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Journal of Power Sources 131 (2004) 340–350

JOURNAL OF POWER SOURCES

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Description and modelling of the solar–hydrogen–biogas-fuel cell system in GlashusEtt

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Received 6 October 2003; accepted 3 November 2003

Abstract

The need to reduce pollutant emissions and utilise the world's available energy resources more efficiently has led to increased attention towards e.g. fuel cells, but also to other alternative energy solutions. In order to further understand and evaluate the prerequisites for sustainable and energy-saving systems, ABB and Fortum have equipped an environmental information centre, located in Hammarby Sjöstad, Stockholm, Sweden, with an alternative energy system. The system is being used to demonstrate and evaluate how a system based on fuel cells and solar cells can function as a complement to existing electricity and heat production. The stationary energy system is situated on the top level of a three-floor glass building and is open to the public. The alternative energy system consists of a fuel cell system, a photovoltaic (PV) cell array, an electrolyser, hydrogen storage tanks, a biogas burner, dc/ac inverters, heat exchangers and an accumulator tank. The fuel cell system includes a reformer and a polymer electrolyte fuel cell (PEFC) with a maximum rated electrical output of 4 kW_{el} and a maximum thermal output of 6.5 kW_{th}. The fuel cell stack can be operated with reformed biogas, or directly using hydrogen produced by the electrolyser. The cell stack in the electrolyser consists of proton exchange membrane (PEM) cells. To evaluate different automatic control strategies for the system, a simplified dynamic model has been developed in MATLAB Simulink. The model based on measurement data taken from the actual system. The evaluation is based on demand curves, investment costs, electricity prices and irradiation. Evaluation criteria included in the model are electrical and total efficiencies as well as economic parameters.

Keywords: Solar; Fuel cell system; Photovoltaic cell

1. Introduction

The need for reducing pollutant emissions and utilising available energy resources more efficiently has led to increased attention towards alternative energy solutions. There has also been an intensified debate and research into small-scale energy generation due to the deregulation of the energy markets in Europe and in North America. As fuel cells approach commercialisation, it becomes increasingly important to investigate the implementation of these new systems into the conventional power systems i.e. how fuel cells and solar cells can function as a complement to existing electricity and heat production. The issue to be solved when using solar cells or wind power is the impact of fluctuating environmental conditions, which often requires energy storage and even complementary energy conversion. One suggestion is the storage of hydrogen for on-time use in fuel cell systems.

Many studies concerned with the intermittence of renewable energy and a fuel cell system focus on simulating stand-alone systems capable of seasonable storage, e.g. [1,2]. Typical questions concern the control strategy and cost of the energy storage. Vosen and Keller [3], found that the cost of the energy storage could be significantly reduced by applying a hybrid energy storage and a 'neural-net type of control system', (48% of the cost of hydrogen-only storage and 9% of the cost of a battery-only option). Others, like Kolhe et al. [4], have developed a method of predicting the performance of renewable (solar and wind) systems, especially where a procedure of estimating hourly solar radiation has been developed. El-Shatter et al. [5], has simulated shorter time periods and uses hydrogen as a daily energy storage with positive results. Iqbal [6] performed dynamic modelling of a 5 kW wind turbine and a fuel cell system and

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doi:10.1016/j.jpowsour.2003.11.094

found transient responses satisfactory, (steady state within 30 s).

The solar–hydrogen part of the renewable system has been more thoroughly studied, as in (Hollmuller et al. [7]). Lehman et al. [8], shows good results of a solar–hydrogen system with an efficiency of the electrolyser of 76.7% (alkaline unit), and a hydrogen production efficiency of 6.2%.

Yet other studies include more economic perspectives in their work, e.g. Santarelli and Macagno [9] have done a thermoeconomic analysis of a stand alone system and found that the largest costs appeared in the following order: (1) the PV electricity production, (2) the generation of hydrogen, (3) the PEFC electricity production and (4) the hydrogen storage.

The actual cost of fuel cell systems are hard to determine since there are very few commercial systems. Lokurlu et al. [10] present a cost as high as 10,000 €/kW. Lipman et al. [11], have shown that stationary PEFC systems can produce electricity at competitive rates with capital costs in the order of 1200 $/kW for offices and homes in California. This is also close to the goals of different development programs, that usual state a capital cost of 1000 $/kW [12]. Another often-quoted future price target is 400 $/kW, and is stipulated by DOE [13].

In order to further understand and evaluate the prerequisites for sustainable and energy saving systems a stationary solar–hydrogen–biogas-fuel cell system was installed in GlashusEtt in Stockholm, Sweden. This installation resembles future installations that could be expected when fuel cells and photovoltaic cells become fully commercialised, and is furthermore studied as a complement to existing electricity and heat production. The aim of this paper is to describe the installation, and to present an empirical simulation model that has been developed as a tool for evaluating of the alternative energy system.

The major focus for the simulation model has been on control strategies, and in the economic section on the fuel costs since most attention could be expected to be focused on fuel cost in the future when there is significantly lower investment expenditure [10]. The model and the alternative energy system is further described in [14].

2. Background

2.1. Hammarby Sjöstad and GlashusEtt

Hammarby Sjöstad used to be an old industrial area, but is now being transformed into a modern, ecological sustainable urban district. The environmental goals in Hammarby Sjöstad are ambitious [15]. The achievement of those goals requires cooperation and a small modification in behaviour by the residents in Hammarby Sjöstad. Hence, Stockholm Vatten AB, Fortum AB and The Real Estate and Traffic Committee established the GlashusEtt project.

