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Operational Experience with Micro-CHP Residential Fuel Cell Systems

P.F. van den Oosterkamp[1], P.C. van der Laag

Energy research Centre of the Netherlands (ECN), PO Box 1, 1755 ZG Petten, The Netherlands

[1] Corresponding author, E-mail: vandenoosterkamp@ecn.nl

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1. ABSTRACT

The Energy research Centre of the Netherlands (ECN) in Petten, is active in many aspects of fuel cell technology. This includes activities in PEM fuel cells and components, SOFC fuel cells and components, fuel processing and fuel cell system design and testing (www.ecn.nl/bct).

The ECN activities are focused on both automotive applications as well as stationary applications. Application of micro-CHP fuel cell technology for residential applications in the Netherlands is a significant part of our activities in the stationary power applications.

In this context, ECN operates two fuel cell systems for the co-generation of heat and power. Both systems operate on natural gas as feedstock and are targeted to European residential applications. Design aspects, modelling and control of a 2 kWe PEMFC system and a 1 kWe SOFC system, together with the main operational characteristics. In addition, the cost aspects and market considerations for the European (Dutch) situation are highlighted.

2. RESIDENTIAL CO-GENERATION (µ-CHP) ISSUES

Given the existing natural gas infrastructure, the Netherlands are ideally suited to apply distributed generation by means of micro-CHP systems. Using on-site power generation maximizes the utilization of waste heat, while minimizing investment for and losses of heat transfer. The increase in power demand can thus be met in a flexible, energy efficient and cost effective way.

In the Netherlands, large land and sea based reserves of natural gas are exploited to feed the energy system. Virtually all households are connected to the natural gas distribution grid, to feed residential boilers for space heating and hot tap water supply. Electric power for residential end-use is generated separately by central power stations that are mainly fuelled by natural gas and coal. Thereby, large quantities of low temperature waste heat are emitted to the environment. The installed central power production capacity is 14.000 MW (2000). From the total inland power production, 29 % (2000) is already generated by means of Combined Heat and Power stations [1].

Energy saving and emission reduction potential

Subject to the Kyoto Protocol, the Netherlands are committed to reduce their CO_2-equivalents emission by 6 % in the period 2008-2012, in comparison with the 1990 emissions level. The adoption of micro-CHP systems contributes to this goal.

Primary energy saving (PES) and emission reduction potentials for implementation of individual micro-CHP systems, with assumed system efficiencies are summarized in table 1. The average Dutch home consumes 3305 kWh of electricity and 1950 m^3 of natural gas per year (1998) [5, 6]. The assumed reference power grid efficiency is 41 % (incl. T&D losses) and the reference conversion efficiencies for space heating and hot tap water are 100 % and 70 % respectively (LHV) [2].

Table 1 Performance of 1 kWe micro-CHP technologies (incl. auxiliary burner and hot water storage) in an average Dutch household.

	El.eff. %, LHV	Th.eff. %, LHV	Tot.eff. %, LHV	PES %	CO_2 red. ton/year	NO_x red. %
Stirling	10	85	95	11.6	0.9	56
PEMFC	32	64	96	24.0	2.2	75
SOFC	39	51	90	23.7	2.5	73

System dimensioning

The choice of nominal power generation capacity of the micro-CHP system is based on the dynamic characteristics of the power and heat demand patterns and on the amount of waste heat that can be utilized locally. At the level of an individual home, strong fluctuations in power demand become apparent. This is illustrated by the following measured demand profile.

