DEVELOPMENT AND DEMONSTRATION OF DANISH FUEL CELL BASED MICRO COGENERATION

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ABSTRACT

Denmark has the largest share of cogenerated electricity in the world (60% of electricity produced). Most of the production units are connected to district heating systems. The future potential of increased cogeneration in Denmark is within industrial processes and micro cogeneration.

For a long time Denmark also holds a strong scientific position in fuel cell research. Based on this, a national demonstration program for fuel cell based micro cogeneration (µCHP) was started in 2005/6 including field tests of up to three fuel cell technologies. The third phase ends in 2013.

Calculations have shown that approximately 100% of the annual electricity demand in a standard Danish single-family home can be produced by a micro cogeneration unit in a thermal load-following operation mode. 50% of this electricity is exported to the grid. A backup boiler and a storage tank are other important parts that may be included in the heating system. The overall system performance has been addressed from an early stage of the project. Storage heat loss, water temperatures and the internal electricity consumption in the cogeneration unit have been studied.

Hydrogen fuelled low-temperature PEM (Polymer Electrolyte Membrane) systems (1.5 kW_e) are field tested in a small hydrogen grid within the project. Hydrogen is locally produced. The electric efficiency is 47% (lower calorific value, LCV) at full load ($H_2 \rightarrow$ AC), and the overall nominal efficiency is 94%.

Natural gas fuelled low-temperature PEM (0.9 kW_e) are also field tested. The electric efficiency is approximately 34% at nominal load (natural gas $\rightarrow$ AC), and the overall efficiency is 95–100% (LCV).

The SOFC (Solid Oxide Fuel Cell) systems are the last to possibly enter field tests. They are natural gas fuelled, and two versions have undergone laboratory performance testing within the project.

The paper will address the following topics:

- Technical design of the micro cogeneration units
- Data and statistics from the field tests
- System integration
- Challenges for the future

Keywords: fuel cells, micro cogeneration, system design, operation, field tests.

INTRODUCTION

The Danish power generation system has undergone a major reshape during the last 30 years. Central coal-fired power plants have partly been replaced, firstly by gas-fired cogeneration plants in district heating grids and secondly by wind power. Today, the Danish power generation is divided between different technologies as shown in figure 1.

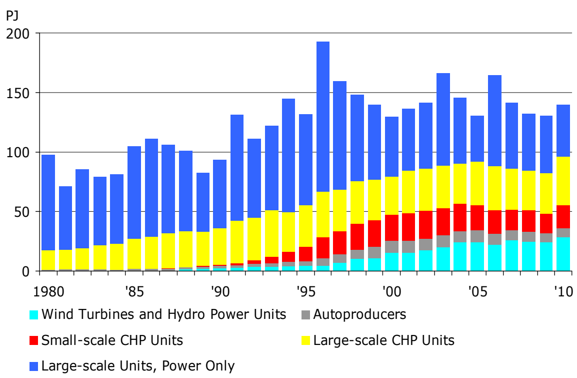

Figure 1: Evolution of Danish power generating sources 1980-2011.

No other country in world has as large a share of electricity from cogeneration plants as Denmark. The CO_2 emission has been reduced from 937 g/kWh (1990) to 505 g/kWh (2010) due to fuel switching, cogeneration and wind power [1]. The long-term Danish political goal is a fossil-free energy supply in 2050. One step worth noticing in the energy agreement in the Danish parliament [2] is that gas boilers are generally not allowed in new single-family houses from 2013 and oil boilers in single-family houses are to be phased out.

The remaining potential for expanded cogeneration is as industrial cogeneration and as micro cogeneration in the Danish residential sector. A study [3] shows that the technical potential for micro cogeneration in Denmark is 1,100 MW_e for units connected to the gas grid and with an output of maximum 15 kW_e.

The electricity and heat production from micro cogeneration units has been simulated in order to evaluate different operation strategies and cogeneration unit sizes. The operating strategies are heat controlled and electricity controlled. The cogeneration output is controlled by the thermal energy demand in the heat controlled operation. Surplus electricity is exported to the grid. The operation is securing a high overall efficiency. Selected results for a heat controlled strategy are shown in table 1. A base load cogeneration unit with an electrical output of 1.0 kW_e and a larger unit capable of covering the heat demand are compared. The house has an annual electricity consumption of 5,000 kWh, a space heating demand of 12,000 kWh and an annual hot water demand of 5,000 kWh. The heat-to-power ratio of the cogeneration unit is assumed to be 2. It corresponds roughly to a unit with 30–35% electrical efficiency. The electricity consumption pattern used in the simulations was based on earlier 15-minute measurements of the electricity consumption in a number of Danish single-family houses.