GlashusEtt (see Fig. 1), is an information centre built to inspire residents to adjust their lifestyle to a more sustainable one. The idea is that GlashusEtt should serve as a natural meeting place and exhibition hall for different interest groups. The façade is made of glass as the name (Glass-house-One in English) suggests. The glass used has a low thermal conductivity and should thus reduce energy losses by half, compared to a standard house [15].

Fig. 1. GlashusEtt (English Glass-house-One).

In order to understand and evaluate the prerequisites for sustainable and energy-saving systems, ABB, and Fortum, with financial support from the Local Investment Programme (LIP) council in Stockholm, and the Swedish Energy Agency (STEM) have complemented the existing energy system in GlashusEtt with an alternative energy system. The system is being used to demonstrate and evaluate how a system based on fuel cells and solar cells can function as a complement to existing electricity and heat production. The alternative energy system is situated on the top level and the roof of the building and consists of a photovoltaic array, a fuel cell system, an electrolyser, hydrogen storage tanks, and a separate control system.

2.2. The alternative energy system in GlashusEtt

The alternative energy system in GlashusEtt constitutes the first public residential installation of a fuel cell system in Sweden. The system combination of an electrolyser, photovoltaic array and biogas is also unique. The alternative system is situated on the top floor and the roof of GlashusEtt, see Fig. 2. The alternative energy system was designed and installed in the building after the conventional system. This means that the conventional system is dimensioned for, and capable of, supplying all energy needed in the house. The house is connected to the power grid, and thus the electricity supply is granted by the usual high standard of the Swedish electricity suppliers. The top floor of the building has a technical exhibition where the fuel cell system and the electrolyser are on display.

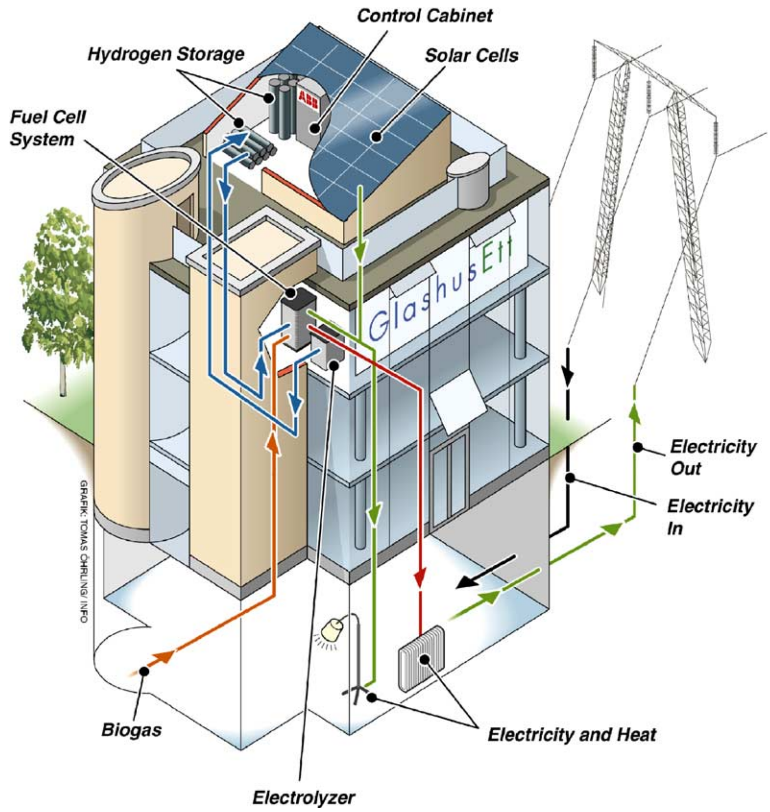

Fig. 2. Drawing of GlashusEtt.

3. The components in the alternative energy system

In the alternative energy system, see Fig. 3, the PV array delivers electricity to the building, after being converted from dc to ac. If there is an excess of electricity (house demand is lower than produced electricity) the excess dc from the PV array is fed to the electrolyser. However, this will never be the case in this particular house as demand is always higher than the maximum power produced by the PV array. The hydrogen produced by the electrolyser is then stored in gas cylinders at approximately 14 bar (g), which is the delivery pressure from the electrolyser. The fuel cell stack can be run with reformed biogas, or directly using the stored hydrogen produced by the electrolyser. The fuel cell system delivers heat and dc, with the latter converted to ac before being used in the building.