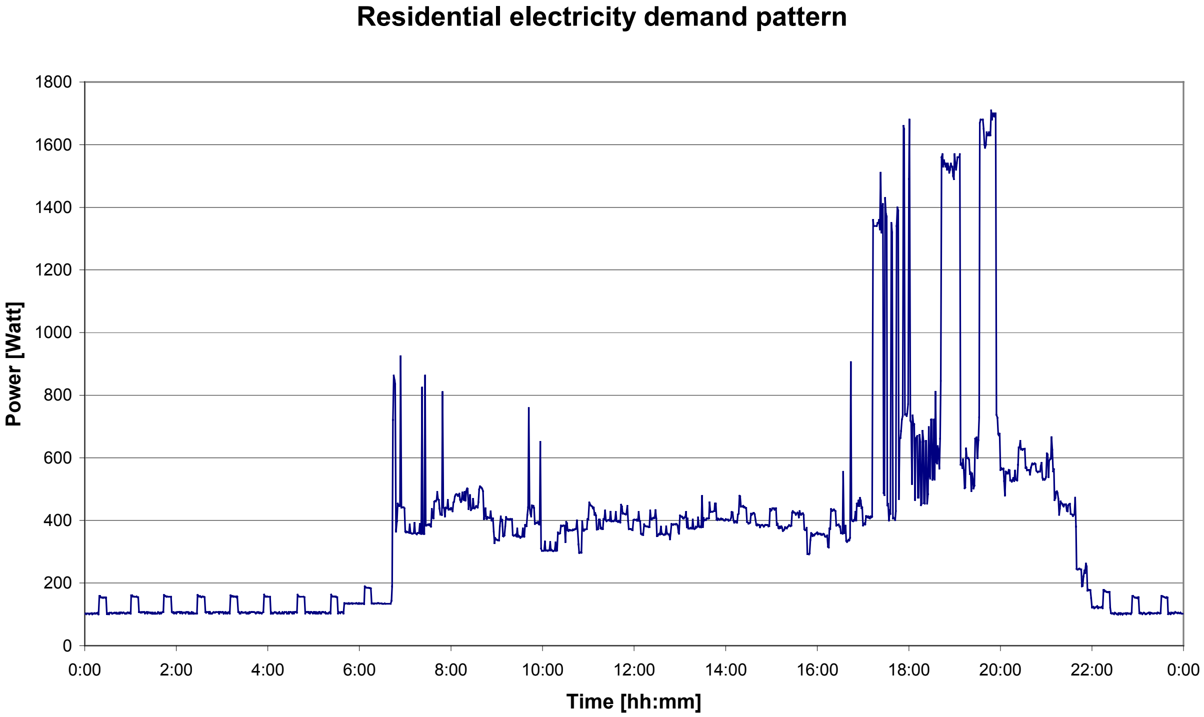


Figure 1 Typical Dutch residential electricity demand pattern (dt = 1 min).

Clearly visible are the refrigerator (periodic power consumption by the compressor) and the electric dishwasher. Electric and microwave ovens and the coffee machine cause other peaks. The average power consumption is 376 Watt, corresponding to the Dutch annual average value of 3300 kWh.

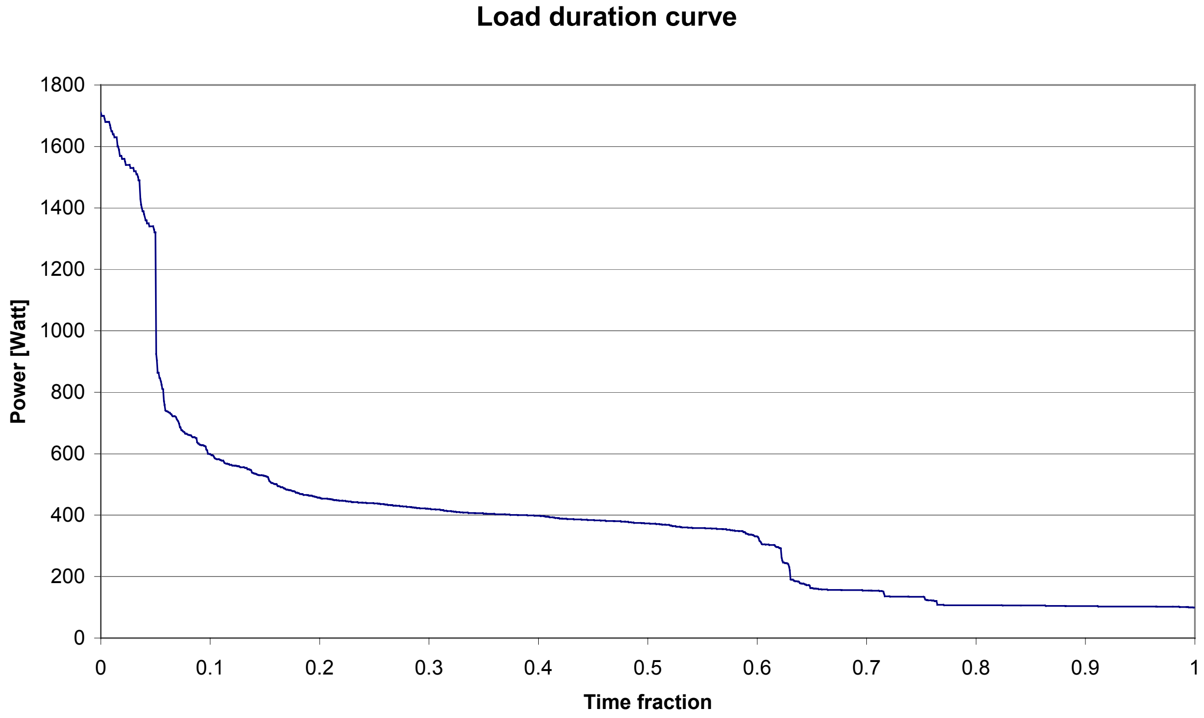


Figure 2 Measured load duration curve corresponding to figure 1.

