Fig. 4. Duration curve of the hour-based power demand.

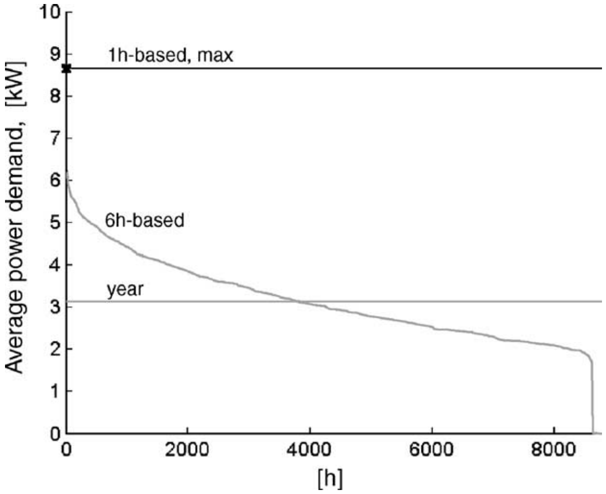

Fig. 5. The average power demand based on the mean value from 6 h segments. The top line shows the maximum hour-based average power demand and the bottom line the yearly value.

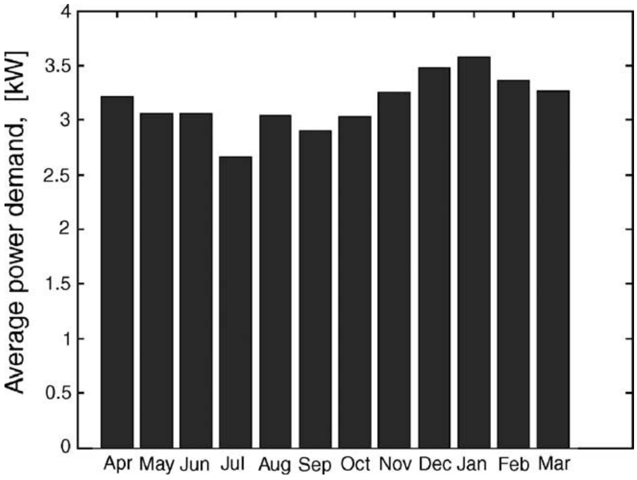

Fig. 6. The power demand distribution over 12 months.

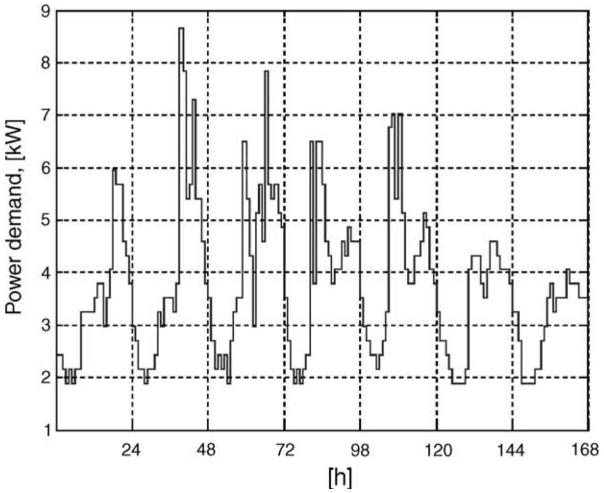

Fig. 7. The hour-based average power demand during the week with the peak average power demand.

illustrate the assumed distributions of the power demand, (measured data from [13]).

An analysis of the measured demand data gives the requirements of the energy system. For the present case the following requirements are needed for an energy system to fulfil the buildings' demands:

- an immediately increase of the power demand of at least 5 kW should be satisfied;
- a maximum power demand of 20 kW should be possible during at least 5 min;
- a continuously power supply of 8.5 kW should be possible during at least 3 h once in a 24 h period.