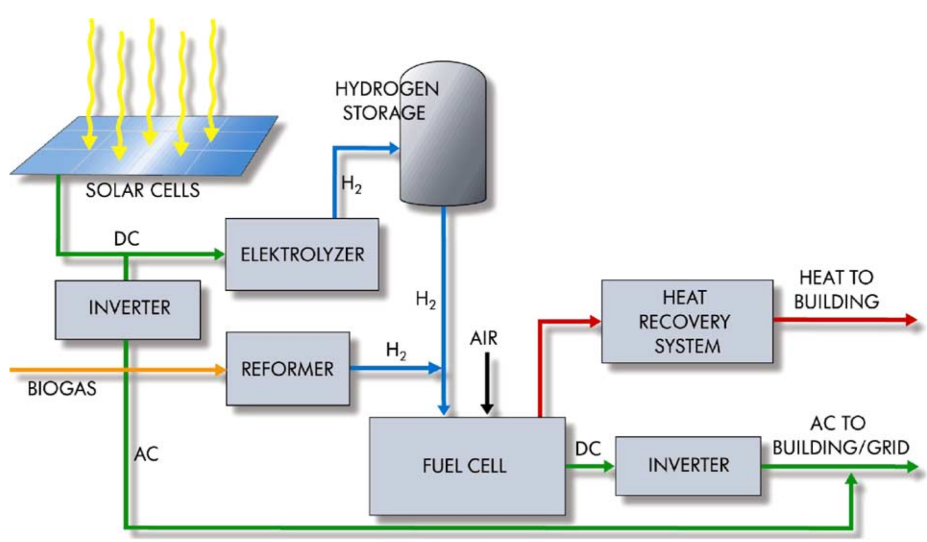

Fig. 3. Schematic view of the alternative energy system.

3.1. The fuel cell system

The fuel cell system consists of a fuel processor (reformer), including a desulphurisation unit and a CO-clean up unit, a polymer electrolyte fuel cell stack, and an electrical compartment.

The fuel cell system is connected to an inverter to deliver the electricity as alternating current (ac). The thermal energy is absorbed by a coolant loop directly connected to the accumulator tank. The principle is to use the water in the accumulator tank as a heat exchanger. Due to the (small) design size of the accumulator tank (500 l), this turned out to be inadequate. To adjust this problem the coolant loop had to be cooled on the roof of the building to ensure that the fuel cell system was sufficiently cooled. However, this implies that some thermal energy is lost on the roof.

The system can be operated with biogas or with the stored hydrogen. In the latter case, the hydrogen is fed directly to the fuel cell stack. The fuel cell system was designed to operate with natural gas or propane. However, as the biogas delivered to the building has a chemical composition close to that of natural gas, it can be operated on this particular biogas as well. The refined biogas is received from the nearby sewage water treatment plant. There is also a biogas infrastructure in the neighbourhood and the biogas is, for example, used for kitchen stoves in the area.

The fuel cell system has only been operated at full load (hydrogen or biogas) i.e. no load-change dynamics or load dependent behaviour have been tested. There is a time-delay when switching from biogas to hydrogen or vice versa due to control and security reasons (Table 1).

3.2. The photovoltaic array

The photovoltaic array (PV) is located on the roof of the building, and consists of 30 modules. It is placed, with its supporting structures, on top of a shed covering an area of 25 m^2. The inverters to the PV array, the hydrogen storage, and the control system hardware and cabinet is located inside the shed.

Table 1
Data for the fuel cell system

Delivered by	H Power
Model	RCU-4500-02 (Residential Cogeneration Unit)
Stack type	Proton exchange membrane
Working pressure	0.9 bar (g) from biogas and 0.35–0.7 bar (g) with hydrogen
Rated unit power output	4.0 kW net, 10 kW peak demand for 15 min
Rated efficiency	18% electrical, 40% total efficiency, biogas operation
Rated thermal output	6.5 kW
Dimensions (L × W × H)	1.6 m × 1.1 m × 1.4 m
Weight	Approximately 1350 kg

Table 2
Data for the photovoltaic array

Delivered by	Naps Systems Oy, Finland
Model	NR100G/24VDC
Nominal maximum power output	3 kW
Number of modules	30
Tilt angle	30°, south direction
Size of array	25 m^2
Rated module (STC) efficiency	11.9%
Calculated annual loss factor	27.8%
Weight	Approximately 1400 kg

The solar cells on GlashusEtt are of polycrystalline silicon material. The photovoltaic array (Table 2) is divided into three different sections. Each section is connected to a dc/ac inverter connected to a three-phase electrical system. The preferred design by the supplier, Naps Systems Oy, is to divide larger installations into several parallel subunits. This improves the system reliability and also makes the design of the photovoltaic array more flexible as well as improving the system efficiency by limiting power losses in case of a partially shadowed array [16]. The 30 modules delivered are rated to a maximum power output of about 3 kW. Besides delivering ac to the building or to the grid, it is also possible to direct the dc directly to the electrolyser without first passing through the inverters.

The performance of photovoltaic modules depends on weather conditions, temperatures, orientation, light dependence and more. The STC (standard test conditions, irradiance 1000 W/m^2, module temperature 25 °C, spectrum AM 1.5) differs from the actual meteorological conditions, and thus the performance of the module is somewhat different. The annual loss factor is calculated by Naps Systems AB, on the system delivered to GlashusEtt, including meteorological data at the site as well as losses in inverters and cables. This factor is thus the difference between the STC rated efficiency and the electricity (ac) delivered to the house.

3.3. The electrolyser

The electrolyser (Table 3) is situated in close proximity to the fuel cell system and consists of PEM cells. It is connected to the grid and can thus be operated on ac as well as on dc directly from the PV array. The hydrogen output goes directly to a hydrogen storage situated on the roof.