Based on a number of similar measurements and their corresponding load-duration curves, we concluded that a 1 kWe nominal capacity is capable of supplying 90 % of the local power demand. Either directly, or indirectly by temporarily storing electricity on the grid. The co-generated heat is available to meet the heating demand of the same household. Peaks in the electricity demand need to be supplied by the grid and peaks in the heat demand are provided by means of a 20 kWth auxiliary burner.

During moments of power grid failure, grid-independent islanding operation of the micro-CHP system enables the continuous supply of 1 kWe to keep essential apparatus for cooling, lighting, audio/video, etc. running.

Annual cost savings for private ownership

Different ownership scenarios are possible. In the Privately Owned scenario, the end-user buys and operates the micro-CHP system; similar to an ordinary natural gas fired residential boiler. In this case, the avoided costs for buying electricity from the utility company, creates a basis for profitable operation of the more expensive micro-CHP system. Alternatively, the Energy Company may buy and install the system at the end-user’s premises. Particularly in a liberalizing energy consumers market, this offers a means to bind the consumer to the Energy Company, selling electricity and heat at an attractive price. The room for investement arises from cost savings when buying electricity on the day-ahead power market. Additional benefits are utilizing the gas distribution system to expand distributed power production capacity in a flexible way, while saving on costs for expansion of the power distribution grid.

A large number of product-market combinations were assessed with regard to their net annual cost savings potential, by dynamic (quasi-stationary) simulation. The mode of operation is heat-demand following, in order to maximize the co-production of electricity, without needing to dump excess heat. A heat storage vessel (ca 100 liters) is included in the system, for providing tap water during brief periods of time. This also creates a degree of freedom for controlling the system to meet a momentary change in demand for electricity. Results including error margins are given in figure.3

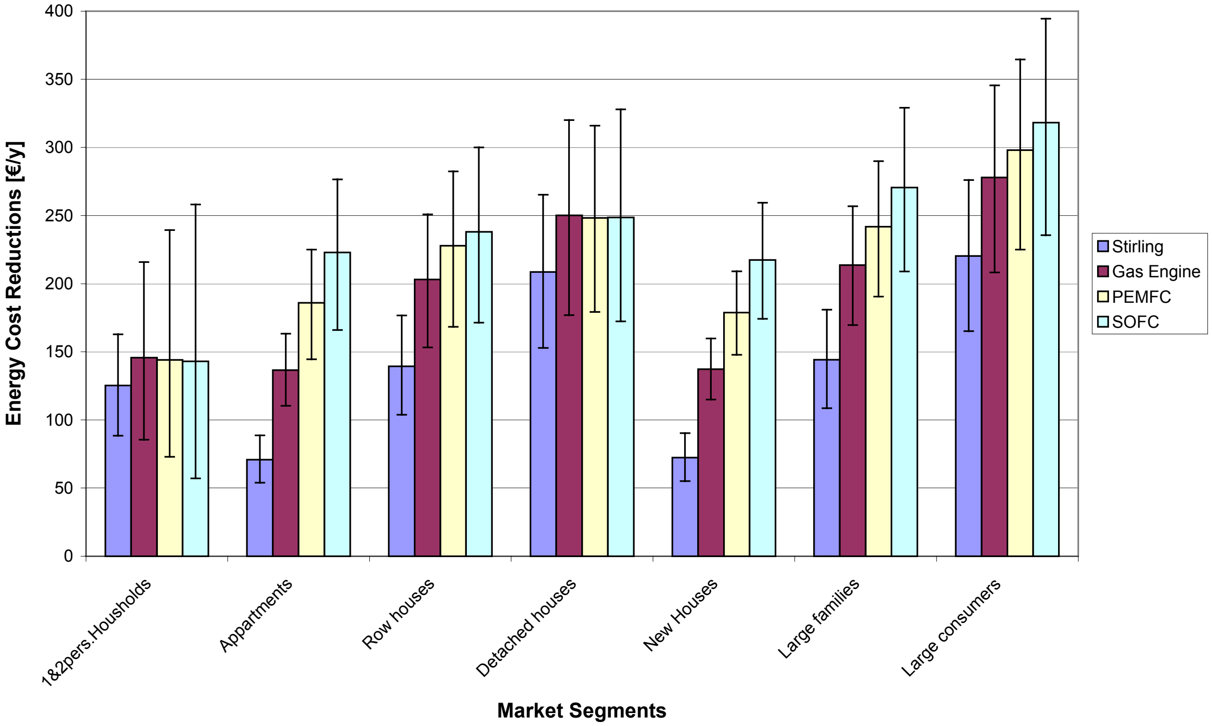


Figure 3 Annual energy cost savings for different product-market combinations of 1 kWe micro-CHP systems, in private ownership [EUR/yr].

