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Residential Fuel Cell Micro Cogeneration – Opportunities and Challenges in the System Design

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1. ABSTRACT

There is great interest in gas-fired micro cogeneration, and it is one way to reduce the overall energy consumption. It is also a possible way for the gas distribution companies to retain customers when the heating demand decreases due to improved heat insulation and better appliance efficiency.

The micro-cogeneration system considered in this paper consists of a fuel cell unit, heat storage, a supplementary boiler and a control system. The full advantages and characteristics of the system can only be evaluated and compared to other solutions when the entire system is considered. The current Danish program for residential cogeneration units based on fuel cells is used as example of approaches and results are presented. Heat losses and electricity consumption are used as an example of the necessity to consider the entire heating system.

The Danish demonstration program is based on earlier fuel cell basic research. Three fuel cell technologies are developed for residential micro-cogeneration purposes. The three technologies are low-temperature PEM, high-temperature PEM and SOFC. The output is 1.0–1.5 kW_e.Both natural gas and hydrogen are considered as fuels. The progress for the technologies is briefly described.

C O N T E N T S

2. INTRODUCTION

There is great interest in gas-fired micro cogeneration, and it is one way to reduce the overall energy consumption. It is also a possible way for the gas distribution companies to retain customers when the heating demand decreases due to improved heat insulation and better appliance efficiency. The gas industry has two options to increase the future competitiveness in the residential sector. It is to combine natural gas and renewable energy such as solar energy, heat pumps or using bio methane injected in the gas grid, or to develop new appliances. Increasing the use of gas appliances (in the kitchen, decorative fires, grill, patio heater or other outdoor appliances) in the homes does not increase the gas utilisation substantially but may show the plethora of natural gas appliances in homes.

The highly efficient state-of-the-art condensing boilers put almost all fuel energy into useful heat for heating and hot water. Solar energy and gas-fired heat pumps use less purchased energy at the point of use while micro cogeneration substitutes power generation, which has a lower overall efficiency. Coal is often used in the power plants, which significantly increases the potential for reduced CO_2 emissions.

Fuel cells are an excellent appliance in natural gas grids as well as in hydrogen grids. The present Danish demonstration program intends to show micro-cogeneration units connected to both the natural gas grid and a micro hydrogen grid. These areas are currently heated by individual residential oil or gas-fired boilers.

The micro-cogeneration system considered in this paper consists of a fuel cell unit, heat storage, a supplementary boiler and a control system. The full advantages and characteristics of the system can only be evaluated and compared to other solutions when the entire system is considered. The current Danish program for residential cogeneration units based on fuel cells is used as example of approaches and recent results and achievements are presented.

3. NATIONAL MARKET POTENTIAL

Simulations were made to identify the control strategy and the CHP size, which gave the maximum operation time in a Danish single-family house. The results act as a base for both unit sizing and overall potential for residential cogeneration /1/. Load profiles for the electricity consumption were created including weekdays and weekends. These were based on 15-minute measurements in Danish single-family houses. The annual energy requirement in the house was an electricity consumption of 5000 kWh, 12000 kWh for space heating and 5000 kWh for hot water. The house is assumed to have 4 inhabitants. The results are shown in Table 1 and Table 2. The ratio between heat and electricity from the CHP unit is 2.0 and corresponds approximately to the current PEM and SOFC based micro-cogeneration units. The results for the electricity controlled operation mode are shown in Table 1 and heat controlled operation in Table 2. Surplus electricity is exported to the grid. The result is clear and shows that heat controlled operation yields the best utilization and highest energy production of the different options.

Table 1: Electricity demand controlled operation strategy

	Elec prod. (kWh/year)	**Share of demand (%)**	**Heat prod. (kWh/year)**	**Share of demand (%)**	**Max power CHP (kW)**	**Annual oper. Time (h)**	**Full load equiv. (h)**
Base Load 1[1]	535	11	1076	6	0.1	8760	5350
Base Load 2[2]	1070	21	2140	13	0.2	8760	5350
Load Following	4675	94	9350	55	5.3 [3]	8760	880
Peak Shaving >2 kW_e	2000	40	4000	24	3.3 [3]	610	600
Peak Shaving >1 kW_e	2850	57	5700	34	4.3 [3]	1120	650