Table 1 shows that a micro cogeneration unit sized for base load will get a satisfactory utilization time in single-family houses. The electricity generation equals approximately 100% of the electricity demand in the house. Due to the actual electricity demand 45% will be used in the house and 55% exported to the grid. The larger load-following unit is sufficient for the entire annual space heating and hot water demand, but does not supply the entire electricity demand. Instead, a large part of the electricity is exported to the grid, which in most circumstances will not be financially attractive for the consumer. A heat storage facility makes long full-load operation possible, thus reducing load and thermal cycles which are amplifying the degradation processes in fuel cells.

Table 1: Example of calculated micro cogeneration electricity and heat production in a Danish single-family house, heat controlled operation.

	Base load	Load following
Max. power CHP (kW_e)	1.0	3.3
Elec. production (kWh/a)	4,545	8,500
Elec. export to grid (kWh/a)	2,307	5,175
Elec. prod. in-house use (kWh/a)	2,238	3,325
Share of elec. demand (%)	45	67
Heat prod. (kWh/a)	9,090	17,000
Share of heat demand (%)	53	100
Full load equiv. (h)	4,545	2,575

Micro cogeneration is one of the possible new gas applications in the residential gas sector. Gas-fired cogeneration reduces the carbon footprint through a higher utilization of the primary energy compared to power generation in a steam cycle and separate heating in the dwellings. Other new gas-fired options are direct gas-fired heat pumps and hybrid systems consisting of an electric heat pump and a gas boiler for peak loads and hot water production. Using solar energy and heat pumps introduces renewable energy into the gas heating system. These are all examples of new gas-fired technologies that improve the primary energy utilization.

These new technologies also make it possible for greener natural gas to be distributed to the customers. Carbon neutral biomethane from anaerobic digestion is already injected in small volumes at several places in for example Germany and Sweden. Denmark has currently only one site where upgraded biogas is injected into the natural gas grid. In a few years it will be possible to supply methane from biomass gasification into the gas grid. Excess wind power may be used for hydrogen production which can be directly injected into the gas grid or converted to methane together with carbon dioxide in the Sabatier process.

A number of examples of integrating the gas and electricity grids into a smart grid are mentioned above. Micro cogeneration and hybrid systems (electric heat pumps and gas boilers) are technologies at the consumer level that also give the possibility of external control in order to use renewable energy as best as possible. Converting excess wind power into hydrogen is a way to store electricity in the gas grid.

Micro cogeneration is one way to reduce the carbon emissions. Other new heating and power generating technologies also offer emission reducing options for the consumer. Photovoltaics, heat pumps and also district heating are technologies that compete with fuel cell micro cogeneration. Both technical and political issues will play an important role.

DANISH FUEL CELL DEMONSTRATION PROGRAM

In a joint effort to develop micro cogeneration fuel cell units a number of Danish enterprises are developing and demonstrating such units. The project partners represent the entire chain from research companies to gas and electricity utilities. The project started in 2006 and ends in 2013.

The fuel cells in the field test are installed in two different gas grids, which are shown in figure 2. Natural gas fuelled low-temperature PEM and SOFC units are connected to the natural gas grid. Hydrogen fuelled low-temperature PEM units are installed in a more future oriented hydrogen grid in a small village. Hydrogen is locally produced in an electrolyzer.

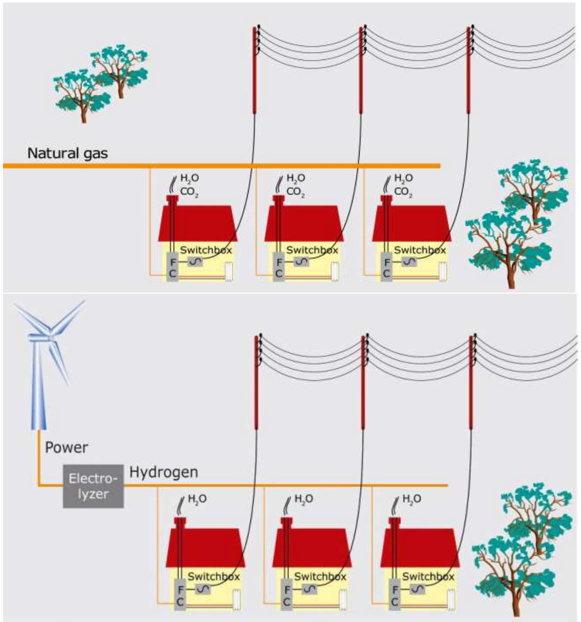

Figure 2: Two energy system designs for fuel cell operation.

