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Design of stationary PEFC system configurations to meet heat and power demands

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Abstract

This paper presents heat and power efficiencies of a modeled PEFC system and the methods used to create the system configuration. The paper also includes an example of a simulated fuel cell system supplying a building in Sweden with heat and power. The main method used to create an applicable fuel cell system configuration is pinch technology. This technology is used to evaluate and design a heat exchanger network for a PEFC system working under stationary conditions, in order to find a solution with high heat utilization. The heat exchanger network in the system connecting the reformer, the burner, gas cleaning, hot-water storage and the PEFC stack will affect the heat transferred to the hot-water storage and thereby the heating of the building. The fuel, natural gas, is reformed to a hydrogen-rich gas within a slightly pressurized system. The fuel processor investigated is steam reforming, followed by high- and low-temperature shift reactors and preferential oxidation. The system is connected to the electrical grid for backup and peak demands and to a hot-water storage to meet the varying heat demand for the building. The procedure for designing the fuel cell system installation as co-generation system is described, and the system is simulated for a specific building in Sweden during 1 year. The results show that the fuel cell system in combination with a burner and hot-water storage could supply the building with the required heat without exceeding any of the given limitations. The designed co-generation system will provide the building with most of its power requirements and would further generate income by sale of electricity to the power grid.

Keywords: PEFC system; Natural gas reforming; Pinch technology; Heat and power demands

1. Introduction

Due to limited natural resources and environmental pollution, an essential issue for the future is how energy demands can be met. Traditional power and heat generation consumes fossil fuels and pollutes the environment by high emissions. In common visions of future solutions to these problems, fuel cells are an important factor. Fuel cells generate heat and power with higher efficiencies and lower emissions than most of the commercial techniques of today.

Fuel cells have been studied for several applications during many years to reach the promising state they have today. One combination close to commercialization is the polymer electrolyte fuel cell (PEFC) system for stationary use in residential buildings. Advantages of this combination are, for example, high reliability, flexibility of a load following system and the high efficiency of co-generation, since heat in distributed generation is generated closer to the user.

Various studies on natural-gas-fueled PEFC systems have been performed during the last years. For example, researchers have presented the dependencies of system efficiencies on system pressure, compressor efficiency [1], and reformer type [2]. Even research on location and system size from an economic point of view is being performed [3]. Several fuel cell companies and users have presented their fuel cell system properties and lay outs [4–6], but have rarely described how the design solutions were found, which is one of the intentions of this paper.

This paper focuses on the design of a PEFC system configuration for use in buildings in Sweden. It describes both the methods used for system design and the resulting system's simulated performance for a given heat and power demand. The main method used for design of heat exchanger network for the fuel cell system is pinch technology. Pinch technology as a tool for design of heat exchanger networks has been used, for example, for SOFC-system [7], and more generally presented for MCFC and PEFC types of fuel cells in the literature [8,9]. Pinch technology has even been rigorously used for similar hydrogen generation processes [10] to those in this study, but the former were separated from the fuel cell stack and furthermore included methanization,

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which has not been used in this study. Pinch technology as described in this paper is different in that it explains how the methodology could be used for a fuel cell system.

The result of a simulation over a year for a fuel cell system in a building in Sweden is also described in this paper. Fuel cell systems have been evaluated for the actual demands of buildings in a few countries, for example, in Japan, the US, and Germany [3,11,12]. But the buildings heat and power demands are quite different in different parts of the world. Placing the system in Scandinavia requires it to provide more heat compared to generated electricity than is usually required in many other countries.

2. Fuel cell system component models

To provide the necessary information about fuel cell systems, simulation models of fuel cell systems have been built up. All main components needed to convert fuel to heat and alternating current are included. The models and the systems are designed to automatically find working points, for example, for the fuel cell stack and heat exchangers, and to minimize fuel needs. The software used is Matlab® and the models of the main components are described below. The assumed turn-down ratio for the fuel cell system is 1/6, i.e. maximum load is six times the minimum power load.

2.1. Fuel cell stack

The fuel cell stack model used is developed at the Royal Military College of Canada [13]. It is a general model with the most important parameters set as variables. In a description of an earlier version of that fuel cell model fuel changes are acceptable for the model if the hydrogen mole fraction is high enough; over 60% is on the safe side [14]. This is not always the case in this study, but the model is assumed to cover all calculated reformate compositions. Especially the hydrogen concentration affects the fuel cell performance.

The fuel cell model parameters used are taken from experimental results from a Ballard's Mark V fuel cell stack [13–15]. The fuel cell stack models used in the different studies are built up for various maximum power levels with the help of the parameters fuel cell area and number of fuel cells. The stacks are assumed to run under different, but always constant, temperatures and pressures.

Specific requirements for the fuel cell stack operation in this study are that as much as 85% of the hydrogen in the reformate is available for chemical reactions in the cells. Furthermore, the fuel cell voltage is limited to a minimum of 0.6 V due to limitations in the fuel cell cooling system. The fuel cell operation is assumed to be isothermal and will work at 72 °C. It is assumed that 0.35 water molecules follow each proton couple through the membrane.

The inlet air to the cathode is humidified to a relative humidity of 80% and when necessary the anode inlet stream is also humidified. Air stoichiometry is two in the calculations. A small air bleed is added on the anode side to protect the catalyst from carbon monoxide.