Table 3
Data for the electrolyser

Model	HOGEN 20
Delivered by	Proton Energy Systems
Stack type	Proton exchange membrane
Hydrogen produced	Approximately 0.6 Nm^3/h
Rated efficiency	48%
Delivery pressure	13.8 bar (g)
Dimensions (L × W × H)	0.97 m × 0.785 m × 1.06 m
Weight	Approximately 230 kg
Power consumption	6.3–9.0 kWh/Nm^3 H_2

Table 4
Data for hydrogen storage

Delivered by	AGA Linde Gas
Total capacity	15 Nm^3
Delivery pressure	13.8 bar (g)
Weight	Approximately 1450 kg

3.4. Hydrogen storage

The hydrogen storage (Table 4) consists of 10 horizontal and 12 vertical standing 50 l gas bottles. No external compressor is used, i.e. the storage pressure has a maximum of 13.8 bar (g), and thus the total capacity amounts to approximately 15 Nm^3 of hydrogen.

3.5. The biogas burner

The biogas burner is connected to a temperature sensor on the outside of the house and to a correlation curve that, depending on the temperature outside, sets a lowest temperature for the water in the accumulation tank. The biogas delivers a thermal output of 24 kW, and may only be turned on and off, i.e. no partial loads are possible.

3.6. The control and logging system

The control system (Table 5) is installed in order to monitor the alternative system and its components. Relevant data, such as the mass flow in the external coolant loop to the fuel cell system, the amount of electricity, thermal energy and hydrogen consumed or produced by the various components, are continuously logged every minute. Data is also taken and logged from the weather station on the roof, measuring the irradiance, wind speed, humidity and precipitation.

The fuel cell system and the electrolyser also contain a small control system each. It is mainly used for trouble shooting, but also in the monitoring process of different activates in the fuel cell system and electrolyser. The data from the fuel cell system has been used to compare the data logged by the alternative energy control system.

3.7. Measured results from the alternative energy system

The first measured results from the system have been used as a basis for the assumptions. The results have been used to calculate the electrical and thermal efficiency of the fuel cell system as well as the efficiency of the electrolyser. The efficiencies were assumed to be constant since no part-load operation has been performed. The efficiencies were further calculated using the lower heating value (LHV) of the biogas, and in the electrical efficiency calculation of the fuel cell system the delivered ac power after the inverters was used. This resulted in an electrical efficiency of 13% and a thermal efficiency of 56% for the fuel cell system, and an efficiency of 43% for the electrolyser.

Table 5
Information about the control system

Delivered by	ABB Utilities
Platform	Industrial IT
Controller	Advant 800 M
Input signals	61 logged each minute
Calculated values	29 logged each minute
Remote monitoring	Via PC anywhere

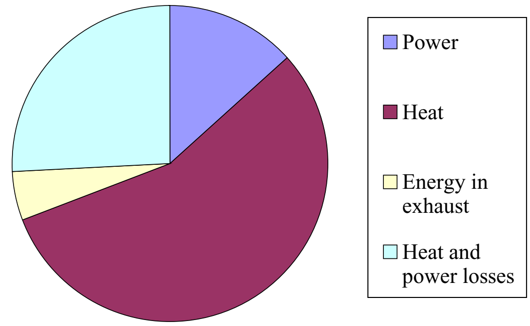

Fig. 4. Approximate energy balance of the fuel cell system. The average input of biogas was 20.4 kW. Exhaust gases are assumed to take 5% of the input fuel.

An approximate energy balance of the fuel cell system can be seen in Fig. 4 in which 5% of the input energy is assumed be lost through the exhaust. The waste heat (25.6% of the biogas input (LHV)) delivered to the room caused the temperature to rise 8 °C.

3.7.1. Delays

There are a few time delays measured on the real system. The electrolyser has a 20 min warm-up delay according to the manual, but start sequences down to few minutes has been measured. The fuel cell system has a start delay of 90 min when operated on biogas. This is the time it takes from the moment the start button is pushed to the moment when the fuel cell system delivers electricity to the inverter. When the fuel cell is operated on hydrogen the start delay is 40 min.

4. The simulation model

4.1. Ambition

The model is constructed with the clear purpose of evaluating different control strategies for the alternative energy system. It should be possible to draw conclusions about different strategies with regard to an economic as well as an energy perspective. The primary use of the model is to look at short time periods. The time step lengths are therefore optional, ranging from minutes to hours, and the overall evaluation period could be as short as a day. In this model the evaluation is based on demand curves, investment costs, electricity prices and irradiation in order to evaluate electrical and total efficiencies as well as economic parameters, such as total costs and costs per kWh.

The model is an empirical model, i.e. mainly based on empirical data from the system being evaluated. The ambition has been to take as much data from the actual system as possible to ensure that the results from the model are based on real data, but also to simulate an existing system, with all its virtues and shortcomings. The model was developed in MATLAB Simulink.

The economic part of the simulation is included in the same model and carried out simultaneously with the rest of the simulation. This facilitates the evaluation process. It is possible to follow the cost development during the simulation. Simulink might not be the optimal simulation program for economic evaluations, but it is advantageous to compare the different curves within the same type of diagrams, with exactly the same graphics, scales and evaluations properties. It also facilitates comprehension, i.e. where different costs are generated and when.

4.2. Potentials

The model contains, at present, 25 diagrams that are continuously updated for every simulation to evaluate different flows, efficiencies and economic parameters. Ranging from consumed biogas and produced electricity by the photovoltaic array to economic properties including costs per kWh and the total cost of the electricity bought. It is possible to choose different evaluation criteria with only small modifications in the model. Further, all input data, including efficiency, demand and irradiance tables are easily exchanged. With mainly parameter value changes, it is possible to apply this model to different houses and different configurations of solar-fuel-cell systems.