In the various market segments the expected annual cost saving, combined with a pay-back period of 5 years, creates a room for investment for a 1 kWe micro-CHP system of 1000-1500 EUR, in excess of an ordinary residential heating system. This additional cost will be profitable thanks to changes in the annual energy bill. Less needs to be paid for buying electricity, while a refund is received for feeding-in excess electricity. However, higher costs for gas consumption and higher costs for maintenance and parts-replacement (e.g. odorant removal, stack replacement), offset this reduction. Energy tariffs for natural gas and electricity, including value-added and ecotaxes in the Netherlands are: 0.435 EUR/m^3 and 0.166 EUR/kWh (2002).

A sensitivity analysis shows the strong dependence of the annual cost saving on the synchronisation between electricity demand and supply (expressed as the direct-supply factor) and on the feed-in tariff [3]. Clearly, it is beneficial to follow the changes in electricity demand as much as possible. This requires a step response of the micro-CHP system of ca 90 seconds or installing local power storage capacity [2].

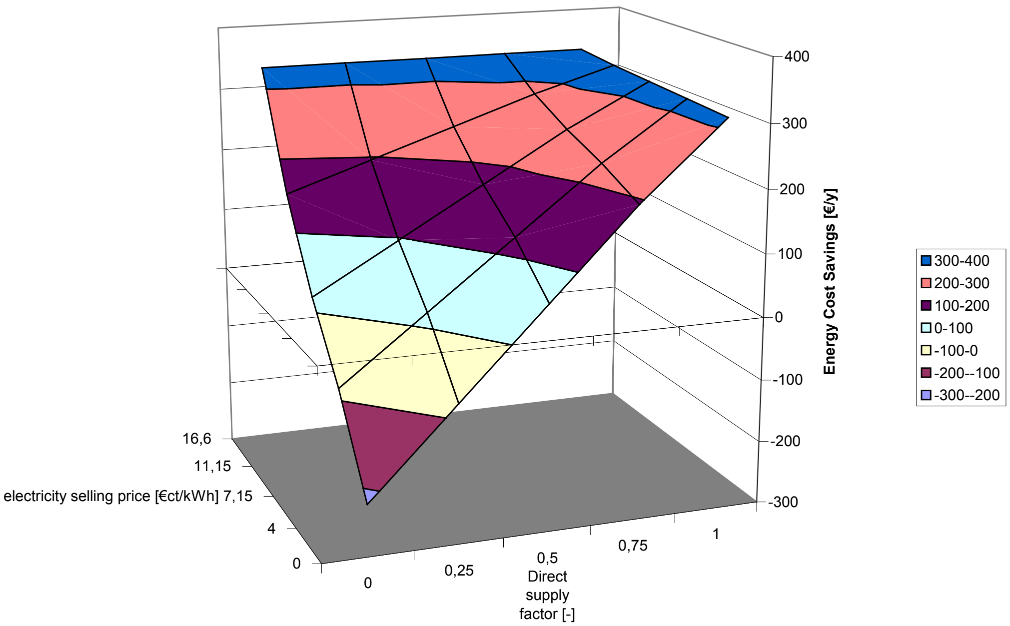


Figure 4 Sensitivity of annual cost savings [EUR/yr] for synchronisation between electricity demand and supply and feed-in tariff [EURct/kWh] [3].

3. PEM BASED μ-CHP

3.1. Process description and simplified flow scheme

The PEM system consists of a FP-3 HotSpot reformer supplied by Johnson Matthey PLC and a PEM fuel cell stack developed at ECN. The DC to AC inverter was supplied by Exendis, NL.The main purpose of this system was to test a Fuel Processor from Johnson Matthey in combination with a PEM fuel cell from ECN and a DC to AC inverter. It was not a prime objective to design a highly integrated system