3.4. The energy system

The studied energy system solution based on a fuel cell system in combination with a battery is shown in Fig. 2. The

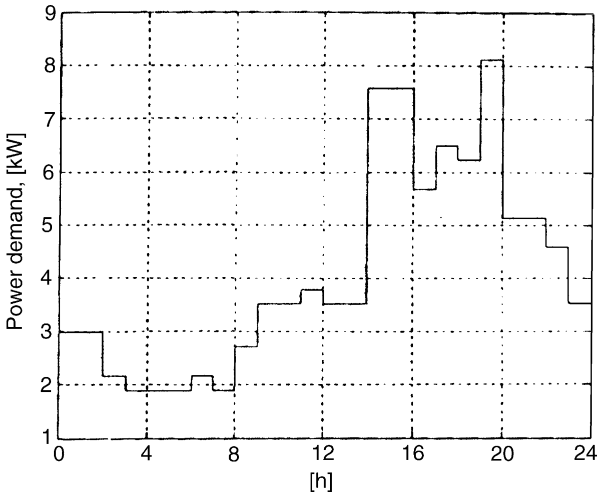

Fig. 8. The hour-based average in power demand during the dimensioning 24 h period in the year.

battery is assumed to cover all momentary changes in the power demand. For an increased power demand the battery will discharge and for a decreased power demand the battery will charge until the power output of the fuel cell system is stable at the new power output level. The internal control system is designed to prevent rapid changes in the power output from the fuel cell system. The short-term power output from the battery is assumed to be approximately the same level independent of the present state of charge. An automatic control strategy will keep the state of charge within a convenient range.

When sizing the main components, the maximum power output from the fuel cell system and the battery are very important, both from the technical and the economic point of view: the power demands must be fulfilled with a high reliability at the lowest possible price. This means that a margin must be included in the size optimisation. Here, three different sizing approaches are discussed. The first extreme is where the fuel cell system has a maximum continuously power level larger than the maximum hour-average power demand. The second extreme is where the power output of the fuel cell system is just above the yearly average of the power demand. The third approach is a compromise between the first two approaches. The third approach shows a convenient solution, while the two first extremes exemplify the problematic nature of component sizing.

3.4.1. With a large fuel cell system

A conceivable installation would be a fuel cell system large enough to cover the hour-based average power level of the building and a battery covering the short-term changes in the power demand. Including a margin, this would give an installation fulfilling the buildings requirements.

An installation of a 9 kW_{el} fuel cell system would require a battery with possibility to give 9.3 kW during 5 min, according to the requirements in Chapter 3.3. The sizing is illustrated in Fig. 9 and described together with the costs in Table 1. The calculation is based on the parameters in Table 3.

As the brief calculation shows, the problem with the large fuel cell system installation is the costs. The yearly cost for the fuel cell-based energy system is 71 kSEK, which should be compared to 48.5 for the power grid installation.

Table 1
The sizing and costs for the case with a large fuel cell system

The fuel cell system	
Max continuously (kW_{el})	9
Momentarily (+20%) (kW_{el})	10.8
Installation cost (kSEK)	135
The battery	
3 h (kW_{el})	2
5 min (kW_{el})	9.3
Installation cost (kSEK)	15
The total cost	
When 20% of power through battery (kSEK/year)	71

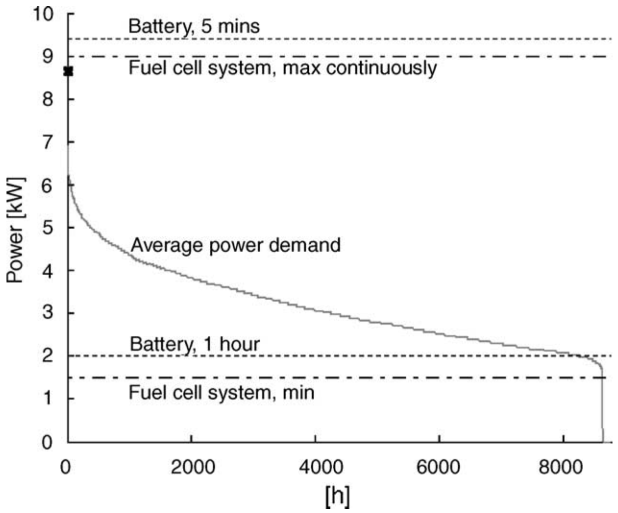

Fig. 9. The sizes of the main components in the energy system are shown in the figure. The min and max levels of the fuel cell system (-··) as well as two chosen performances of the discharge of the battery (···) are shown as straight lines in the figure. The average power demand is based on the mean value from 6 h segments.

3.4.2. With a small fuel cell system

The cost for the fuel cell-based energy system in the previous chapter could partly be replaced by reducing the size of the fuel cell system, which is technical possible by enlarging the energy storage capacity instead. However, as long as other power generation units are not involved in the energy system, the fuel cell system could never be smaller than the total average value of the power demand. Furthermore, if it has the size of the yearly average power demand a seasonal storage of electricity would be required. From Fig. 6 it is obvious that the electrical demand during the winter is larger than during the summer, hence a fuel cell system working on the yearly average power demand must be completed by, not only a battery taking the short-term variations, but also a seasonal storage.