4.3. Efficiency assumptions

Efficiencies for the fuel cell system as well as the electrolyser are assumed to be those presented in Section 3.7. The assumption concerning the efficiency of the photovoltaic system is based on product information from the supplier (Naps Systems, Oy) who specifies a single module efficiency of 11.9%. Naps Systems have performed a theoretical study on the actual system with all relevant data, such as location, (59.35° N, 17.95° E, 12 m above sea level) temperature, and irradiance. Naps Systems reached an annual loss factor of 27.8%, giving an average annual system efficiency of 8.6% (compared with 11.9%), for use in the model.

According to the product information sheet of the inverters, an efficiency of up to 93% should be attainable, but analyses carried out in an installation in Älmhult, Sweden, showed efficiency closer to 90% [17], and thus this later efficiency has been used in the model.

4.4. Economic assumptions and reference system

The aim has been to avoid assumptions about future costs as far as possible since it has been proven hard to do accurate predictions about future costs.

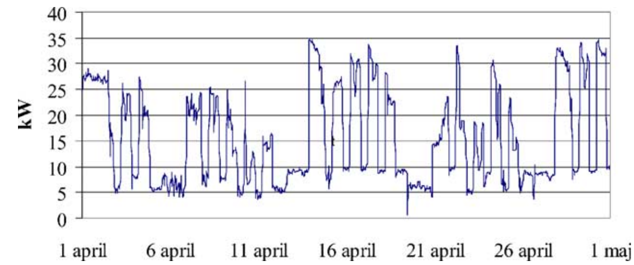

Fig. 5. The thermal energy demand in GlashusEtt, generated from an estimated average demand of 15.6 kW applied to fluctuations measured in Aronssons study.

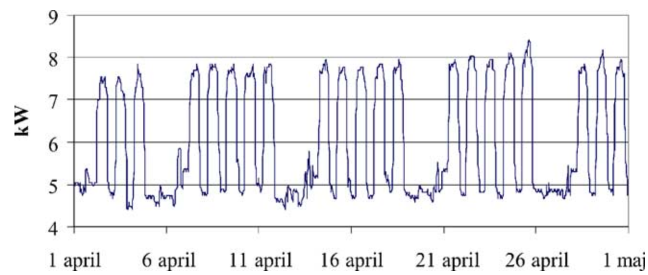

Fig. 6. The electricity consumed in GlashusEtt, generated from an estimated average consumption of 6 kW applied to fluctuations measured in Aronssons study.

Actual costs of the components installed in GlashusEtt have been used in the economic simulation. The biogas cost consists of an annual cost of 369 SEK,[1] and an energy cost of 8.36 SEK/m^3, the electricity cost for private persons (including tax and grid charge) under the simulation period was 0.72 SEK/kWh.

The economic simulation contains a reference system. In the reference system, the electricity costs are calculated as if all electricity, generated by the fuel cell system and the photovoltaic array, was to be bought from the grid. Fuel costs are calculated as if a biogas burner supplied the thermal energy supplied by the fuel cell system.

4.5. The building's heat and power demand

The simulated time period for the studies presented in this paper is one month (April). The only available numbers concerning both the thermal and electrical demand in the house were total consumption figures. To distribute this demand to hourly mean values, reasonable for the season, an earlier study [18] was consulted. The relative fluctuations in that study were calculated and applied to the estimated average thermal demand of GlashusEtt to ensure a realistic load profile (Fig. 5).

The same method was applied to the electrical demand. An average was estimated from total consumption figures available in GlashusEtt. The hourly average was calculated and applied to Aronssons relative fluctuations (Fig. 6). Both

[1] 1 € = 9.02 SEK, 20 September 2003.

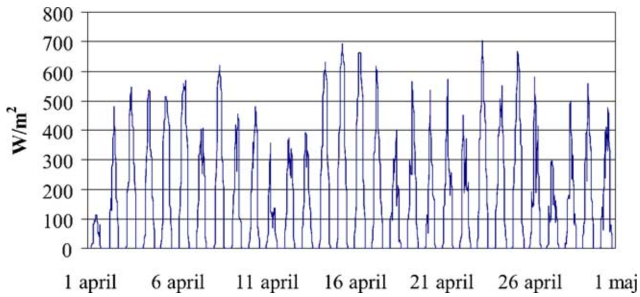

Fig. 7. Hourly mean values for the irradiance in April generated from known total irradiance in April 2000.

the electrical and thermal demand curves that are generated through this method can easily be altered and the appropriate time period may be chosen for the specific simulation.

4.6. Environmental conditions

4.6.1. Irradiance

The irradiance was available in monthly averages. PVsyst is a 'PC software package for the study, sizing and data analysis of complete PV systems' [19], and used to convert these monthly average values into useful data. PVsyst also includes the useful feature to do synthetic hourly data generations. In this process PVsyst uses known average monthly values to construct hourly meteorological data. The data in the model are constructed from the April average taken from an earlier study [20], which was performed to establish the irradiance incident on GlashusEtt (in order to calculate the contribution from the sun since it is a glass façade) (Fig. 7).

4.6.2. Outdoor temperature

Temperature differences from the relevant period (April) (Fig. 8) were taken from an earlier study [18]. The average temperature was altered to be 4 °C.