[1] Based on all time lowest 24 hours demand (=night)

[2] Twice the base load during daytime compared to Base Load 1

[3] More peak power is presumably needed; calculations are made on an hourly basis

Table 2: Heat demand controlled operation strategy

Strategy	**Elec. prod. (kWh/year)**	**Elec. export to grid (kWh/year))**	**Elec. prod. In-house use (kWh/year)**	**Share of demand (%)**	**Heat prod. (kWh/year)**	**Share of demand (%)**	**Max power CHP (kW)**	**Actual oper. time (h)**	**Full load equiv. time (h)**
Base Load	4545	2307[2]	2238	45	9090	53	1.0	8760	4545
Load following	8500	5175[2]	3325	67	17000	100	3.3 [1]	8760	2575

[1] More peak power is presumably needed; calculations are made on an hourly basis

[2] If a sophisticated predictive control/algorithm is available, some of the heat production might be moved even more to release less electricity for export.

Similar results were obtained for heat controlled 1 kW_e CHP units in German homes /2/. This study also showed that an increased electric efficiency for the cogeneration unit increased the share of thermal energy delivered by the supplementary boiler. An increased electric efficiency means that the gas distribution company delivers more gas to the customer in case of heat demand controlled operation.

Denmark has currently the largest amount of electricity generated in cogeneration plants in the world. During the last 20 years the power production has partly moved from a few central power stations to a large number of cogeneration plants and wind turbines. In Figure 1 /3/ the amount of electricity in cogeneration plants and other distributed energy plants are shown. The next step is to develop even smaller cogeneration plants, i.e. residential micro cogeneration.

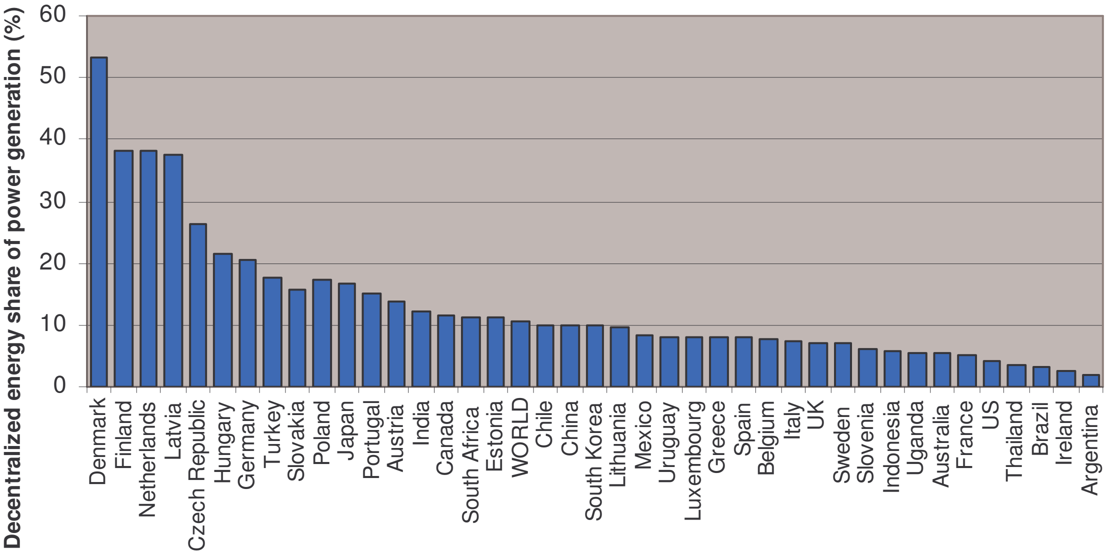

Figure 1: Distributed electricity generation (including cogeneration) in some countries /3/

Despite a limited number of individual gas (and oil-) fired residential boilers, the technical potential for micro cogeneration in Denmark in this sector is estimated to approximately 1100 MW_e power production capacity for units with an electric output less than 15 kW_e (totally 850 MW_e in single-family houses) connected to the gas grid and 1100 MW_e in other areas. This corresponds to 8.5% of the current electricity generation capacity in Denmark. Due to better overall fuel utilization the CO_2 reduction potential for Denmark is 1 million ton per 1000 MW_e micro-cogeneration capacity, 1.7% of Denmark's current emissions. A substantial part of this potential is in the range of 1–3 kW_e

These calculations form the base for the sizing of micro-cogeneration units in the Danish development and demonstration program. The program started in 2006 and today three fuel cell technologies are subject to the development, low-temperature PEM, high-temperature PEM and SOFC. After the three project phases the overall goal is to commercialize the technologies in 2012. Selected project targets for the first field test units in phase 2 are shown in Table 3.