The main difference between the units connected to the natural gas grid and the hydrogen grid respectively is the absence of a fuel reformer in the latter case. Hydrogen units are expected to show a significantly higher electrical efficiency than the natural gas fuelled low-temperature PEM units.

A similar ongoing demonstration program is the German Callux program.

Method

The method used in the Danish project is a straightforward one. The system integrator develops the micro cogeneration unit, adding the necessary balance of plant (BoP) parts such as heat exchangers, reformer, inverter and cooling. The demonstration program involves system integrators that develop the entire system from the stack design to system integrators using parts from other developers. Danish Gas Technology Centre (DGC) performs safety analysis and laboratory performance testing. The fuel cell based unit is tested separately regarding performance and benchmark, and later for CE certification in the DGC laboratory.

Test plans for each fuel cell version have been developed independently by DGC, based on the fuel cell standard IEC 62282 [4]. The European Union Gas Appliance Directive is applicable for the fuel cell units. The tests include performance and safety aspects. The CE marking is valid for the specific test site only. The project partners have gained in this exercise, much experience which is essential when commercial units rather than prototypes are to be built.

Field test data is collected and sent to DGC for continuous evaluation during the field test. The project contains three phases, which can be described as proof of concept, early field test and field test with improved units. Each project phase contains performance and cost targets.

FUEL CELL UNIT DESIGNS

The description of the different fuel cell units refer to the phase 3 design.

Hydrogen low-temperature PEM units

The hydrogen fuelled cogeneration units have been both laboratory and field tested in project phase 2 and 3. The hydrogen low-temperature PEM units are developed and built by IRD. The stacks are also from the same company. The stack gross output is 1,660 W_{DC} and net (230 V) output is 1,500 W_{AC}. The stack is water cooled. The performance data from laboratory tests are shown in table 2. The start-up time is defined as the time from cold start until electricity can be delivered.

Table 2: IRD hydrogen PEM Gamma 1 laboratory performance.

Parameter	Value
Stack gross output (W_{DC})	1,660
Unit net output (W_{AC})	1,500
Unit heat output (W)	1,500
Gas supply pressure (mbar)	400
Operating temperature (℃)	67
Net electric efficiency (%)	47
Heat efficiency (%)	47
Overall efficiency (%)	94
Start-up time (min)	2
Stand-by power (W_{AC})	15

Figure 3 shows at the top an image of the fuel cell unit in preparation for wind tests. The unit is designed as a closed unit where air and exhaust is transported in a standard gas boiler balanced flue. The vertical air and flue terminal passes through the simulated roof. Air speeds up to 12 m/s towards the terminal exit are used to check the sensitivity to heavy wind.

The inverter in the IRD Gamma 1 version is located in a separate box to allow flexibility in the installation. The wall-mounted fuel cell installed at a field test site is seen at the bottom of the image.

Figure 3: IRD hydrogen PEM Gamma 1 unit for phase 3 in laboratory tests and installed at a field test site.

Natural gas low-temperature PEM units

The natural gas PEM units are designed and built by Dantherm Power. The unit contains a fuel cell stack from Ballard and a Japanese reformer. These units have a fixed output and do not have the modulation capability like the hydrogen fuel cell. Laboratory performance data is shown in table 3.

Table 3: Dantherm natural gas PEM Beta laboratory performance.

Parameter	Value
Unit net output (W_{DC})	900
Unit heat output (W)	1,650
Gas supply pressure (mbar)	20
Operating temperature (°C)	65
Net electric efficiency (%)	33.6
Heat efficiency (%)	54.9
Overall efficiency (%)	88.5
Start-up time (min)	56

The exhaust flow is cooled as much as possible, and the exit temperature is approximately 10 K higher than the return water temperature to the unit. The exhaust temperature is then clearly below the dew point. Integrated burners are used for heat generation. The NO_x emissions are below the instrument detection limit of 2 ppm.