4.7. Control strategy

It is assumed, in this first evaluation of the alternative energy system, that the fuel cell system as well as the electrolyser operates on a constant power level with constant efficiencies. This is due to the fact that the system has not been operated at part-load yet, and thus no input data exists. The time delays measured on the system were used in the model.

The control strategy utilised involved operating the fuel cell system on hydrogen (produced by the electrolyser) every second week.

5. Results

5.1. Results from a standard simulation

In this chapter the results from a standard simulation with the semi-empirical simulation model is presented. The standard case is based on the conditions described above, i.e. the time range is 1 month. The simulation results are viewed within 25 evaluation diagrams, of which eight are displayed in Fig. 9 here.

Diagram 1:2 clearly indicates that the alternative system is unable to supply the electricity demand in GlashusEtt, which implies that even if it would be possible to sell electricity to the grid, there was no opportunity to do so during this simulation period. The hydrogen storage tanks can be seen to be emptied after 4 h of hydrogen operation, and refilled by the electrolyser within 34 h (diagram 1:4). The burner can in diagram 2:3 be seen to often turn on and off; nevertheless a lot of thermal energy has to be rejected on the roof (diagram 2:4).

5.2. Evaluation of thermal control strategies

Different control strategies to minimize the amount of thermal energy lost on the roof could be evaluated with the help of the simulation model. For example, two hypothetical correlations curves to the biogas burner were simulated in combination with two different stop levels. The stop level is the temperature in the hot-water-storage tank for which the biogas burner turns off. The stop levels for the biogas burner were 105 or 120% of the starting level, which in turn is determined by the correlation curves in Fig. 10.

The thermal simulation shows that the choice of correlation curves and stop percentage does not affect the outcome

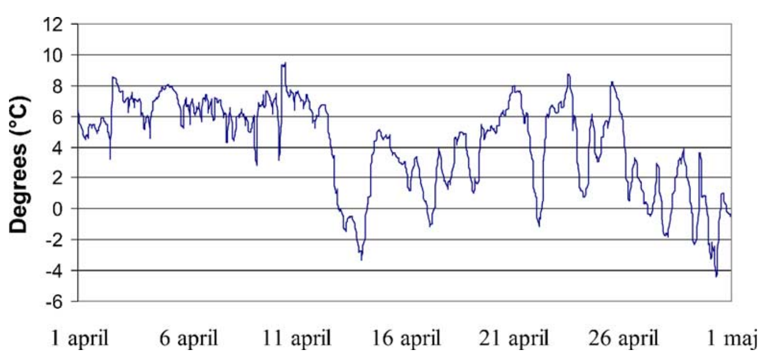

Fig. 8. The outdoor temperature fluctuations in April, generated from an average temperature of 4 °C and the fluctuations taken from an earlier study [18].