2.2. Fuel processing

The fuel processing and clean-up units are modeled in several steps, as described in [2,16,17]. Steam is added to the first reactor where steam reforming is performed and hydrogen produced. The chosen steam-to-carbon ratio is three. That step is endothermic and heated by a burner, burning the anode outlet gas and additional natural gas. In the two following reactors, water–gas shift is performed (at two different temperature levels), required to decrease the CO-level from a few volume percent. The last step included is preferential oxidation, where a small flow of air is added to decrease the CO-level under the limit decided by the sensitivity of the fuel cell, in this case 20 ppm CO. The preferential oxidation is assumed to have 40% selectivity for CO reactions; the rest reacts with hydrogen [18].

Temperatures for reactor inlets and outlets are predefined according to Twigg [17] (see Fig. 1). Chemical equilibrium of H_2, CH_4, CO_2, CO, H_2O are assumed at the outlet temperatures, giving variable gas compositions, respectively. Catalytic reactors and stay time will support that assumption. The higher carbons are assumed to react fully in the steam reforming, and after the steam reforming both methane and higher carbons are assumed inert.

2.3. Other components

Air compression is made with a fan modeled with a load dependent efficiency (see Fig. 2). The inlet pressure to the system is 1.1 atm, and outlet pressure is due to pressure drops near ambient. The natural gas is assumed to have the required pressure at the inlet. The natural gas composition used in the calculations is a typical Danish composition [19].

Deionization of water is also included in the system, as well as filtration of water, although neglected in the calculations. The water pump is assumed to work with 60% efficiency, although the power demand could have been neglected. The two motors needed, for the air fan and the water pump are also assumed to have constant efficiencies of 90%.

The total efficiency of the rectifier and inverter are dependent on the fuel cell stack voltage and decrease rapidly

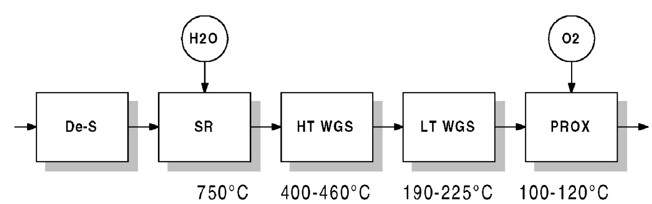

Fig. 1. The reforming and cleaning process includes desulfurization, steam reforming, high and low temperature shift and preferential oxidation.

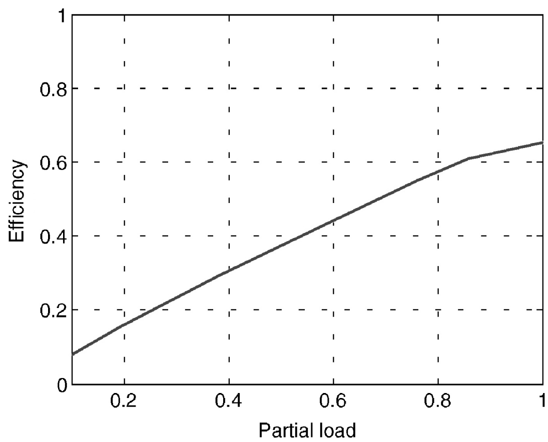

Fig. 2. Efficiency of air fan, as function of partial load [20].

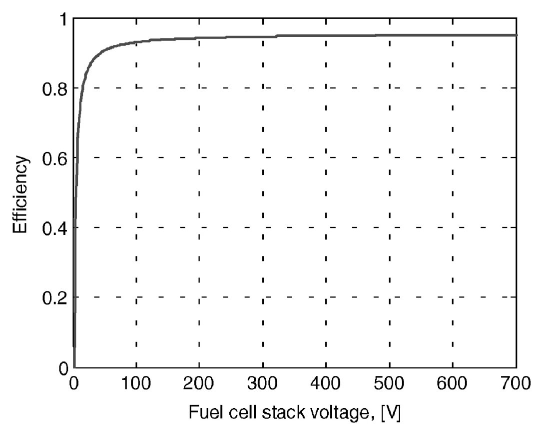

Fig. 3. Total efficiency of rectifier and inverter as function of fuel cell stack voltage [21].

for stack voltages below 100 V (see Fig. 3). Furthermore, the fuel burner needed for heating the fuel reforming process is assumed to have full fuel utilization with 5% air excess. The heat exchangers used all have sufficient temperature differences and are assumed to give roughly the same output temperatures for all load levels.

3. Heat exchanger network

Pinch technology is a method that reduces both capital and energy costs of industrial processes by deploying heat exchangers efficiently. It has been used since the 1970s and is often used in retrofit situations [22].

The pinch technology consists of rules to be followed [23]. In this study the following rules were important.

- Start network design at the pinch point, and solve the parts above and below separately.
- Do not use external cooling above the pinch temperature or external heating below.
- Try to match streams with similar heat capacities.
- Try to allow only heat exchangers that exhaust one of the streams.
- Neglect streams with comparatively small heat capacity.

In this study pinch technology was used to identify a suitable heat exchanger network for the fuel cell system. Because of the co-generation application, the goal was to maximize the use of unavoidable heat losses, for a given power production.

The heat exchanging problem to be solved was very specific, with all reactors and internal processes known, and with their respective working temperatures fixed (see Fig. 1 (simplified) and Fig. 4). The different temperatures were allowed to vary slightly, but were preferably seen as fixed, to match functions of diverse reactors presented in the literature, functions verified either experimentally or theoretically.