Table 3: Selected performance targets for the Danish fuel cell micro-cogeneration project

	LT-PEM	**HT-PEM**	**SOFC**
Electric output (net)	1.5 KW_e	1.0 KW_e	1.0 KW_e
Fuel efficiencies	Electric efficiency (H_2 – electricity) Phase 2: 45 % Overall electric and heat efficiencies (H_2) Phase 2: 80 % + 10 % by condensing operation	Electric efficiency (N-gas – electricity) Phase 2: 35 % Overall electric and heat efficiencies (Natural gas) Phase 2: 80 % + 10 % by condensing operation	Electric efficiency (N-gas – electricity) Phase 2: 33 % Overall electric and heat efficiencies (Natural gas) Phase 2: 75–80 % + 10 % by condensing operation

The stack and the entire cogeneration unit with low-temperature PEM is designed and built by IRD Fuel Cells. Dantherm Power acts as system integrator for the cogeneration units with high-temperature PEM stacks from Serenergy and SOFC stacks from Topsoe Fuel Cells. Danfoss and its subsidiaries are responsible for certain heating parts, a dedicated inverter, heat storage and control system. DGC is responsible for third-party laboratory tests of the units, certification, aspects of the system design and field test design and evaluation. DONG Energy performs various studies and finds field-test objects for the natural gas part. COWI performs general studies. Two regional and local energy companies, SYD ENERGI and SEAS-NVE, participate in the field test part with funding and end user contacts. Both electricity and gas distribution companies are participating. The project gives a unique opportunity to compare the fuel cell technologies in laboratory tests as well as in field tests. A few field test sites may also be used for testing two fuel cell technologies; however, not at the same time.

Field tests will be carried out in phase 2 and 3. In phase 2 approximately 12 fuel cell units are placed at various users. Five hydrogen fuelled low-temperature PEM units are installed in ordinary single-family homes while the natural gas fuelled high-temperature PEMs and SOFCs are installed at more “professional” users. These could be plumber offices etc. In phase 3 approximately 100 fuel cell units will be placed at ordinary users.

4. DANISH RESIDENTIAL COGENERATION FUEL CELL UNITS

The micro-cogeneration units developed in the current demonstration program intends to commercialize earlier basic Danish fuel cell research results. The units comprise the fuel cell stack, balance of plant components, inverter, heat storage, system integration and data transmission over the Internet. The possibilities of virtual power-plant operation are also studied. The cogeneration units are connected in parallel with the existing heating system during the field tests. The operation is heat controlled. Surplus electricity is exported to the grid.

Both natural gas and hydrogen grids will be used. High-temperature PEM and SOFC units are connected to the natural gas grid, while the low-temperature PEM units are connected to a micro hydrogen grid. The two systems are shown in Figure 2.