Figure 4 shows a phase 3 field test unit in a single-family house. Natural gas is supplied through the copper piping. The maximum natural gas input is 2.7 kW. The air and flue terminal is located at the top of the cabinet. There is a potential for significant size reduction in future versions.

Figure 4: Dantherm natural gas PEM Alpha in phase 3 installed at a field test site.

Natural gas SOFC units

The SOFC units have a stack developed and designed by Topsoe Fuel Cells. Integration of the stack in a micro cogeneration unit is made by Dantherm Power.

Due to the less mature SOFC technology compared to the PEM technology the units have so far not been field tested. Tests have been done at the manufacturer and at DGC. The work has focused on the stack durability and degradation issues, accelerated tests, eliminating the need for protecting gases and size reduction. The design has evolved from the planar fuel cell stack and separate balance of plant parts into an integrated package incorporating the fuel cell stack, natural gas reformer, start-up burner, off-gas burner, heat exchanger and heat insulation. The unit (PowerCore) generates 1.5 kW_{DC}. The stack is air cooled and operates at approximately 750°C.

The required gas pressure is low enough, 20 mbar, for the unit to be connected to the distribution gas grid.

FIELD TEST SITE SELECTION

An important and useful part of the demonstration project has been to move the cogeneration units from the developer to the certification laboratory and finally to the field test sites. Invaluable experience has been collected on the installation and operating aspects through these steps. However, the complete installations including the fuel cell unit, heat storage facility and supplementary boiler were not tested as a system before the field test began. The reason being that existing heat generators in the buildings act as back-up or supplementary heater.

Many of the field test sites are ordinary single-family homes. The fuel cells will then operate in as real conditions as possible. The test sites will also present real installation aspects valuable for the developers, installers and service companies engaged in the project. The test sites were selected among the consumers that showed an interest in the project at presentation meetings for the inhabitants in a selected area. The energy utilities played an important role in this selection.

FIELD TEST RESULTS

The cogeneration units' internal data acquisition systems are used in the ongoing field tests. The sampling frequencies for the field test evaluation are 6 minutes for the hydrogen fuel cells and 60 minutes for accumulated and momentary values for the natural gas fuel cells. The internal sampling frequency is 10 seconds. Data is transmitted to DGC for evaluation.

Hydrogen low-temperature PEM units

The hydrogen fuel cells are connected to a small hydrogen distribution grid in the village of Vestenskov 150 km south of Copenhagen. The overall grid length is 500 m and the pipe material in phase 2 is stainless steel. PE (Polyethylene) is used in phase 3. Hydrogen is produced in commercial alkaline electrolyzers with a capacity of 32 m^3/h. Gas pressure in the grid is 4 bar.

5 fuel cells were tested in phase 2, and 30 will be tested in phase 3. The hydrogen PEM fuel cells are installed with a 200 l heat storage tank. The existing heat generator acts as back-up and supplementary heater.

The faults experienced in the second project phase for the hydrogen PEM fuel cells are shown in figure 5. It is clearly seen that a large share of the faults are related to the communication and control system. The fuel cell stack was responsible for only a small part of the faults. The fault distribution resembles the fault distribution in early Japanese fuel cell demonstration projects.

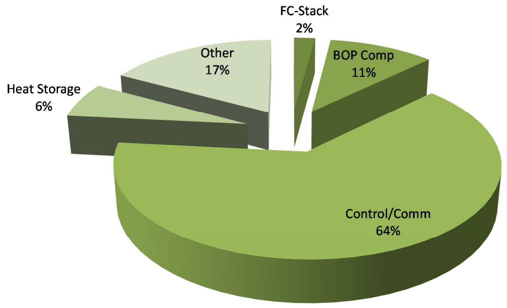

Figure 5: Fault statistics for hydrogen PEM units, phase 2.

Ten (10) hydrogen fuelled micro cogeneration units are presently installed in Vestenskov. Another 20 units will be installed from December 2012 to January 2013. Two of the ten units have been in operation for a full year. One of these two units has been operated on a continuous-mode basis and one unit has been operated according to a simulated smart-grid operation with four full thermal cycles a day. Figure 6 shows the daily operation during this period. The operation pattern is five hours of full load followed by one hour of zero load and cooling. Observe the quick response from the cold stage to full AC power output. The hydrogen fuelled PEM unit fulfils every transient response necessary for a smart-grid ready cogeneration unit.