The system composite curves were drawn in order to give a good view of the possibilities for a heat exchanger network.

The composite curves are two curves describing a systems totally cooling and heating demand, respectively, as a function of temperature intervals. For the composite curves, heating and cooling demand between reactors was calculated, and all internal streams forced to their working temperatures, and all heating or cooling demands for all streams registered. Note that every single inlet stream to the fuel cell system was preheated to its working temperature and also included.

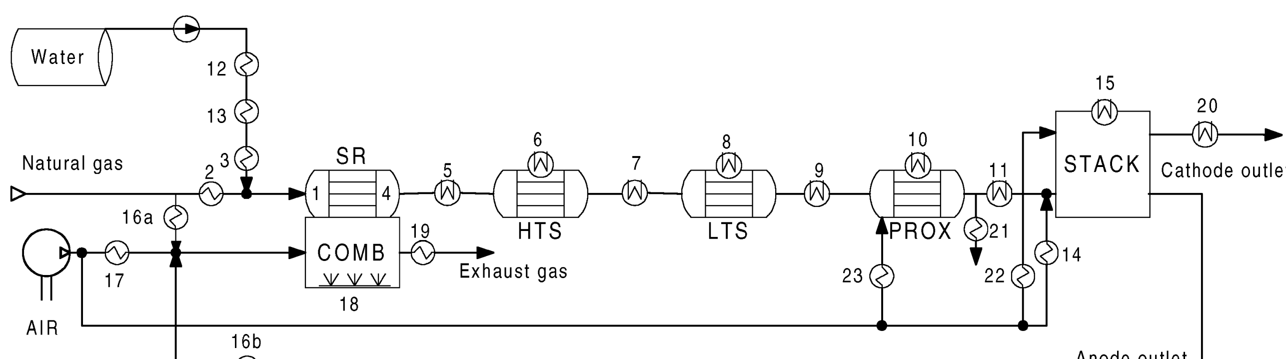

Fig. 4. The fuel cell system components and their heat exchange needs, compare with Table 1.

Table 1
Heat needed for cooling or heating of streams and isothermal reactions

Name[a]	Number	Type	T_{start} (°C)	T_{target} (°C)	Q (kW)
SR HC	1	Cold	749.4	750.35	0.2461
Ref_NG	2	Cold	25	750	0.276
Ref_H_2O	3	Cold	120	750	0.5924
SR	4	Cold	749.4	750.35	1.1815
SR–HTS	5	Hot	750	400	0.5512
HTS	6	Hot	400.5	399.5	0.1097
HTS–LTS	7	Hot	400	250	0.2289
LTS	8	Hot	250.5	249.5	0.0369
LTS–PROX	9	Hot	250	100	0.2198
PROX	10	Hot	100.5	99.5	0.1332
PROX–stack	11	Hot	100	60	0.1754
H_2O preheat	12	Cold	25	120	0.2879
Steam gen.	13	Cold	119.7	120.73	1.5108
Cathode_in	14	Cold	54.14	60	0
Stack	15	Hot	60.5	59.5	3.0663
Comb_fuel	16	Cold	60	775	0.4961
Comb_air	17	Cold	25	775	0.6589
Comb	18	Hot	775.4	775	2.4691
Exhaust	19	Hot	775	35	1.4728
Cathode_out	20	Hot	60	35	0.6604
Ref_cond	21	Hot	60	35	0.0051
Airbleed	22	Cold	60	25	0.0007
PROX_air	23	Cold	100	25	0.0014

[a] SR: steam reforming; Ref: reformer; HTS: high temperature shift; LTS: low temperature shift; PROX: preferential oxidation; comb: combustion; cond: condensation; steam gen.: steam generation; HC: higher carbons (CH_4 not included); NG: natural gas; H_2O: water; *x–x*: cooling between two reactors; *x_x*: stream to or from reactor.

From the result, shown in Table 1 and Fig. 5 for a 2 kW stack system with steam reforming, it can first of all be seen that a few streams were too small to be taken into consideration, i.e. the three at the bottom of the table.

As seen in the upper right part of Fig. 5. the external heat needed for the reforming is already provided. Burning of the anode gas and additional natural gas supplies that demand. The demand of external cooling, seen in the lower left part of Fig. 5, is simply combined with the building's heat demand, thereby representing the total usable heat in the system. To combine the rest of the streams the pinch rules are needed. Whenever the matches are badly made, additional external heat will be needed, causing a decrease of the overall power efficiency.

Collecting the various demands into groups simplifies the problem. A deeper study of Table 1 and Fig. 5 (concerning the middle, non-horizontal lines), will reveal a few main demands. On the cold side is heat needed for preheating of streams for reforming (fuel and heating of steam) and combustion (fuel and air), and also steam generation of water (both preheating and steam generation). On the hot side are the cooling needs of the diverse reforming steps (flow 5–10) and the possibility to use the heat of the burner's exhaust. Altogether there were three cold groups and two hot ones.

With the help of the software pro_pi1 from CIT Industriell Energianalys AB (the pinch software also used for drawing of composite curves), every possible match of one hot and one cold stream was drawn. It was an efficient tool to find good combinations for the heat exchanger network.