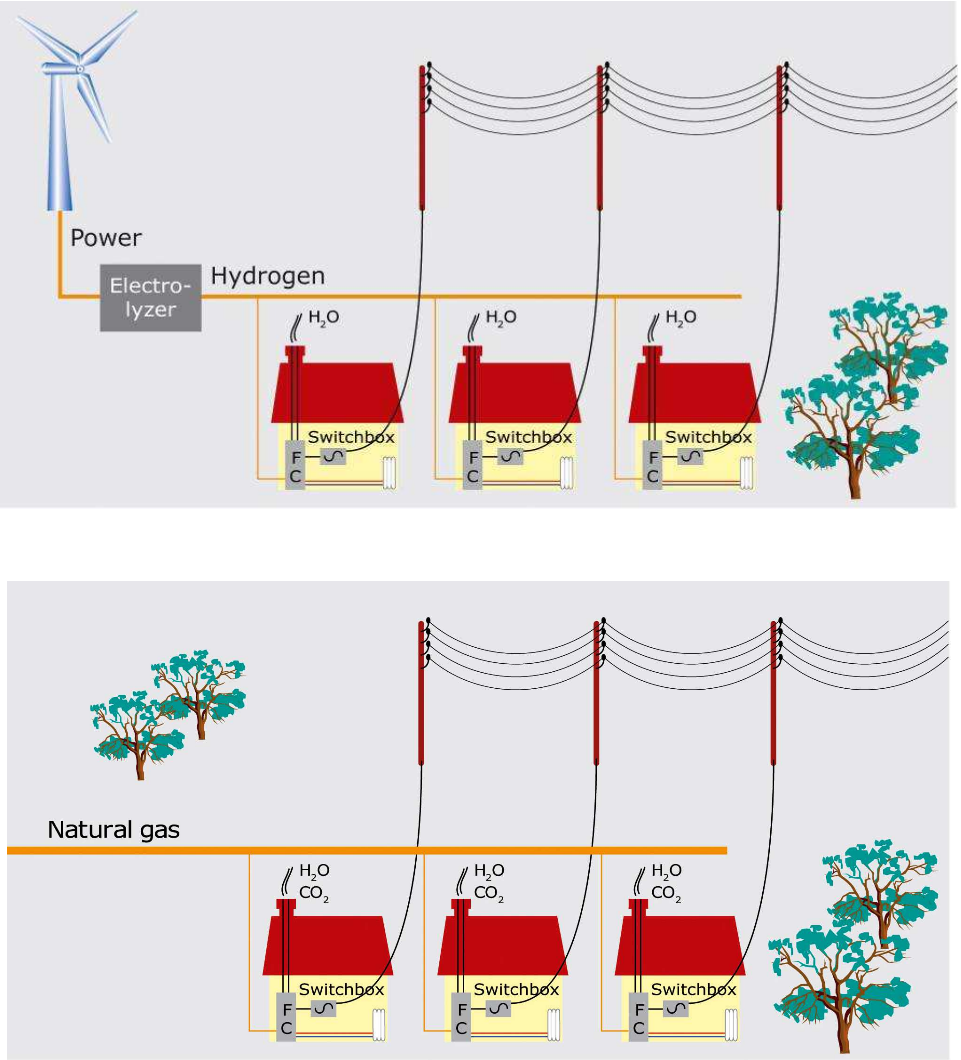

Figure 2: Grid structures for fuel cell use

The competing technologies are Stirling-engine and combustion-engine based micro-cogeneration units. These are characterised by lower electricity efficiency, i.e. a lower electricity-to-heat ratio. Micro-cogeneration units based on internal combustion engines for residential use – for example Honda Ecowill 1 $\mathrm{kW_e}$ – have an electrical efficiency of approximately 20%. The Stirling based units have an electrical efficiency of 10–15%. These technologies will enter the market before the fuel cell cogeneration units.

4.1. Fuel cell units

The three technologies have significantly different operating temperatures, 70 °C for the low-temperature PEM, 160 °C for the high-temperature PEM and 750 °C for the SOFC. This clearly indicates the different approaches that have to be taken regarding minimising the heat losses from the cogeneration unit. One has to remember that heat losses also occur from the supplementary boiler and the heat storage and that the surface areas are considerably larger than for the conventional installation with a boiler and a hot water tank.

The electric efficiency for micro-cogeneration units shall be calculated as the net power to the grid divided by the fuel input. The electricity consumption in pumps, control system, fans etc.

and the loss in the inverter shall then be minimised. The low-temperature PEM unit from IRD has been under a detailed investigation regarding the electricity consumption; and the consumption in generation 1 was reduced in the following generation and these measures alone increased the electric efficiency by approximately 3 percentage points. The HT-PEM cell stack is designed for a low pressure drop on the cathode side without suffering a good heat transfer. This avoids temperature gradients in the cell stack and the fan power input will be very low. For a 1.5 kW_e unit the fan input is only 8 W. A careful design of the Balance of Plant (BoP) parts may alone increase the net electric efficiency by a few percent.

The overall control system decides the operation of the micro-cogeneration unit, the supplementary boiler and the heat storage. A number of alternatives are possible, but the cogeneration unit operation shall basically be heat controlled for a maximum operation time for the cogeneration unit. This is normally also the alternative that gives the largest overall primary energy savings.