An often discussed seasonal storage is a hydrogen storage. It would not only require that the fuel cell part of the fuel cell system (excluding the fuel processor) would be sized to satisfy the higher power demands, and also a huge storage of the hydrogen rich reformate would be required. The reformate storage should in this case correspond to more than 200 bottles á 50 l and 200 bar, storing approximately. 2.7 MWh_{fuel} from May–October to November–April. Additionally, a high pressure compressor would be needed, which both is expensive and has a high maintenance demand.

This alternative is not studied further in this paper, but hydrogen storage will fit better into neat hydrogen-based systems where the fuel cell system is already concentrated on hydrogen usage.

3.4.3. With a compromised size of the fuel cell system

From the assumed power demand distribution over the year it can be found that the hour-average power demand only exceeds 6 kW once or seldom twice a day. Furthermore, Fig. 4

Table 2
The sizing and costs for the compromised fuel cell system

The fuel cell system	
Max continuously ($\mathrm{kW_{el}}$)	6
Momentarily (+20%) ($\mathrm{kW_{el}}$)	7.2
Installation cost (kSEK)	90
The battery	
3 h ($\mathrm{kW_{el}}$)	2.7
5 min ($\mathrm{kW_{el}}$)	12.4
Installation cost (kSEK)	20
The total cost	
When 30% of power through battery (kSEK/year)	60

shows that an average value exceeding 6 kW is uncommon. 6 $\mathrm{kW_{el}}$ is therefore chosen as the exemplifying size of the fuel cell system in this third case. This requires a battery with the possibility to give 12.8 kW during 5 min, according to the requirements in Chapter 3.3. The sizing is illustrated in Fig. 10 and described together with the costs in Table 2. The calculation is based on the parameters in Table 3. This energy system

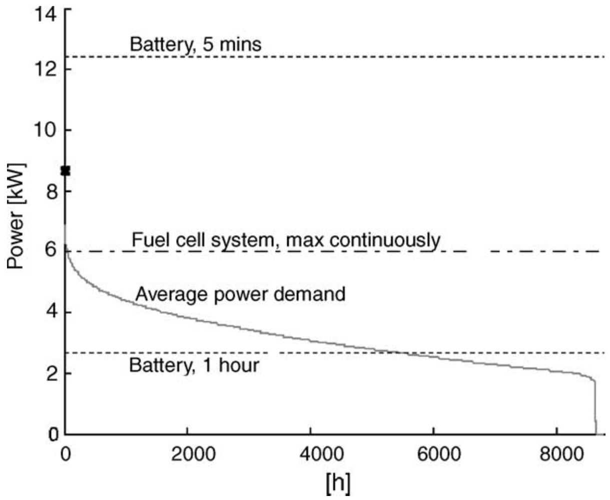

Fig. 10. The sizes of the main components in the energy system are shown in the figure. The min and max levels of the fuel cell system (-··-) as well as two chosen performances of the discharge of the battery (···) are shown as straight lines in the figure. The average power demand is based on the mean value from 6 h segments.