Figure 5 gives an outline of a simplified flow scheme for this system. Natural gas is desulphurised and converted to a hydrogen rich gas in the Hot Spot reformer which contains a primary reforming step on the basis of auto thermal reforming (ATR) in the presence of air and steam, a Water Gas Shift reactor and a preferential oxidation reactor (PROX) for removal of CO to a level to below 10 ppm. In the PEM fuel cell, the hydrogen utilisation at the anode compartment is about 80 % and the remaining hydrogen in the anode off-gas is utilised in an after burner where steam is produced for use in the reformer. Both the PEM fuel cell stack and the PROX unit are being cooled with water; these heat sources can be utilised for co-generation of heat. The exhaust gases after the after burner can also be utilised for co-generation purposes. The Johnson Matthey P3 reformer converts the Natural gas, air and steam to a hydrogen rich reformate, containing CO up to 1 % (dry basis). The CO is further removed to a level below app. 10 ppm using the preferential oxidation reactor. This reactor is cooled with water and is executed in two consecutive reactors with intermediate air supply. The reformate to the PEM fuel cell is saturated with water. Also the air to the cathode of the PEM is humidified. The anode off-gas from the PEM is combined with air and converted in the

Afterburner/steam generator. The water which is fed to the system is deionized to 3-5 micro Ω/cm.

The JM P3 Fuel Processor has a nominal capacity of 10 kWe and can be used at turn down of below 10 %. In combination with the PEMFC of 2 kWe, the fuel processor was therefore used at a turn down of 20 % or lower.

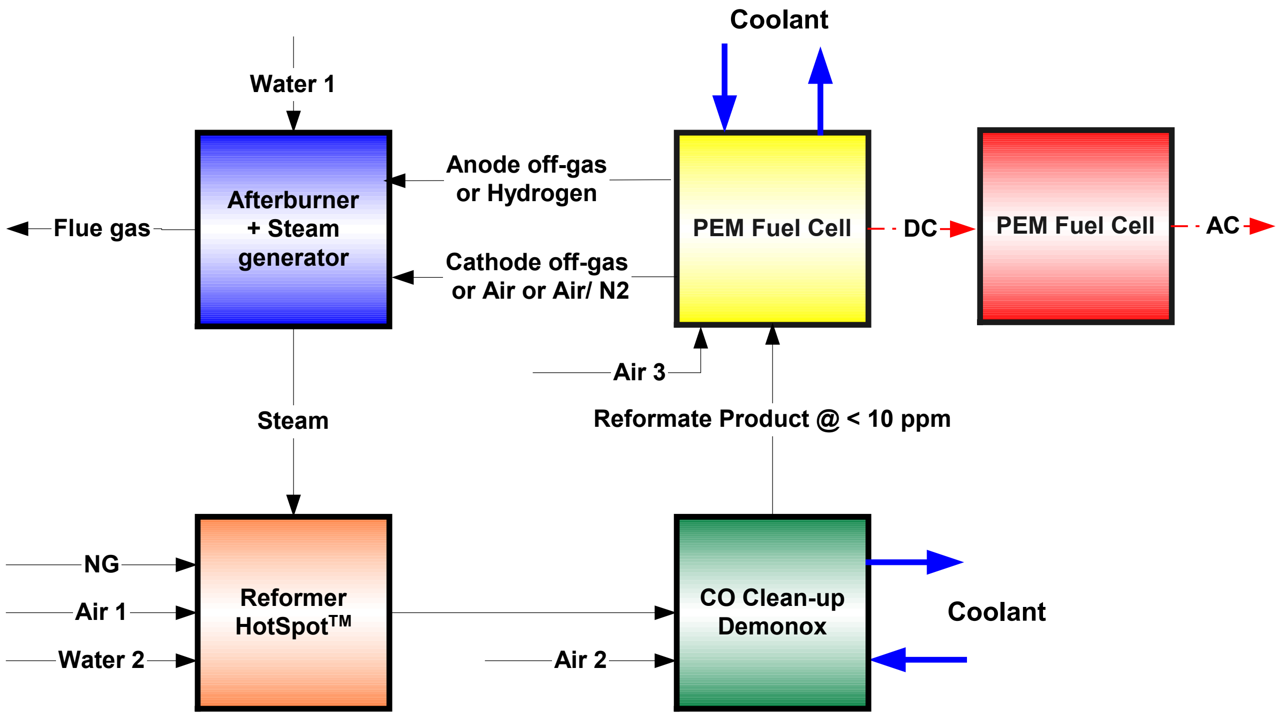


Figure 5 Simplified flow scheme PEMFC system.

The balance of plant equipment was designed and procured by ECN and ECN executed the assembly of the complete system, together with the implementation of the control system and safety system, figure 6 and 7.