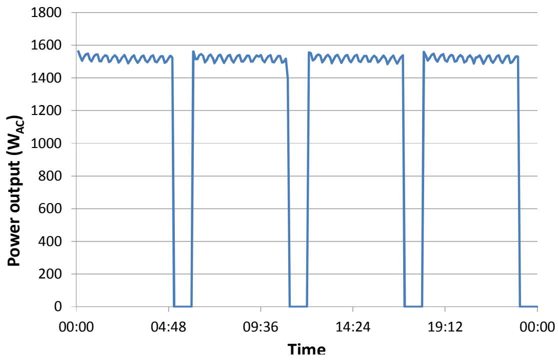

Figure 6: Operation pattern for a hydrogen fuel cell CHP unit in a simulated smart-grid situation (House 1).

The two units have obtained the following operational hours during the first test year: 6,000 and 4,000 hours, respectively. The hydrogen fuelled µCHP unit in continuous operation has provided 86% of the house heat and hot water demand during the heating season 2011/12; and 97% of the demand during the summer 2012. The smart-grid operated unit has provided much less of the thermal demand, not only because of the operational pattern, but mainly due to being installed in an old un-insulated house.

Figure 7 shows the operation from October 2011 until the end of June 2012 for one selected site. Accumulated data for periods of four weeks are shown in the bar graphs. At the end of the period shown in the graphs the unit operation time had reached 6,500 hours. During this period has the unit produced 6,700 kWh electricity and 8,900 kWh heat.

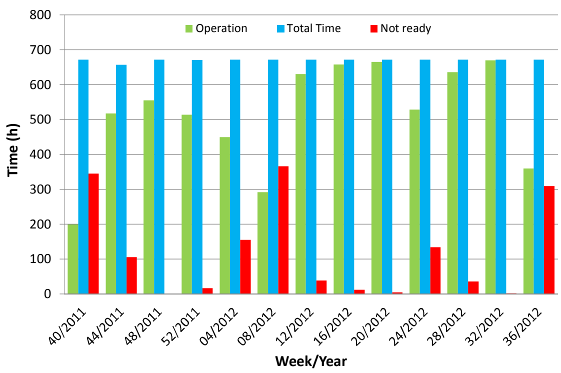

Figure 7: Operating example for a hydrogen PEM Gamma 1 fuel cell unit (House 18).

The unit covers a large part of the heating and hot water demand at the site. Figure 8 shows the thermal heat demand and the seasonal variation.

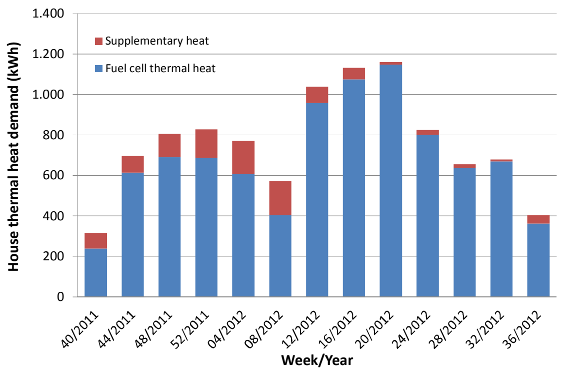

Figure 8: Thermal heat supply from a hydrogen PEM Gamma 1 fuel cell unit and supplementary heating (House 18).

The electric and overall efficiencies of the hydrogen PEM unit are shown in figure 9. The electric efficiency is close to the laboratory performance. The operating time is currently not long enough to evaluate the possible field test degradation.

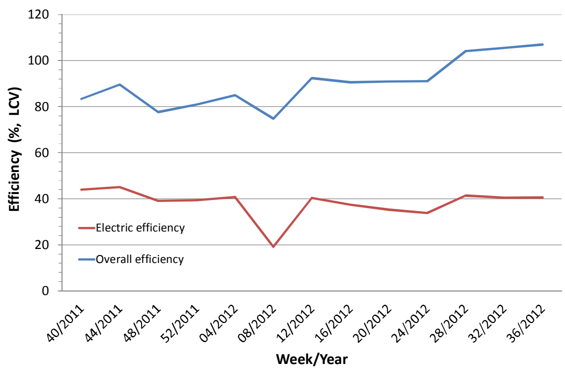

Figure 9: Hydrogen fuel cell electric efficiency from October 2011 until summer 2012 (House 18).