A new inverter is designed in the project. The current inverters for fuel cells have an efficiency of approximately 90 %, partly due to the low stack voltage, which has to be transformed. The target for the new inverter is 94–95 % efficiency.

Cogeneration units with the three fuel cell technologies are shown in Figure 3. The top left image shows the low-temperature hydrogen fuelled PEM cogeneration unit ready for field tests. On the right hand is the hydrogen fuelled high-temperature PEM fuel cell module. The tube on the right side of the module is only for test purposes. At the bottom left is the first generation of the natural gas fuelled SOFC during initial testing.

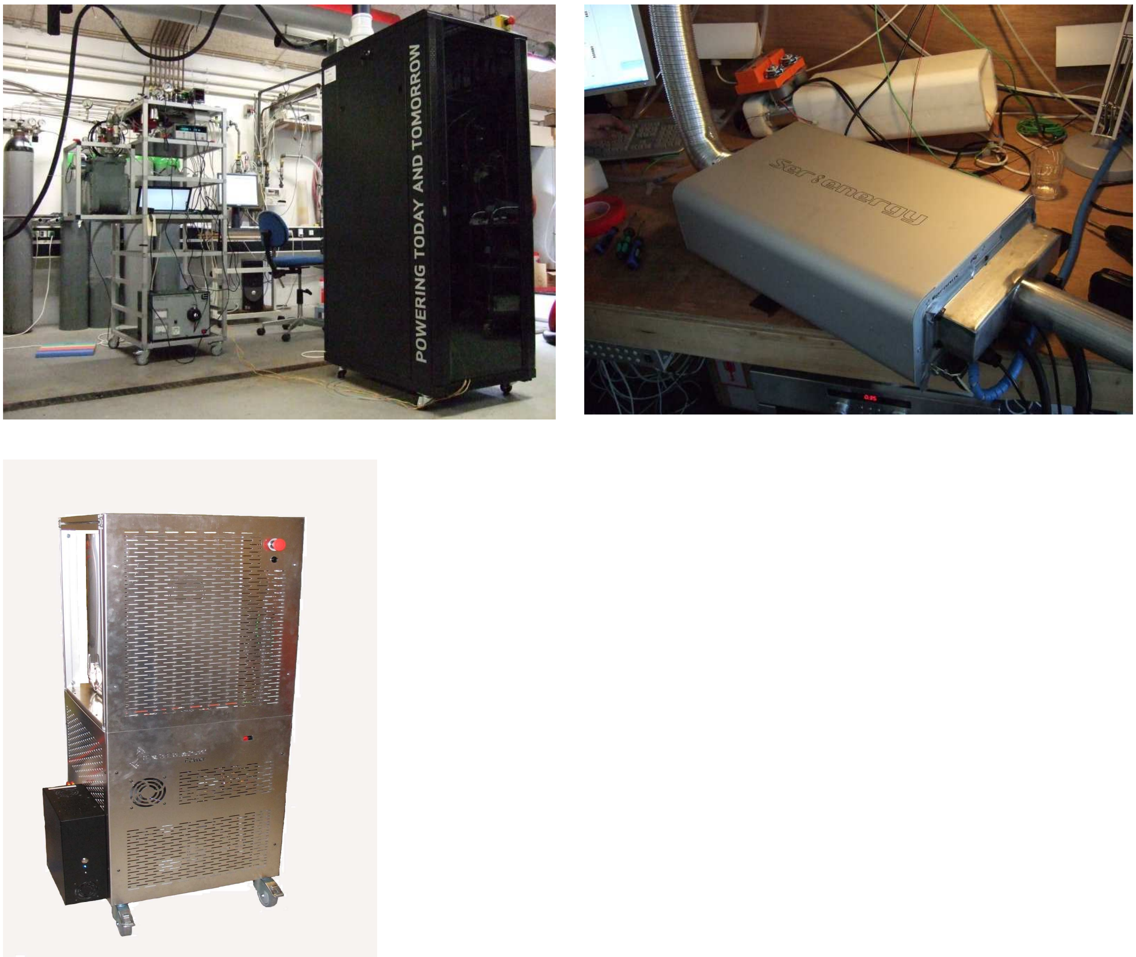

Figure 3 Fuel cell units.
IRD low-temperature PEM (top left), Serenergy high-temperature PEM module (top right) and Dantherm Power SOFC (Topsoe) fuel cell

4.1.1. Low-temperature PEM

The low-temperature PEM cogeneration unit is entirely designed and built by IRD Fuel Cells. It was decided that low-temperature PEM fuel cells should be developed for hydrogen fuel only in the Danish demonstration program. These PEM units do not have a natural gas reformer.