Table 3
Parameter values, both known facts and assumptions

Category	Parameter	Value	Unit[a]
Fuel	Ethanol price [9]. No tax on ethanol [14]	0.70	$\mathrm{SEK/kWh_{fuel}}$
	Delivery cost of ethanol, <40 km	300	SEK/delivery
	Size of the ethanol tank	4	$\mathrm{m^3}$
	Rental cost for the fuel tank	1,600	SEK/year
Electricity	Base cost for electricity purchase in Småland, Sweden [15]	152	SEK/year per household
	Price of electricity, variable cost	0.27	$\mathrm{SEK/kWh_{el}}$
	Cost for power grid connection, fix cost, power grid	2,400	SEK/year per household
	Price of electricity, variable cost, power grid	0.131	$\mathrm{SEK/kWh_{el}}$
Pellet burner	Efficiency, pellet burner [7]	80	% $\mathrm{LHV_{fuel}}$
	Total size, pellet burners	50	kW
	Costs for heat from pellets (tax excluding)	0.344	SEK/kWh
Fuel cell	Base cost for fuel cell system	15,000	$\mathrm{SEK/kW_{el}}$
	Additional costs for unforeseen expenses, fuel cell system [16]	10	% of base cost
	O&M fuel cell system [16]	10	% of base cost
	Electrical efficiency, fuel cell system	35	% $\mathrm{LHV_{fuel}}$
	Total efficiency, fuel cell system	85	% $\mathrm{LHV_{fuel}}$
	Size of fuel cell system	6	$\mathrm{kW_{el}}$
	Lifetime, fuel cell system	5	Years
Battery	Size of battery, calculated for the specific recharging time 5 min and 3 h, respectively	12.4, 2.7	kW during 5 min, kW during 3 h
	Efficiency, lead-acid battery charge and discharge at varying voltage level [17]	80	%
	Cost for battery [17]	20,000	SEK
	Percentage of power intermediate stored in the battery	30	%
	Deprecation time, battery	6	Years
Power grid	Present value including O&M for 1.8 km high voltage grid and 0.25 km low voltage [15]	736	kSEK
	Deprecation time, power grid	30	Years
Other	Interest rate	7	%
	Number of buildings	3	
	Total power demand	27,300	kWh/year

[a] US$ 1 could be rounded to 10 SEK.

is evaluated as the cheapest and most probably of the three studied cases, and consequently analysed further in the next chapter.

The calculation shows that this energy system is approximately 12 kSEK/year more expensive than the power grid installation.

3.5. The parameter values

Parameter values, both known facts and assumptions are given in Table 3.

4. Results

Although both a lower cost and a longer lifetime are assumed for the PEFC system than available at the present, the calculations point out that it would not be economically viable to replace a power grid with an ethanol-based fuel cell system. The costs for the conventional installation and the fuel cell installation are shown in Fig. 11, as well as the cost distribution for the both cases.

The calculations give that nearly 40% of the buildings heat demand will be supplied by the fuel cell system. The pellet burner will supply the rest of the heat. A few percent of the generated heat must be dumped, but the amount depends on both the automatic control strategy for the pellet burner, and the size of the hot-water storage.

An analysis of the results shows that if any of the following will happen, the total cost for the fuel cell system installation will reach the same level as the conventional installation:

- The total costs for the fuel decreases with 19%.
- The cost for a new power grid increases with 19% (longer distance, worse ground conditions).
- The cost for the fuel cell system would decrease with 43%.
- The incomes from the sold heat increases with 79% (partly by a higher total efficiency of the fuel cell system).
- The variable part of the electricity increases with 143%.

Of course a combination of changes of the presented situation would be the case, which also increases the probability for the fuel cell system to be commercial for this stand-alone application. Fig. 12 illustrates the differences in the calculated results as function of the ethanol price, the electrical efficiency of the fuel cell system and the variable part of the cost of electricity. A lower part of the power being intermediately stored in the battery corresponds to a smaller increase in the total electrical efficiency.

If the installation cost of the fuel cell system would decrease to 4000 SEK, which is the goal for year 2015 [18], the cost for the fuel cell system-based energy system would decrease to 40 kSEK/year, with the present assumptions.