Natural gas low-temperature PEM units

In phase 3, 20 natural gas PEM fuel cells are field tested in Varde in southern Jutland. These units were installed in February/March 2012. Test sites include both single-family houses and larger buildings such as schools. No heat storage tank was installed at any of these field test sites. The accumulated operating time for these units exceeds 75,000 hours in December 2012.

In figure 10 operating conditions and performance are shown at a selected site from the start in beginning of 2012 until the unit was shut down for the summer. The upper graph shows electric and thermal heat output during the first week of April. The unit operated constantly at nominal load with 900 W electric and 1,650 W heat output. The cooling water temperatures were 30℃ return temperature and 60℃ forward temperature, high enough for hot-water production. The second and third graphs show accumulated data for periods of two weeks. In the beginning the unit was not fully available due to installation aspects. After that the unit was operating well until some maintenance, which stopped the operation for a while. The rightmost bar indicates that the unit was stopped for the summer period. The bar graph with the electricity and heat production shows a fairly constant two-week production reflecting the constant full load operation.

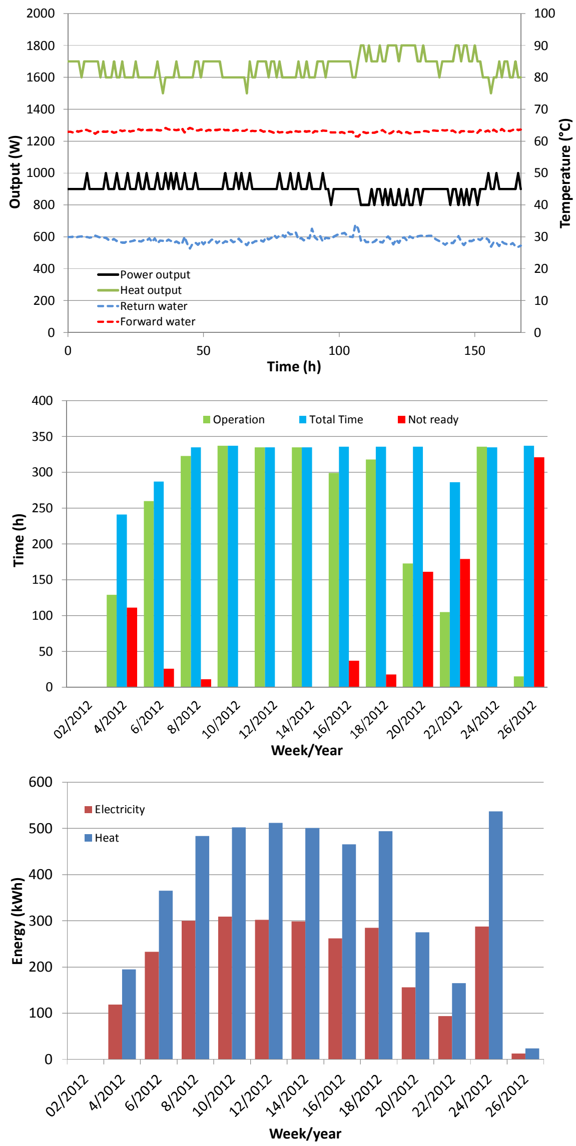

Figure 10: Operating conditions and performance for a selected natural gas PEM fuel cell during the first 5 months of operation (House 2).

At the end of the period shown in the graphs the unit operation time had reached 3,100 hours and the number of starts was only 7. During this period the unit had produced 2,660 kWh electricity and 4,520 kWh heat. Often the number of starts is very low for the units at the field test sites. It is explained by the fact that some sites have a considerably higher heat demand than the fuel cell output. No replacement of a stack or a reformer has so far (December 2012) been necessary.

The efficiency for the natural gas PEM unit is close to the laboratory performance. Figure 11 shows the electric and overall efficiency for the same unit as in figure 10. The performance of this unit is representative for all units in the field test. The electric efficiency is in the 33–35% range, while the overall efficiency shows a larger range, 90–100%. The variation is due to slightly different temperatures in the field test site heating systems.