The field tests started in September 2007. The island of Lolland in southern Denmark has a large wind power production. Sometimes a wind power production surplus occurs and the idea is that this surplus can be used for hydrogen production. The electricity is supplied to an electrolyser, to which a micro hydrogen grid is connected. The total length of the network is a few hundred meters.

Laboratory tests of the field test units carried out in 2008 show that efficiency targets are met for the IRD unit. Selected test results are seen in Table 4. A slightly higher electric efficiency may be expected with the improved inverter. Observe that the fuel is hydrogen.

Table 4: IRD low-temperature PEM fuel cell unit performance

Parameter	**Value**
Electric output (AC)	1.6 kW_e
Thermal output	1.6 kW_{th}
Electric efficiency (net)	46.6 %
Overall efficiency	94.4 %

4.1.2. High-temperature PEM and SOFC

The high-temperature PEM cogeneration unit will be based on a fuel cell module from the Danish company Serenergy. The module can be used in various applications, from UPS to micro cogeneration. The module is air cooled and the hot air from the module will be transferred in a heat exchanger to the cooling circuit. Data from tests with the basic fuel cell module are shown in Table 5. The calculation of the electric efficiency includes 8 W for the air fan and 25 W for the control system. The module has a 70 W heat loss to the surroundings.

Table 5: Performance for hydrogen fuelled high-temperature PEM

Parameter	**Value**
Electric output (DC)	1.5 kW_e
Electric efficiency (DC net)	52.8 % (1.5 kW_e)
	49.5 % (1.0 kW_e)
Stack temperature	160 °C
Estimated heat recovery potential	40–45 %

SOFCs have the potential for the highest electric efficiencies but at the same time the high temperature is a challenge regarding heat insulation and heat loss. The system integration and integration with the heating system are also important to minimise the thermal cycling. Another potential problem is the possible need for a protection gas during start and stop. This gas has to be avoided in a mature technology. The SOFC cogeneration unit is designed for a 1 kW_e net output. The SOFC stacks consist of planar cells developed by Topsoe Fuel Cells and Risø in Denmark. The cell technology has been frequently described, for example in /4/. An early version is shown in Figure 3 and this version was used to confirm the concept and to identify areas of improvement. The natural gas is processed in a CPO (Catalytic Partial Oxidation). Two stacks are connected in parallel and the stacks are insulated in the hotbox. The stack temperature is 750 °C. The cogeneration unit is heated during start-up by a natural gas fuelled catalytic burner. The first version showed an electric efficiency of approximately 30 % (DC) but this figure should only be seen as an indication since improvements are necessary on for example the heat insulation and the heat exchangers. The cogeneration units in the field tests will have these improvements.

4.2. Heat storage

The heat storage is the interface between the cogeneration unit and the heating system. Among the design criteria for the thermal storage are the effective volume, i.e. a measure of operation time for the micro-cogeneration unit for loading, heat loss to the surroundings and the point where loading starts and finally the sizes (practical installation). The storage also has a strong influence on the cycling of the fuel cell unit. The size matter can be illustrated with the following assumption. If the footprint should not exceed 600×600 mm, the height is maximum 1800 mm and insulation 100 mm, then the maximum volume becomes approximately 250 litres. This corresponds theoretically to 15 kWh energy at a temperature difference of 50 K (7 kWh at ΔT = 25 K) and 5–10 hours of continuous operation with a 1.5 kW thermal output. With a 5000 kWh annual hot water demand this corresponds to a 14 kWh daily demand and 16.5 kWh including a 100 W heat loss from the storage. 2000 kWh hot water demand is also used as calculation input in Denmark and this gives a daily demand of 7.9 kWh. Reference /5/ determines the optimal heat storage from an economic aspect to a storage capacity of 6–8 kWh for 1–2 kW cogeneration units. Larger heat storage is, however, only slightly less favourable, while small heat storage may give larger differences. Tests at DGC of an early system of heat storage have shown the importance of efficient stratification in the heat storage to keep a high temperature at the outlet and thus to allow longer continuous operation for the micro-cogeneration unit and less use of the supplementary boiler/burner.