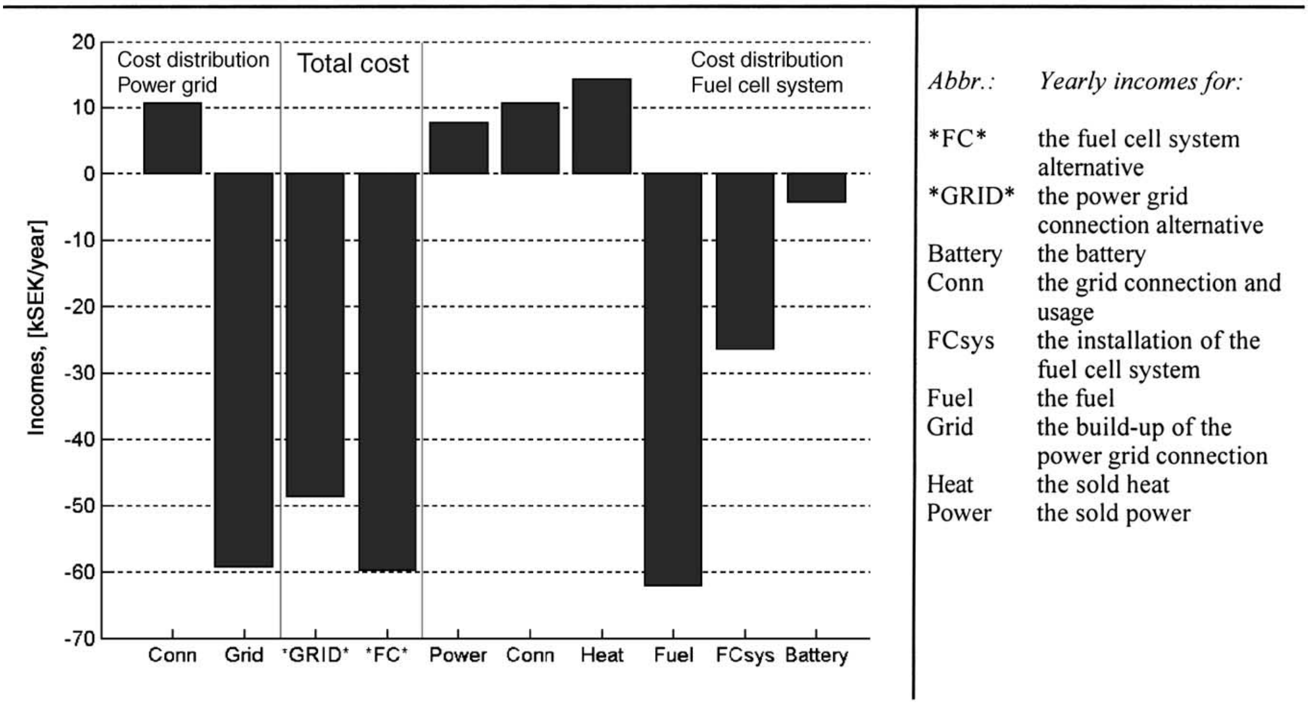

Fig. 11. The total cost per year is shown in the third and forth stacks in the figure, for the alternative to invest in a new power line and to install a fuel cell system, respectively. To the left in the figure the cost distribution for the power grid investment is viewed and to the right for the fuel cell system installation. Approximately 6% of the fuel cost is the cost for the fuel transportation and storage tank.

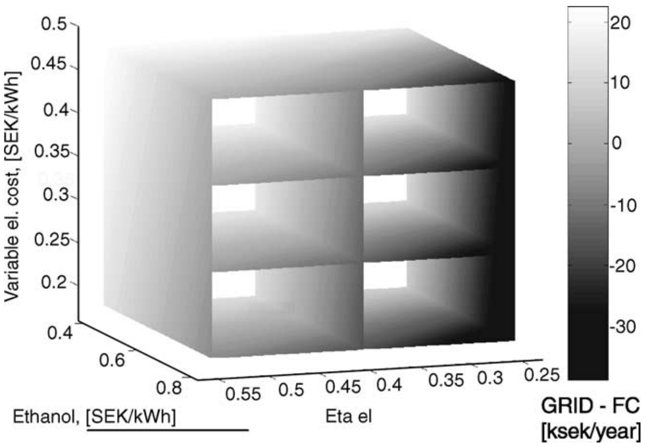

Fig. 12. Difference (kSEK/year) between the power grid installation and the fuel cell system installation, as function of the ethanol price, the electrical efficiency of the fuel cell system and the variable part of the cost of electricity.

5. Discussion

If the power demands of the studied buildings would have been smaller, the situation would have been more economically viable than shown in this report under the present conditions. For example a controlled change in the use of power as function of the time of the day would help up the economics. But, it is important to note that it is not sufficient if the fuel cell system installation reaches the same costs as the power grid alternative. It must be even cheaper to be a real alternative to the conventional installation. It would require a new area of expertise for the utility company, which will make it more problematic. It could on the other hand initially be an important demonstration project for a utility company announcing a green profile.

The main cost for the alternative with a fuel cell system installation is shown to be the fuel. This shows that other distributed technologies able to work with local fuels would be better alternatives in rural stand-alone applications than fuel cells, which require clean gaseous or liquid fuels. This is especially true if the house owner, that has an own wood-based fuel available for the heating, stands for the installation. For example, Stirling motors in the kW-range are being investigated for distributed co-generation in residential buildings [19].

Another factor featuring the traditional power grid installation is the possibility of variable power feed. To a certain limit an existing power grid can cover an increased demand, for example, due to newly built buildings. The fuel cell system would not have the margin for additional buildings, but are on the other hand ex-changeable and their cost is believed to be quite insensitive to size, hence an additional installation could be the solution. Other forecasts have even predicted that local installations in each building would be cheaper than central installations for a few buildings [1].