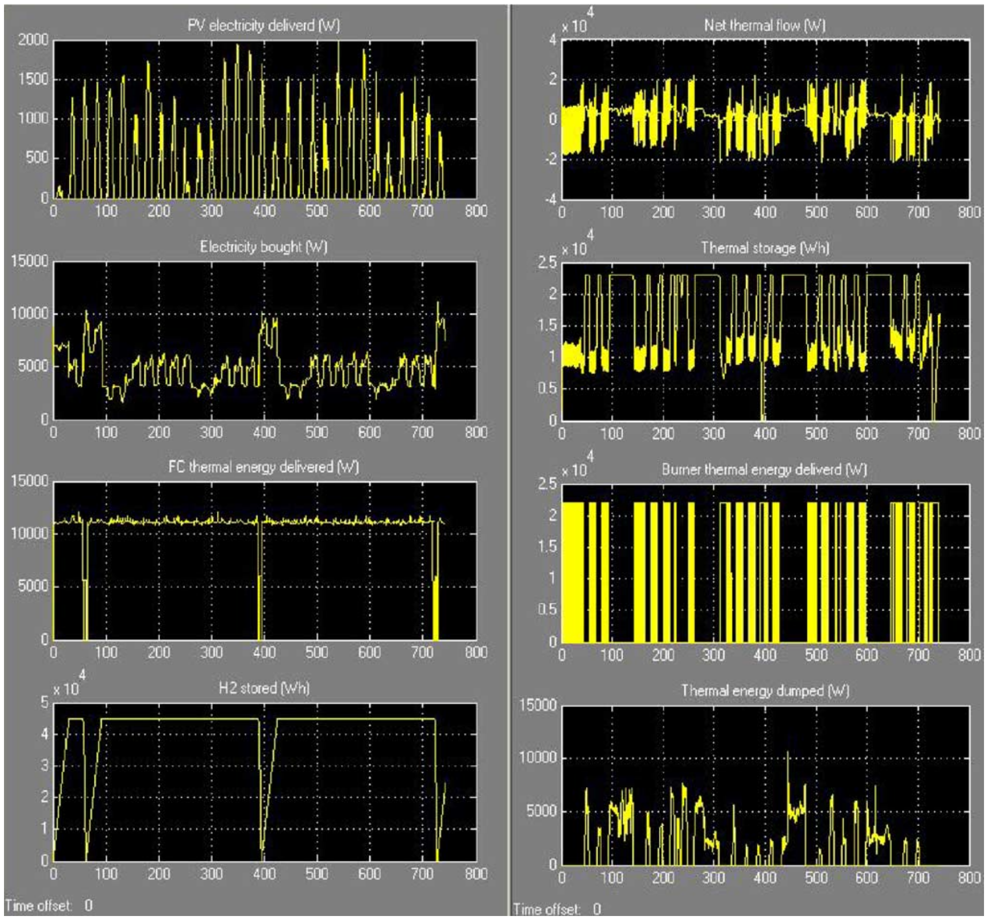

Fig. 9. The simulation results for the standard case during 1 month (0–744 h). In the first column from the top, 1:1: delivered electricity from the photovoltaic array; 1:2: electricity bought from the grid; 1:3: thermal energy delivered from the fuel cell system and 1:4: amount of hydrogen in the hydrogen storage. The second column from the top, 2:1: net thermal flow to and from the accumulator tank; 2:2: thermal energy in the accumulator tank; 2:3: delivered thermal energy from the biogas burner and 2:4: thermal energy lost on the roof.

significantly, see Fig. 11. This is due to the facts that (1) most of the thermal energy lost during this time of the year results from a lower heat demand than the total heat supplied by the fuel cell system and (2) the small accumulator tank (500 l) in combination with the relatively low maximum temperature set by the cooling demand of the fuel cell stack (60 °C) is not big enough to function as a thermal storage over time, as shown in (Fig. 9, diagram 2.2).

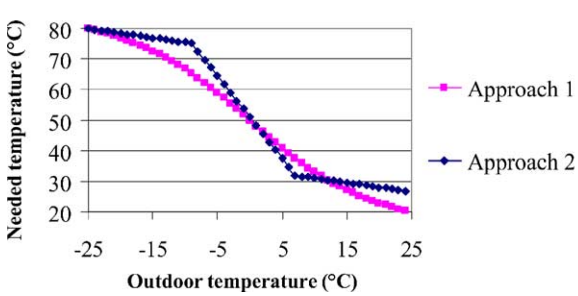

Fig. 10. Two hypothetical correlation curves for the biogas burner, determining which temperature is needed in the accumulator at specific outdoors temperature.

5.3. Electricity and fuel cost

In this study, the fuel costs of the alternative energy system are compared with the fuel and electricity costs of the reference system presented in Section 4.4. All produced heat and electricity was assumed to be used in the building. The

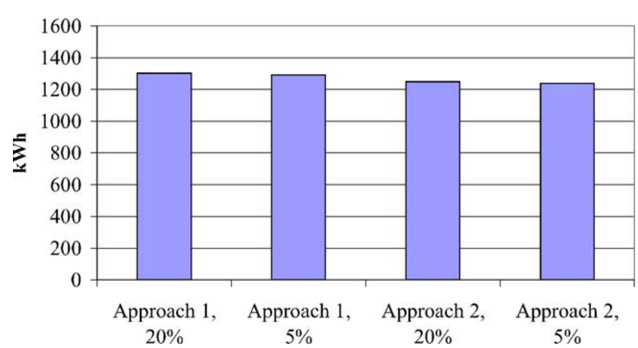

Fig. 11. Lost heat on the roof for four different control strategies for the biogas burner. None of the strategies can be seen to significantly reduce the amount of energy loss.

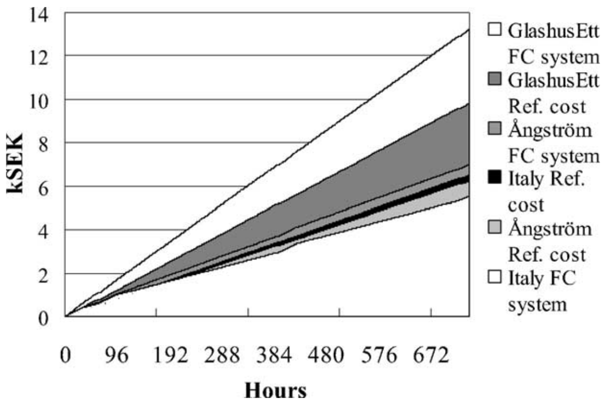

Fig. 12. Comparison of fuel costs during one spring month for the three different cases presented in Table 6.

aim of this study is to find out how the difference in fuel costs affects important parameters of the alternative system, such as: if the fuel cell system could be allowed to loose heat during summer, if the fuel cell system could be allowed to be more expensive, or maybe have a shorter lifetime than conventional systems.

A cost limit in fuel prices is investigated, under which fuel cell systems would be theoretically competitive. Of course, problems concerning longer lifetimes, lower costs, and fuel infrastructure have to be solved, but if this cost condition is not met those solutions would not help in a general installation. It is clearly seen in Fig. 12 that the alternative energy system has a significant higher fuel cost than the reference system in the GlashusEtt simulations case. The combination of a low electricity price and a high biogas price is the main explanation to this phenomenon. Furthermore, the present cost for the alternative energy system in GlashusEtt has been compared in Fig. 12 with two more cases that are presented in Table 6.

One minor change from the GlashusEtt simulation compared with the two following cases is that the PV array has been left out in those simulations. The simple reason is that when investment costs are ignored, the PV array only contributes by lowering fuel cost for the alternative energy system, since it does not consume any fuel or electricity. On the other hand, the relatively low efficiencies of the components in GlashusEtt is kept through all simulations on purpose to avoid assumptions on future properties.