An efficient stratification may also be important for low-temperature fuel cells to ensure temperature/cooling of the cell stack. An off-the-shelf heat storage designed for heat pumps was tested but was found not to meet the requirements. A new design was made and it was apparent that knowledge from heat storages from solar systems is valuable.

The overall system will require a number of circulation pumps. Low-energy circulation pumps are now being introduced in condensing boilers and are reducing the electricity consumption significantly. It is important to use these pumps also in the micro-cogeneration systems to reduce the parasitic consumption. It is worth noticing that the German eco-labelling scheme “Blaue Engel” has limits for the electricity consumption in gas-fired (sorption/absorption) heat pumps /6/. The electricity consumption shall be below 30 W per kW thermal output.

5. SYSTEM AND EFFICIENCY MODELS

Today, efficiency models for the annual performance of residential boilers are well developed and used. In a European work the BoilSim model /7/ was developed and now this model is used in the Danish energy labelling system for residential gas boilers. The model is used to calculate the part load efficiency for a number of operation points representative for the entire year. The boiler and a storage tank for hot water are included in the calculations. Is an equivalent model for micro-cogeneration systems available and how will such a model influence and assist the development work? BoilSim is a grey-box model where the performance of different parts is described with simplified correlations based on measurements and thermodynamics. Most models seem to be either focussed on the fuel cell stack and its processes or simulations of the entire building including the fuel cell or cogeneration unit operation. An example of the latter is the work within Annex 42 of the International Energy Agency /8/.

The efficiency of micro-cogeneration units can be calculated locally as the sum of heat and net electricity generation divided by the fuel input or more globally (nationally) as a measure of the fuel supplied to the micro-cogeneration unit related to the fuel necessary for local heat generation with a boiler and central electricity generation in a power plant. The latter method includes a number of national parameters, which makes a comparison of data difficult. In this paper the local efficiency will be discussed. The cogeneration unit efficiency is often limited to the CHP unit alone and does not include the efficiency for a supplementary boiler and heat storage. The electric and overall efficiencies are always given at continuous part or full load. Part load in a boiler often includes on-off operation of the burner.

The flue from the stack anode and cathode is sometimes emitted at stack temperature, approximately 70 °C. This corresponds to a flue loss of 3 % at 100 % excess air. This loss can be recuperated, for example by heat exchange to the heating system water. Tests at DGC have shown that the overall efficiency could be increased by up to 10 % with a low return temperature.

The Dutch HRe® /9/ label can be given to cogeneration units with a maximum output of 2 kW_e and 70 kW thermal energy. Efficiency η_{HRe} is defined as

$$\eta_{H\,\mathrm{Re}} = \frac{\dfrac{Q_{CHP,100\%}}{Q_{in,100\%} - \dfrac{P_{CHP,100\%}}{\eta_{e,ref}}} + \dfrac{Q_{CHP,part}}{Q_{in,part} - \dfrac{P_{CHP,part}}{\eta_{e,ref}}}}{2}$$

Where Q_{CHP} is the thermal output at full and part load, Q_{in} is the fuel input at full and part load and $\eta_{e,ref}$ is a reference value for power generation = 0.456. The label is given when η_{HRe}>125 %. The efficiency is the average value of full-load and part-load performance. The equation shows that the efficiency is the thermal output divided by the fuel input, which is reduced by an amount corresponding to the substituted electricity production in a large power plant. It also shows that if the electric efficiency exceeds the efficiency of the central power plant the denominator gets a value less than zero. The method is apparently best suited for the cogeneration units in the near future.

In a British method /10/ to evaluate the energy performance of micro-cogeneration units a primary energy efficiency η_{prim} is defined as

$$\eta_{prim} = \frac{Q_{ann,gen} \times F_{fuel}}{\dfrac{Q_{ann,gen}}{\eta_{th}} \times F_{fuel} - P_{ann,gen} \times F_{elec}}$$

Where $Q_{ann,gen}$ is the annual generated heat, $P_{ann,gen}$ is the annually generated electricity and F_{fuel} and F_{elec} are primary energy factors for the cogeneration fuel and electricity, respectively. The primary energy factors for natural gas and electricity are 1.15 and 2.8.