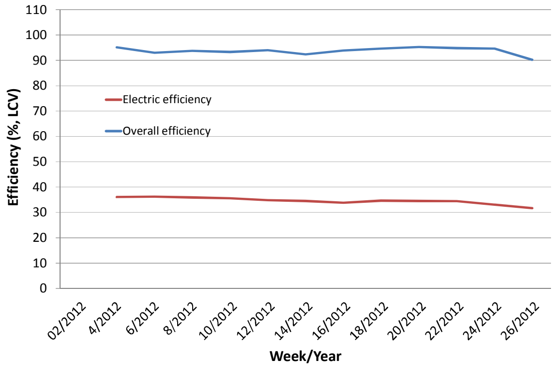

Figure 11: Electric and overall efficiency during 5 months for a field test of a natural gas PEM Beta unit (House 2).

Three of the natural gas PEM fuel cells are also set up for inclusion in a smart grid. It is possible to externally control the operation of the units. This is a step further compared to the hydrogen PEM fuel cells, which operated according to a pre-defined pattern.

Gas quality issues are currently being thoroughly discussed among European gas utilities and appliance manufacturers. The natural gas composition in Denmark has been very stable, but is likely to show larger variations as expected in other parts of the European gas grid. The reason is for example increased import of LNG (Liquefied Natural Gas), biomethane from anaerobic digestion and biomass gasification. Some experience has already been gained. Firstly, the unit must pass tests with different test gases in the certification phase, but this does not show any long-term effects. Pure methane (G20) is the reference gas for natural gas H. The test gases are specified in the European standard EN 437 [5]. Natural gas H is the gas quality distributed to the majority of customers in Western Europe. It is a natural gas quality with a high heating value. Two units have also been operated on upgraded biogas in order to test the long-term performance on a gas that may contain traces of compunds not found in natural gas. The biogas was imported on bottles from Sweden. These tests lasted for 6 months with no apparent problems.

System integration aspects

The overall system efficiency is dependent not only on the cogeneration unit efficiency, but also the overall integration of the different parts of the heating system. This is a more challenging task than a standard heating system consisting of a boiler or furnace for space heating and hot water production, either in a separate gas heater or an electric heater.

The system integration is meant to give the opportunity for the cogeneration unit to operate at an optimum operating point. This usually means long operating times at highest possible output. Often a heat storage device is necessary. The storage size or volume determines the possibility to operate the cogeneration unit in full load or the possibility to externally control the unit operation in a virtual power plant or smart grid concept.

The micro cogeneration system is more complex than a traditional heating installation, and the losses in the cogeneration unit have potentially a much larger influence on the overall efficiency

Table 4: Energy losses due to storage heat loss and pump electricity consumption.

Source	Heat/ elec. cons. (W)	Time (h)	Annual energy (kWh)	Share of produced elec. or heat (%)	Reduction in overall efficiency (%)
Heat storage	70	8,760	613	6.7	5.0
	150	8,760	1,314	14.5	8.7
Circulation pump	25	4,545 – 8,760	113 – 219	2.5 – 4.8	0.7 – 1.4
	75	4,545 – 8,760	340 – 657	7.7 – 14.5	2.2 – 4.3

than in a traditional heating system. The net electric efficiency is for example dependent on the internal power demand for electronics, pumps and fans. Special emphasis has been put on minimising this parasitic loss in the project. The IRD Gamma 1 unit has a stand-by electricity consumption of 15 W, which is close to the stand-by consumption of condensing gas boilers. An evaluation of heat loss from storage and electricity consumption in circulation pumps is shown in table 4. These parts are not included in the fuel cell unit. The table shows that the losses are 5–15%, and the conclusion is that these losses cannot be neglected.

CONCLUSIONS

This paper has described the development and testing of Danish fuel cell based micro cogeneration with an electric output of approximately 1 kW. The development and field tests are a joint effort by Danish partners representing the entire chain from fuel cell developers to energy utilities. The ongoing (2012) field tests include hydrogen and natural gas fuelled PEM fuel cells. Experience at the end of 2012 shows high net electric efficiencies (33–35% for natural gas and 45–47% for hydrogen), and the overall efficiencies often exceed 90%.

The future challenges include fuel cell degradation and lifetime, unit size and cost reduction. Installation and heating system integrations aspects are also important, especially when a micro cogeneration unit is added to an existing heating system rather than a full appliance replacement. So far, each generation of the fuel cells has shown good agreement with the project's internal goals on these topics. Another challenge strongly related to the technical challenges mentioned above is the competition of other emerging residential energy technologies such as photovoltaics, electric and gas heat pumps and a wider use of district heating using renewable energy sources.

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