Starting from the pinch point, slightly below 100 °C, the water heating are combined with the reforming steps. Both below and above the pinch point, streams can preheated with the help of a split exhaust stream-using the exhaust down to as low temperature as possible. The rest of the exhaust heat and heat need for the water are also combined. The rest of the preheating will then be done inside the reformer and combustion chamber, respectively. How well the four main streams (both preheating needs taken together) fit over two heat exchangers, is shown in Figs. 6 and 7. Note that the warmest part of the exhaust heat in Fig. 6 will later be used for steam generation in the heat exchanger network.

Heat is supplied to the building from the fuel cell stack, and from cooling of the cathode outlet and the main stream between the PROX and the stack. The temperature difference used for condensing the exhaust was 20 °C.

The designed heat exchanger network was introduced in the model and evaluated for various load levels and input parameters. Common to the various tests was a high level of

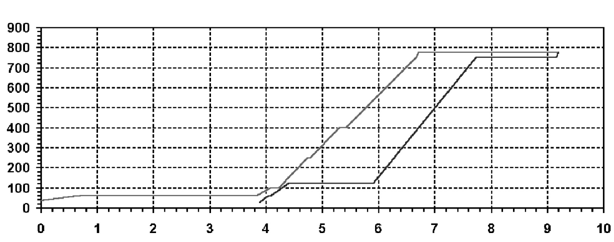

Fig. 5. Composite curves corresponding to Table 1. The upper curve is the hot composite curve and below is the cold one.

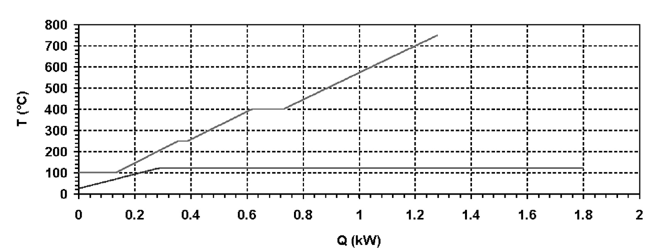

Fig. 6. Heat exchange between the reformer steps (above) and the water preheating and steam generation.

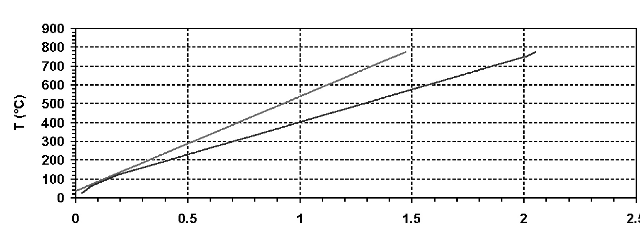

Fig. 7. Heat exchange between burner exhaust (above) and preheating of streams to reformer and burner.

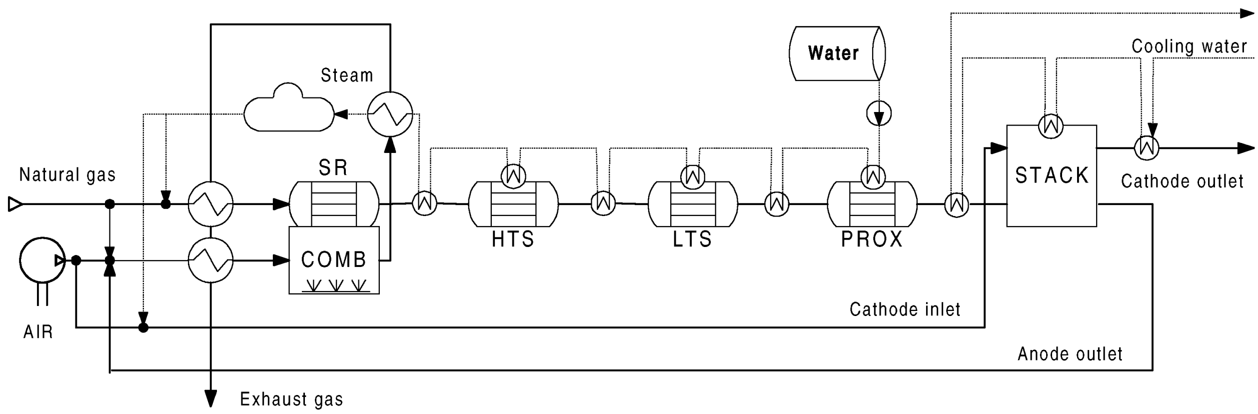

Fig. 8. Evaluated heat exchanger network for the described fuel cell system.

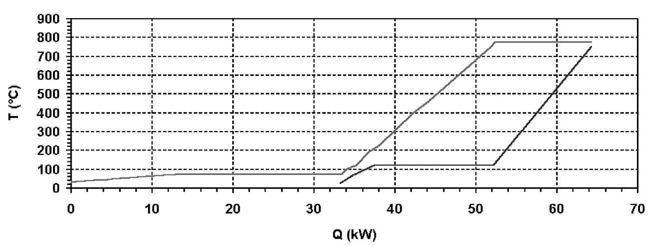

Fig. 9. Composite curves for the completed system, 15 kW_{el}, at maximum load. The upper curve is the hot composite curve and below is the cold one.

heat utilization. The network is, as preferable, robust. The resulting system including heat exchangers is viewed in Fig. 8. The composite curves for the completed system, without the isothermal assumptions for reactors, is shown in Fig. 9.