Figure 6 Micro-CHP PEM system with stack, humidifiers and inverter, control system.

Figure 7 Johnson Matthey P3 Fuel Processor.

The PEM stack from ECN has an active area of 159 cm^2 and consists of 50 cells with a nominal power of 2 kW under reformate condititions and a stack voltage of 30 tot 32 V. The normal operating temperauture of the stack is 65 ^0C.

Figure 8 gives the I-V characteristics of the cells in this stack for different conditions.

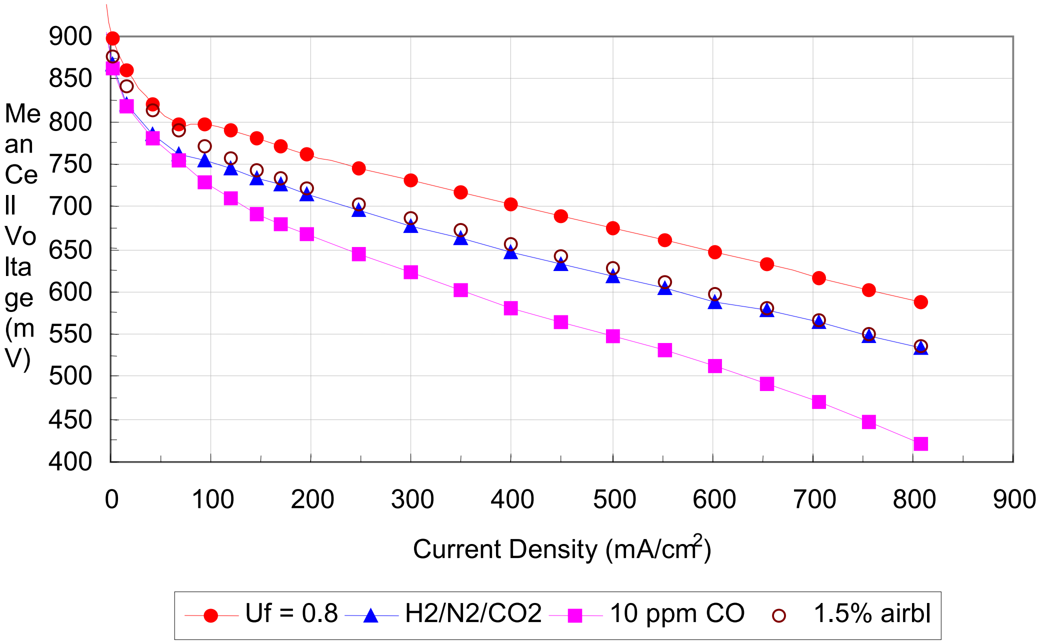


Figure 8 I-V characteristics (average performance) under H_2 , simulated reformate w/o CO, simulated reformate @10 ppm CO and simulated reformate @ 10 ppm CO and 1.5 % airbleed (T_{FC} = 65 ºC, p_{FC} = 0.15 barg).

The hydrogen utilisation of the PEMFC is about 80 % under normal operating conditions.

The architecture of the control system is given in figure 9.

The process control of the system is based on a modular rapid prototyping systeem from dSPACE. This system combines a robust processor with flexible I/O. The controller communicates exclusively via a Control Area Network (CAN) protocol. The controller and the CAN interface are mounted in a standard PC. The safeguarding of the system is done with a PLC which communicates with the process control system