In the Ångström simulation, the biogas cost has been reduced to half of that available in GlashusEtt, and furthermore, the electricity price has been raised to 1.10 SEK/kWh,

Table 6
Electricity and fuel cost simulation parameters

Simulation	Electricity cost (SEK/kWh)	Biogas cost (SEK/Nm^3)	Excluded components
GlashusEtt	0.72	8.36	None
Ångström	1.10	4.16	PV array
Italy	1.81	3.03	PV array

which would be the production cost if scientists at Ångström Solar Centre, Uppsala, Sweden, would reach their cost goal of 700 SEK/m^2 for large scale thin film solar cell production [17]. Even so the reference system still generated a lower total cost. In the Italy simulation the costs of electricity for households in Italy [21] and the average natural gas price in Europe [22] was applied. The simulation indicates a lower fuel cost for the alternative system than for the reference system.

The difference in total cost in the GlashusEtt simulation suggests that the alternative system must have an investment cost of 300,000 SEK [14] less than a conventional system in order to be competitive to a conventional system. On the other hand in the Italy simulation illustrated in Fig. 12, the alternative system would be allowed to cost 80,000 SEK [14] more then the reference system, assuming equal lifetimes for both systems, and still be economically competitive.

6. Discussion

The alternative energy system in GlashusEtt is an evaluation and demonstration facility, and as such it has not been optimised for GlashusEtt. Furthermore the results are the first results from the system, which is continuously improved. The rated thermal effect given was 6.5 kW from the supplier, but the measured one is almost the double. The large thermal contribution from the fuel cell system indicated by measurements in GlashusEtt is not fully understood. It was simply assumed that the thermal contribution was the one measured.

Limitations in the presented simulations is the relative short simulation period (1 month) assumed steady state operation, including the constant (low) efficiencies of the fuel cell system as well as the electrolyser, and the fact that the system is under dimensioned and thus that all produced energy, (thermal and electrical) is utilized. However, the result from the first simulations demonstrates the possibilities and limitations of the alternative system as well as they indicate areas of interest for continued research.

The relatively constant increase in the fuel cost simulation in Section 5.3 is a result of the above mentioned constant operation conditions. If the fuel cell would be operated more dynamic and with different efficiencies at different loads the curves in Fig. 12 would be fluctuating more and fruitful conclusions might be drawn. The results and use of this perspective would become even more interesting if the electricity cost would be allowed to fluctuate on an hourly basis as on the Nordic energy market, Nordpool.

The economic simulations further indicate that small-scale stationary fuel cell systems are going to have their first European applications in the south. It is the internal relationship between fuel cost and electricity cost per kWh, which is the prevailing factor if fuel cell systems in this sort of applications could be competitive as also shown in an earlier study [23].

In this specific configuration, the fuel costs had to decrease significantly in combination with a slightly higher electricity cost in order to make the alternative system competitive. Another system with higher efficiencies would certainly produce even more favourable economic figures in the Italy simulation. Simulations with fuel cost could be extended to include investment cost and maintenance costs, but it has been shown almost impossible to make correct predictions about future equipment costs and maintenance costs, that is why this 'reversed' economic perspective is utilised.

7. Conclusions

7.1. The alternative energy system

A solar–hydrogen–biogas-fuel cell system has been installed in GlashusEtt, Hammarby Sjöstad, Stockholm, Sweden. The system includes a photovoltaic array, a fuel cell system, an electrolyser, hydrogen storage and a separate control system. The components in the alternative energy system installed in GlashusEtt are in operation and are under evaluation.

The system has been proven to work on both biogas, and hydrogen produced by electrolysis of water. The first results indicate a efficiencies close to or below the rated efficiencies of the included components. The electrical efficiency of the fuel cell system is lower than rated whereas the thermal efficiency is higher.

7.2. The semi-empirical simulation model

A simulation model is constructed for the evaluation of the alternative energy system in GlashusEtt. The aim with the model is to enable evaluation of control strategies. It is possible to draw conclusions about different strategies with regard to an economic as well as an energy perspective. The model is based on the on-site experimental results.

The simulation results from the simulation case named Italy suggest that the installation and maintenance cost of this specific system may exceed a conventional system with 10,000 € and still be competitive. The results also indicate that today's fuel costs in Sweden is unfavourable for the system configuration in GlashusEtt.

The model could be used for dimensioning of new components for the alternative energy system. It is clear from simulations that the size of the thermal storage not is optimised for this installation. A larger accumulator tank then today's 500 l, would probably reduce the heat cooled off on the roof. With a larger photovoltaic array, the costs for bought electricity for internal use in the alternative system could be improved.

8. Future work

Future work includes fine-tuning and problem-solving in order to replace the assumptions made in this paper with empirical data taken from the control system, and also to investigate the reason behind the fluctuating efficiencies and the large thermal contribution of the fuel cell system.

It might be possible in the near future to operate on variable loads. Thus further development of the model would be needed to include more advanced dynamic features and evaluate transient events.

It would also be interesting, in a dynamic model, to include economic parameters as control parameters, e.g. one of the many concepts for the future that is frequently discussed is the possibility to sell electricity to the power grid when the electricity price is favourable and buy electricity when that possesses the best option. Such a control strategy would certainly be possible to include in the model.

Acknowledgements

Dr. Peter Wilson, University of Southhampton, is acknowledged for supplying his early Simulink models (described in [24]) which were used for ideas in the development of the simulation model.

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