4. Fuel cell system efficiencies

Efficiencies for a calculated, near atmospheric gross 15 kW_{el} fuel cell system are shown below, first for full load and then for a case of partial load (Tables 2 and 3), and finally the heat and power efficiencies are shown for all partial loads (Fig. 10).

The stack efficiency is defined as generated net electricity divided by the in-going hydrogen's lower heating value. The reformer efficiency is defined as the quotient of lower heating value of hydrogen in the outlet gas from the preferential oxidation to natural gas in inlet gas to the desulfurization. The auxiliary efficiency includes pumps, fans and motors. Furthermore, the power conditioner efficiency includes both rectifier and converter. The total efficiency—including usable heat and power—is defined for a system placed where heat losses could not be utilized. Note that heat losses from the heat exchangers and reactors are neglected, making the calculated partial load efficiencies differ from presented, measured efficiencies of existing fuel cell systems (e.g. [24]).

Table 2
Efficiencies of the 15 kW_{el} fuel cell at full load (net power 13.0 kW_{el})

	Efficiency (%)
Stack	40.8
Fuel processing	72.8
Power conditioner	93.4
Auxiliary equipment	96.5
Net power	26.7
Heat and power	92.4

Table 3
Efficiencies of the 15 kW_{el} fuel cell at partial load, gross power 7 kW_{el} (net power 6.20 kW_{el})

	Efficiency (%)
Stack	48.3
Fuel processing	73.9
Power conditioner	94.7
Auxiliary equipment	93.9
Net power	31.6
Heat and power	91.3

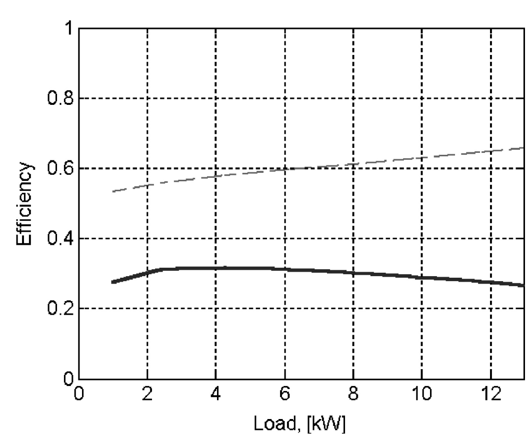

Fig. 10. Heat (segmented line) and power efficiencies of the 15 kW fuel cell system with a return temperature of the cooling media of 40 °C.

5. Buildings heat and power demand

Compared to many other countries a building in Scandinavia requires much heat compared to generated electricity. Measured data from Gothenburg 1990–1991, discussed in a Ph.D. thesis from Department of Building Services Engineering, Chalmers University of Technology, shows this particularly well [25]. For several kinds of buildings, heating demand for the building itself, and for tap water, as well as heating system temperature levels and power demand are measured and saved as mean values per hour for a whole year. Only some short periods during the year are not included in the data. With kind permission from the author Stefan Aronsson and the department, this data has been used as a basis in this study.

The buildings in Aronsson's study are supplied with district heating, i.e. several have high temperature heating systems. For a heat supply with lower temperatures larger areas of the radiator system are required. In some buildings a new adjustment of existing radiators could be enough, for others installation of additional radiators might be necessary. It is interesting to note that new laws do not permit higher dimensioning inlet temperatures for water systems than 55° [26]. The goal is to build systems applicable for alternative energy solutions.

The hot tap water must not fall below 50 °C if circulating and 60 °C if stagnant because of the risk of Legionnaire's disease, and should not exceed 65 °C because of the risk of scalding [26,27]. If the hot tap water risks exceeding 65 °C at a tap, thermostat mixers are installed to mix cold water in to it. To keep the high tap water temperature it is slowly circulated in larger buildings. The temperature decrease of the returning water could be 5–10 °C [25].

A building's heat supply should at least manage to keep the indoor temperature at lowest three degrees lower than the normal indoor temperature, at such extreme low outdoor temperatures only expected once during 20 years [26].

6. Fuel cell system in a building

In this paper a building with 25 apartments, from the middle of the 20th century, is studied. The building has a heat demand (both floor and tap water heating included) of less than 150 kW and a power demand fluctuating between 4 and 20 kW during the measured year. The building's total heat demand during the measured year was 308 MWh and the total power demand was 61 MWh.

6.1. Design of a co-generation system

In the design of a co-generation system with a fuel cell there are many prerequisites and limitations to take into account. A fuel cell system of today cannot simultaneously support both heat and power demands by itself. It is not fast enough for direct power supply and not flexible enough to

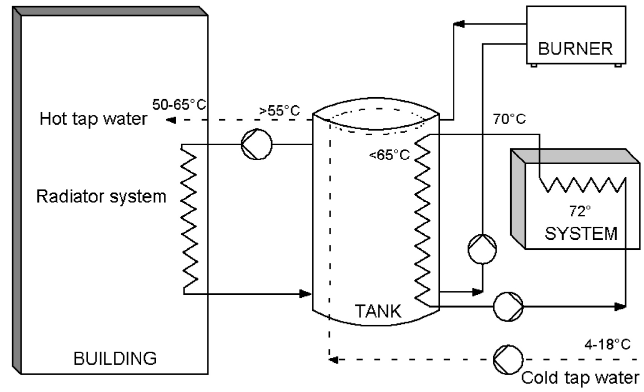

Fig. 11. Heat for tap water and heating of the building are supplied from the storage tank. Heat is transferred from the fuel cell system and burner to the hot-water storage (maximum 65 °C at tank top is valid when burner is off).

change its power to heat ratio on demand. For that reason either stores or grid connections must be used together with the fuel cell system. For power supply, batteries or electrical grid connections are common. To extend the fuel cell system operating range it is preferably connected to a heat storage as well, smoothing out both maximum and minimum matches of heat and power demands.