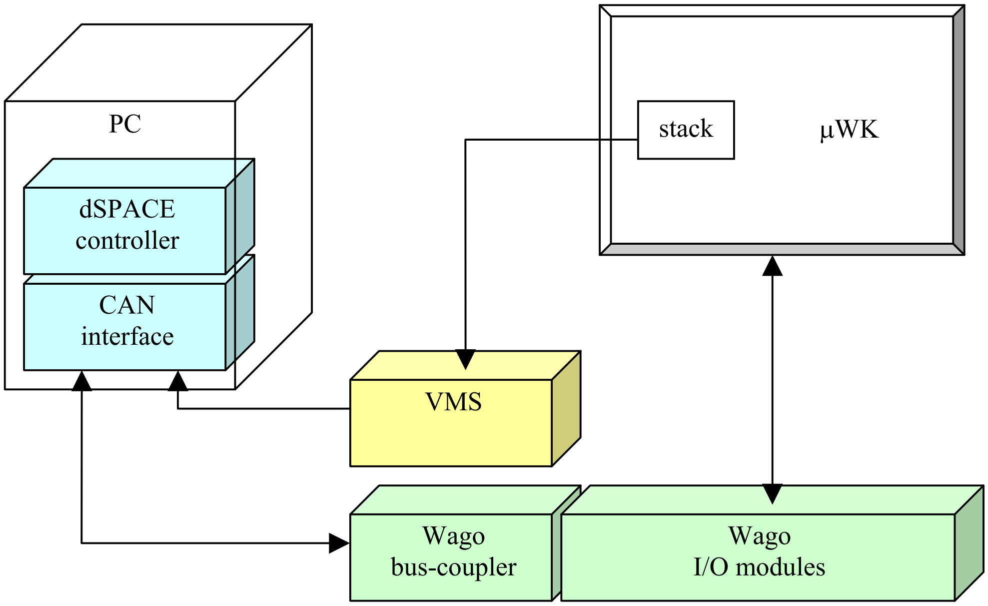


Figure 9 Architecture control system.

The Voltage Monitoring System (VMS) of the PEM stack (checking and monitoring each individual cell) is directly connected with the CAN interface.

3.2. Operational results PEM µ-CHP system

The PEMFC system has been in operation since August 2002. The system has mostly been operated for about 8 hours per day and was kept at hot stand-by conditions using the cooling loops for the PEMFC stack and the PROX reactor.

The system was operated on Dutch natural gas (table 2) and was located in- doors. During commissioning the system was tuned to deliver the reformate suitable for a PEM fuel cell. In particular, the air dosing to the PROX reactor was tuned to establish a suitable reformate for the PEM fuel cell.

Table 2 Composition Dutch natural gas.

Component	Contents (%)	LHV[1] (kJ/mol)	LHV (kJ/mol fuel)	C (mol/mol fuel)	H2 (mol/mol fuel)
N_2	13.74%	0	0	0	0
CO_2	2.37%	0	0	0.0237	0
CH_4	78.18%	-802.6	-627.47268	0.7818	1.5636
C_2H_6	4.41%	-1428.6	-63.00126	0.0882	0.1323
C_3H_8	1.03%	-2043.1	-21.04393	0.0309	0.0412
C_4H_{10}[2]	0.11%	-2657.3	-2.92303	0.0044	0.0055
$C_6H_{14}+$[3]	0.10%	-3855.1	-3.8551	0.006	0.007
Total	**99.94%**		**-718.30**	**0.94**	**1.75**

1. [Perry's 7th ed., Table 2-195]
2. Assumed to be n-butane
3. Assumed to be n-hexane

A typical start up profile of the JM P3 reformer at low throughput is given in figure 10.

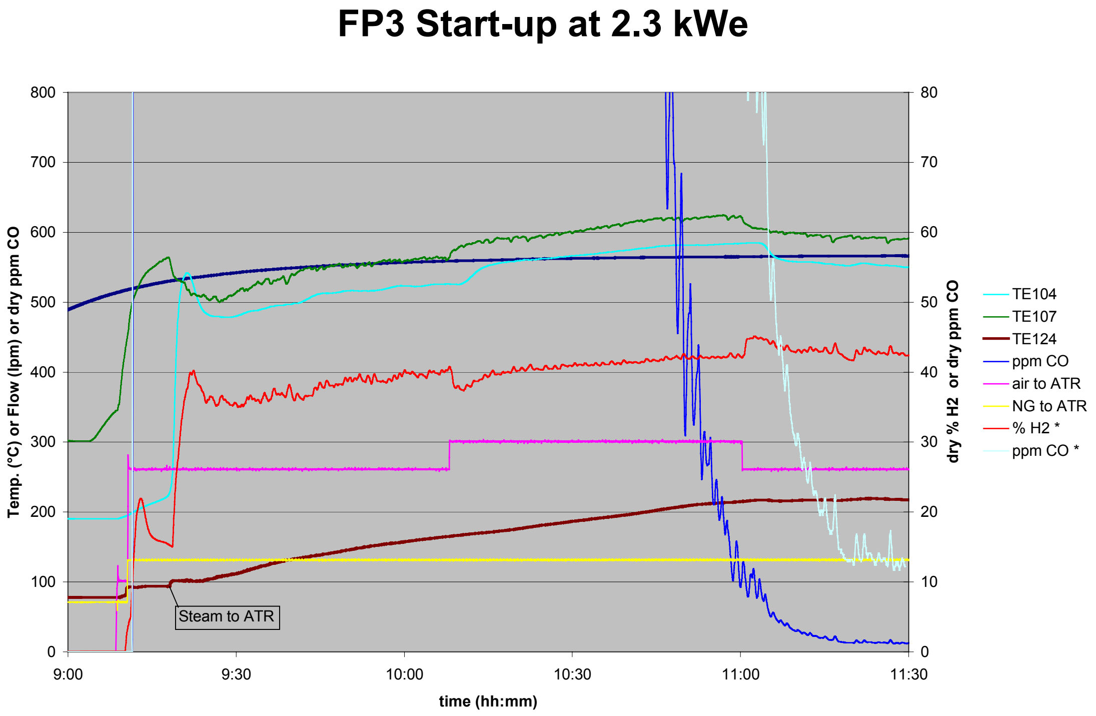


Figure 10 Typical start up profile JM P3 reformer at low throughput.