6. Conclusions

- The presented alternative to install a stand-alone fuel cell system instead of upgrading an ageing rural power grid is a future option for a utility company.
- The fuel cell system installation is not economically viable for the present conditions, but future feasible scenarios are presented. The main factor in the economic presentation is the fuel price, which contributes more than half the costs for the fuel cell system-based energy system. The cost of the power grid is also determining for the result, where the distance to the main power grid is the important factor.
- The importance of sizing the included components in the energy system is presented in economic terms. The size of the fuel cell system and the energy storage system (battery, hot-water storage and hydrogen storage) are discussed in relation to the yearly distribution of the buildings' power demand. The main idea is to decrease the size of the fuel cell system without making the battery too expensive and that the power requirements are fulfilled over test periods with decided length and power output. Hydrogen storage is rejected, since as a seasonal storage it would require a lot of space and a fuel cell system with a higher capacity of the fuel cell stack than of the fuel processor.

7. Future work

This paper is part of a series whose goal is to identify the prerequisites, requirements and possibilities for PEFC systems in typical and specific buildings in Sweden. The series was started with [20]. Future studies will include deeper studies into the fuel cell system configurations and modelling, and furthermore cooling demands.

Acknowledgements

This work was financed by the Swedish Energy Agency, STEM.

References

[1] M. Ohlsson, An investigation on fuel cell economy and fuel availability for distributed generation in Sweden, KTH/KET/Energy Processes, 2001.
[2] R. Leisten, J. Mathiak, Wirtschaftlichkeit von Brennstoffzellenanlagen, BWK 53 (2002) 48–52.
[3] T.G. Kreutz, J.M. Ogden, Assessment of hydrogen-fueled proton exchange membrane fuel cells for distributed generation and cogeneration, in: Proceedings of the 2000 US DOE Hydrogen Program Review, 2000.
[4] S.R. Vosen, J.O. Keller, Hybrid energy storage systems for stand-alone electric power systems: optimization of system performance and cost through control strategies, Int. J. Hydrogen Energy 24 (1999) 1139–1156.

[5] L.E. Lesster, G.B. Lansberry, E. Homansky, Grid parallel and stand-alone conditioning of fuel cell power, The Fuel Cell Home, Lucerne, 2001, pp. 157–166.

[6] K. Agbossou, R. Chahine, J. Hamelin, F. Laurencelle, A. Anouar, J.-M. St-Arnaud, T.K. Bose, Renewable energy systems based on hydrogen for remote applications, J. Power Sources 96 (2001) 168–172.

[7] H. Gulliksson, Energikontor Sydost, Personal Communication and http://www.energikontor-so.com, May 2002.

[8] A. Bauen, D. Hart, Assessment of the environmental benefits of transport and stationary fuel cells, J. Power Sources 86 (2000) 482–494.

[9] R. Friberg, E. Nilsson, Potentiella bränslen inom ramen för LIP-kansliets teknikupphandling av bränsleceller, Catella Generics, Center of battery technology, Rapport nr. R00-129-R (in Swedish).

[10] Sulzer Hexis, http://www.hexis.ch, 2002.

[11] Nuvera, Caterpillar, Williams, Bio-energy, in: Proceedings of the Presentation to US DOE, 31 October 2001.

[12] T. Ioannides, S. Neophytides, Efficency of a solid polymer fuel cell operating on ethanol, J. Power Sources 91 (2000) 150–156.

[13] S. Aronsson, Heat load of buildings supplied by district heating—an analysis based on measurements in 50 buildings, CTH, Department of Building Services Engineering, 1996 (in Swedish).

[14] Riksskatteverket, Energy Taxes, http://www.rsv.se, 2002.

[15] A.B. Birka Nät, http://www.birka.se, April 2002.

[16] H.T. Karlsson, Projekteringsmetodik, Kemicentrum LTH, 1992 (in Swedish).

[17] A.B. Hawker, Karlstad, Personal Communication, Leif Jonsson and Jens Ohlsson, April and September 2002.

[18] US Department of Energy, http://www.doe.gov.

[19] ERA 2002-01-07, ‘‘Biokraftverk för småhus testas’’.

[20] C. Wallmark, P. Alvfors, Design of stationary PEFC system configurations to meet heat and power demands, J. Power Sources 106 (2002) 83–92.