The fuel cell system in this study is connected to the electrical grid for backup and peak demands and to a hot-water storage to meet the varying heat demands for the building. The hot-water storage includes tap water heating coils in the top (see Fig. 11). The hot-water storage is assumed to have a constant temperature difference of 15 °C between the top and the bottom. The thermal recovery from the fuel cell system depends on the return temperature of the cooling media. To supply a building's heat and power demand an additional burner is required in some cases. Then a simple burner with 90% efficiency and one constant load level is used. The burner is quickly started and stopped and used on or off, i.e. no partial loads are promoted.

6.2. Sizing of the co-generation components

For the co-generation system the sizes of fuel cell system, hot-water storage tank and burner must be decided, a problem discussed below.

A first approach to component sizing can be obtained from a duration curve. In this case when the co-generation system is to provide the building with all needed heat a heat demand duration curve is a valuable resource for the calculations. A duration curve is shown in Fig. 12 for the studied building. In a case when the building's average heat falls short of the minimum heat supply from the fuel cell system some strategies are applicable, provided that no heat should be dumped (for economic reasons). Either the fuel cell system is easy to start and stop, since the problem is solved by having it run under shorter periods of the day, or the system is turned off during that part of the year. In the

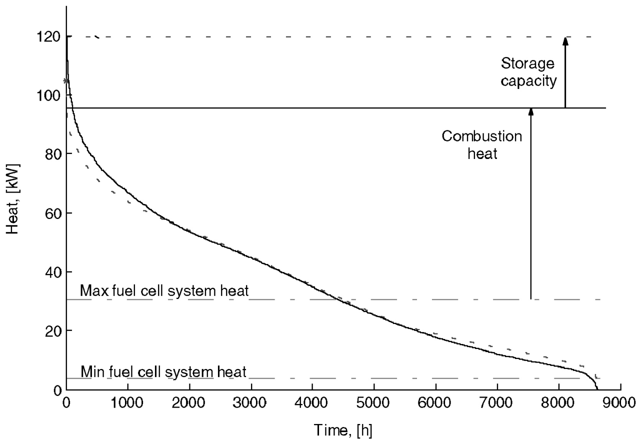

Fig. 12. The building's heat demand over 1 year as duration curve, and sliding average heat demand over 6 h as dotted line.

last-mentioned case, for example, an additional burner or electric heater must be used for at least tap water heating, equipment in that case necessary for peak shaving during the winter. The other alternative is to choose the fuel cell system minimum heat level below the building's minimum average heat requirements, which is the case in the example below and also shown in Fig. 12.

Also assuming that fuel cell systems are manufactured for certain power levels, and that the demand duration curve will change over the years, a fuel cell system with gross 15 kW_{el} is chosen for the calculations. Its generated heat varies between 3.5 and 32 kW, depending on load level and the return temperature of the fuel cell system cooling media. These two levels are drawn in the same figure as the duration curves (see Fig. 12). The burner size could be estimated as the difference between the fuel cell maximum line and the upper part of the demand curve. In retrofit situations the hot-water storage could already exist, which implies the needed size of the burner. The size of the burner will be dependent on the storage capacity. The earlier mentioned law regarding the extreme outdoor temperatures requires a certain margin of heat capacity. Nevertheless, in this study a 65 kW burner and a 12.6 m^3 hot-water storage are modeled, to manage the demands of the measured year.

The storage capacity in Fig. 12 is maximum useable for 6 h for a temperature decrease in the tank of 10 °C. The sliding average curve in the figure is also made up of intervals of 6 h.

6.3. Simulation prerequisites

Measured floor and tap water heat demands must be supplied by the modeled system for each hour in the calculations. The measured electricity is also required, and in the calculations supplied by fuel cell system or power grid, but not giving as reliable comparisons as the heat demand, since the electricity is normally fluctuating in much shorter periods than an hour. It would in reality cause a lower usage than calculated of direct generated power from the fuel cell system. A decrease of power would temporarily only give a higher heat supply, but all power increasing periods would imply a higher external power demand. Earlier studies have discussed in detail the significance of fast load changes (e.g. [28]).

In this study the fuel cell system is static, for example, no changes of parameters, to cause various heat and power ratios depending on load levels or demands, are permitted. Conversely, examined is how a specific fuel cell system fits a specific building's demands. The fuel cell system delay at load changes is not taken into account, but assumed to be corrected during the already long time steps of 1 h.

With control algorithms further developed than the ones used in these simulations a better match between the fuel cell system and the buildings demand could have been accomplished. Control strategies have earlier been shown to be important for a similar system operation [29]. Of the calculated period of 8760 h, 8617 h were included in the calculations, the rest was excluded because of lack of measured data.