The models described show that a common model for evaluating cogeneration efficiency does not exist. Nor do these two models include heat storage. The primary energy factor for power generation also differs. The need for a common model was stressed at a workshop on micro cogeneration in Paris in May 2008 /11/. A commonly accepted model should make it possible to evaluate the performance for different system configurations.

Often the published data for a cogeneration unit does not include heat storage and a supplementary boiler. To DGC’s knowledge there are no test standards for an entire heating system based on a cogeneration unit. Consider the heat-controlled and load-following scenario in Table 2. If we add heat loss and electricity consumption for circulation pumps we move towards a performance for the entire heating system. We assume 70 and 150 W heat loss from the heat storage and also 25 or 75 W electricity consumption for circulation pumps around the heat storage. If these values are used for a period of 8760 hours annually for the heat loss and

4545–8760 hours annually for the circulation pumps we get the results in Table 6. The overall efficiency for the pure fuel cell unit is assumed to be 90 %.

Table 6: Energy flows around a heat storage

Source	**Heat loss/ pump elec. cons. (W)**	**Time (h)**	**Annual energy (kWh)**	**Share of produced thermal or elec. energy (%)**	**Reduction in overall efficiency (%)**
Heat storage	70	8760	613	6.7	5.0
	150	8760	1314	14.5	8.7
Circulation pumps	25	4545–8760	113–219	2.5–4.8	0.7–1.4
	75	4545–8760	340–657	7.5–14.5	2.2–4.3

This simplified example shows the wide range of losses and that the overall efficiency may drop roughly between 5 and 15 %. The complete heating system also includes a supplementary burner or boiler. In case of a supplementary boiler it should be observed that the boiler has to cover only a part of the buildings heating requirement, i.e. a lower load. A short example of the consequences in lowering the heat load of heating boilers is summarized in Table 7. The boilers are modern condensing boilers and labelled with either A or B in the Danish boiler energy labelling system. Calculations of the annual heating efficiency are made for 10,000 and 20,000 kWh/year, which are approximately the heating demands that a boiler has to cover when it is installed together with a micro-cogeneration unit or alone for the entire heating demand. The result shall only be regarded as an indication of the efficiency changes that can occur in a supplementary boiler.

Table 7: Annual heating efficiency for some modern condensing boilers

Boiler model	**Max burner input (kW)**	**Danish energy label**	**Energy demand, 20,000 kWh/year**	**Energy demand, 10,000 kWh/year**
A	16	A	104	101
B	15	B	102	99
C	15	A	104	102
D	18	A	103	101

The calculations are made for a low-temperature heating system and show an efficiency reduction in the 2–3 % range. A traditional heating system shows an efficiency reduction on the same level or larger. It is evident from these short examples that the entire heating system has to be carefully integrated for a maximum efficiency. No model seems yet able to predict the performance in the same way as models for space heating boilers alone.

6. CONCLUSIONS

Fuel cells offer the opportunity for highly efficient fuel utilization and an environmentally acceptable use of fossil fuels. Fuel cells are also an excellent appliance in a hydrogen grid. Residential micro cogeneration is also an opportunity for the gas distribution companies to offer an application that defends the grid connection of single-family houses when the heating demand decreases due to better houses and higher appliance efficiency.

Earlier Danish basic research on fuel cells is today being used in a development of micro-cogeneration units. The three technologies low-temperature PEM, high-temperature PEM and SOFC are developed by separate companies but tested and evaluated in a common demonstration program.

The cogeneration units have an electric output of 1.0–1.5 kW_e and are expected to operate in a heat demand controlled mode. The performance is on level with or better than comparable developments around the world. In 2008 begins a field test with approximately 12 units.

This paper also shows the importance of models and tests of the entire heating system, including heat storage and supplementary burner or boiler, for a fair evaluation of the performance. With a few simplified examples the influence of heat loss from the storage, electricity consumption in the circulation pumps and the changed operating conditions for a supplementary boiler are shown.

7. ACKNOWLEDGEMENTS

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