7. Simulation results

The described grid connected co-generation system with fuel cell system, burner and hot-water storage has been simulated to supply the described building with floor heating, tap water heating and power. The control strategy depends on the hot-water storage temperature and the outdoor temperature.

First of all, note the match between the duration curve (Fig. 12) and the figure showing the fuel cell system load level over the year (Fig. 13). The maximum heat level is in both cases close to 4500 h. Fig. 14 shows the corresponding power levels of the fuel cell system. The bar at the bottom left of Fig. 14 represents hours without measured data.

It is shown that the system can be controlled by partial load operation of the fuel cell system. The higher heat demands during the day fit well with the higher power demands (see Figs. 13 and 14). During the summer hardly

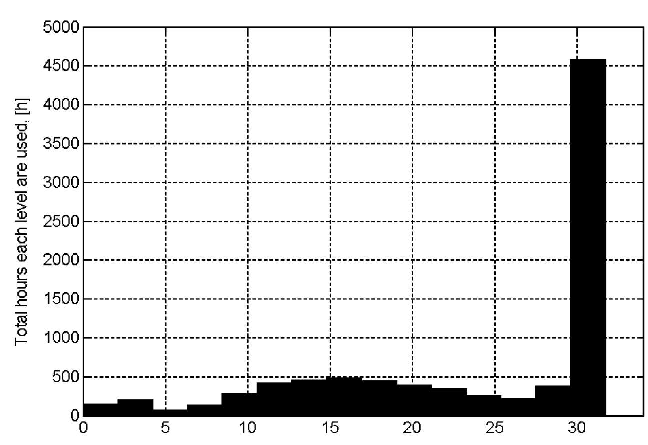

Fig. 13. Hours each heat level of the fuel cell system are used.

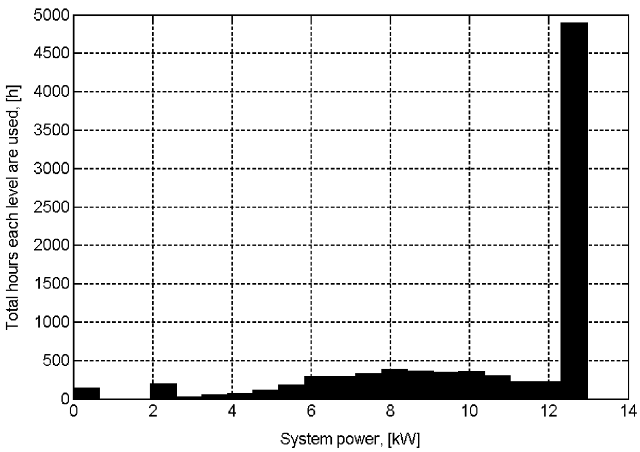

Fig. 14. Hours each power level of the fuel cell system are used.

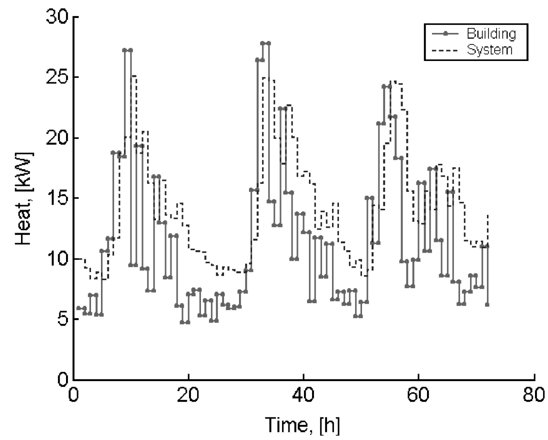

Fig. 16. The building's heat demand and heat supply from the fuel cell system during 3 days in the summer.

any combustion was needed and during the winter the fuel cell worked at full load during longer periods. The combustion can temporarily increase the hot-water storage temperature over the fuel cell system supply limit of 65 °C, even in the summer, as seen in Figs. 15–17.

The chosen equipment and operating strategy could provide the building with its heat demand and also provide 96% of its power demand. It would also sell approximately 38% of the generated electricity to the power grid. The installed burner would give 40% of the buildings heat demand.

7.1. Costs

Although a stationary fuel cell installation in Sweden today would not be made for economic reasons it is interesting to view some economic calculations. Fuel cell systems are conversely believed to be installed where high electrical reliability or power quality is required, or for environmental reasons. Furthermore, a fuel cell system is very expensive and power in Sweden is still quite cheap.

However, a simple cost estimation of the difference between a supply system on one hand with only natural gas burner and electrical grid connection, and on the other hand, the fuel cell based system, is presented below. Only variable costs are included. For the natural gas connections the same service and equipment costs are applicable for the two compared cases and not discussed. The following prices are valid in August 2001.

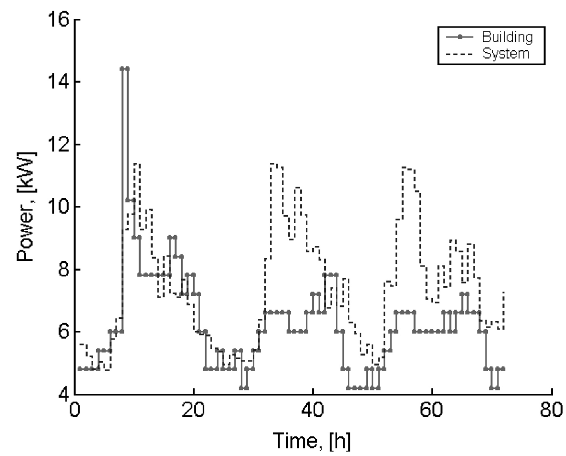

Fig. 17. The building's power demand and power supply from the fuel cell system during 3 days in the summer.

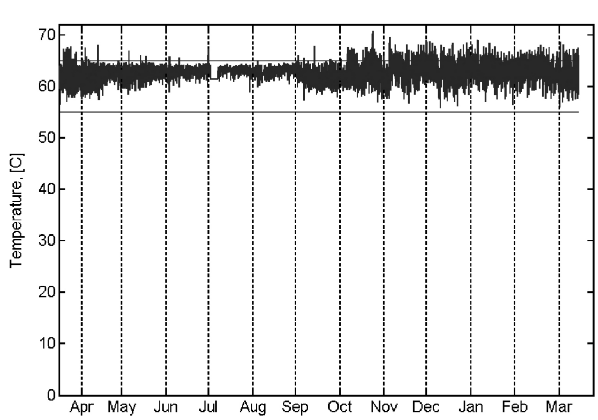

Fig. 15. Temperature at the top of the hot-water storage. The lower limit 55 °C is never exceeded.

- The electricity price is approximately 0.80 SEK[1]/kWh when buying from the grid, taxes included.
- The natural gas price varies between 0.335 SEK/kWh for maximum 200 kW applications and 0.575 SEK/kWh for residential buildings, taxes included.
- When selling electricity to the grid from a small power plant 0.40 SEK/kWh is given, subsidies included. A yearly equipment and service cost of 1200 SEK is added [30,31].

Assuming 90% efficiency of the burner and the same constant heat loss from the hot-water storage as for the fuel cell system based calculations gives a variable cost of 172,000 SEK for the calculated year, for a natural gas price

[1] 1 SEK is equal to 10.40 USD, in August 2001.

Table 4
Variable costs for the both compared system alternatives supplying the 15 apartment building with heat and power during 1 year

Natural gas price (SEK/kWh)	Fuel cell system (SEK)	Conventional system (SEK)
0.335	149000	172000
0.450	204000	215000
0.575	263000	261000

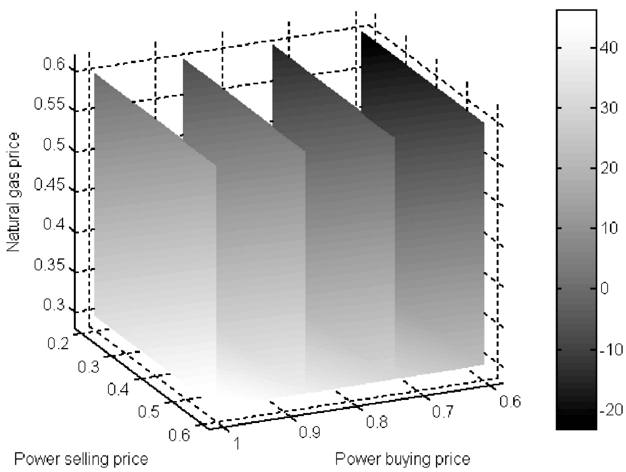

Fig. 18. Difference in variable costs between the conventional system and the fuel cell based system during 1 year. The difference is shown in thousands of SEK (units on the axis are SEK/kWh).

of 0.335 SEK/kWh. It should be compared with the studied fuel cell based system which costs 149,000 SEK. In Table 4 the costs are compared for the two alternatives—run with the same operational strategy—for different prices of natural gas.

In Fig. 18 all three prices are varied and the cost difference between the conventional system and the fuel cell based system is presented. The figure shows that the economic part is very dependent on the natural gas and electricity prices. The price difference in Fig. 18 should be compared to the installation cost for a fuel cell system. For example, an installation cost of 20,000 SEK/kW (still a futuristic price), would hardly be covered by any of the calculated price combinations shown in Fig. 18. With an interest rate of 8% and a deprecation time of 7 years it would give an average yearly cost of approximately 57,000 SEK. Altogether, it shows that the system is unlikely to be economic in the near future, unless the prices on the energy market change substantially. Nevertheless, it is promising, especially for an investor valuing the advantages of a fuel cell system, who could partly finance such a system by selling electricity to the power grid.

8. Conclusions

This paper has discussed:

- modelling of components in a PEFC system;
- design of heat exchanger networks;
- efficiencies of a PEFC-system and its components;
- buildings heat and power demand in Sweden;
- use of a fuel cell system in a building in Sweden.

The conclusions from the combined building and fuel cell system simulations are:

- Measured demand data could preferably be used for sizing and needs estimations of fuel cell system, stores and additional equipment.
- The PEFC-system could fulfil the requirements for heat and power supply, even with operating temperatures below 80 °C.
- In the simulated example the fuel cell system would provide the building with about 60%, and maximum 96% respectively, of its yearly heat and power demand, at the same time as 38% of the generated power would be sold to the power grid.
- There is a potential for small scale-fuel cell installations in Sweden, although they are still too expensive.

9. 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.

Future studies will include equipment costs, heat losses and fuel availability. Dynamic models of the fuel cell system components will be included in the system to increase the reliability level of the result. The models will also be improved by results from experimental work. Then further studies of fuel cell installations in buildings in Sweden will be performed.

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