From cold conditions to reformate conditions which are suitable for the PEMFC stack (< 10 ppm CO) at reduced throughput, start-up took about 2.5 hr. From hot stand by conditions to suitable reformate sart-up took about 45 minutes. Start up time is considerably faster at nominal throughput. The P3 represents former technology, which has now been superceded.

The dynamic capabilities of the system were quite good. Typically, a instantaneous change in load of 10 % of the fuel cell , can be followed by the reformer within 30 seconds.

The gross efficiency of the fuel processor (expressed as *LHV of reformate* H_2*/ LHV nat gas feed)* varies from 70 % at part load conditions (1 kWe) to 78 % at full load conditions (10 kWe). At 2 kWe , the gross fuel processor efficiency was measured to be 74 %.

The efficiency of the PEMFC stack (expressed as *DC produced/LHV of reformate* H_2) 40 % at 2 kWe capacity and 42 % at 1kWe capacity.

The inverter in the prototype system was not optimised for this application and has an efficiency (expressed as *AC produced/DC fed*) of 90 %.

The gross system AC efficiency is therefore 25 % at 1 kWe and 28 % at 2kWe.

At 2 kWe, the cogeneration heat that can be derived from the system was measured to be 53% (LHV basis), of which 28 % can be extracted from the stack cooling system and 25 % from the flue gas leaving the after burner. Therefore, the total efficiency for this situation is 53 + 28 = 81 %.

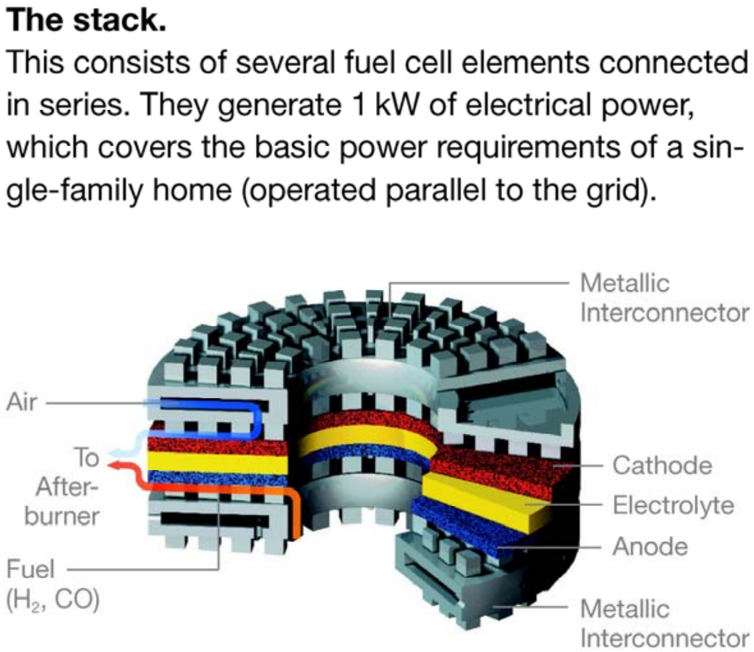
4. SOFC BASED µ-CHP

4.1. Process description

ECN operates a HXS 1000 Premiere fuel cell system which is based on a high temperature SOFC technology. The HXS 1000 Premiere system is a pre-series system and was installed at ECN in September 2002. The HXS 1000 Premiere system is designed to produce max. 1 kWe and 2.5 kWth with Dutch natural gas as fuel. An auxiliary heater cuts in automatically if required. ECN will operate the system for a period of one year and will in particular investigate the system capability for use in Dutch house holds. The HXS 1000 Premiere system can cover the basic electricity needs and the entire heat requirements of a typical European single-family home. The SOFC cells for the HXS system 1000 Premiere system are manufactured by InDEC, an independent spin-off company from ECN. These SOFC cells are integrated in a stack assembly by Sulzer, figure 11.

A.Thermal insulation
B.SOFC stack
C.Heat Exchanger
D.Heat storage tank (200 l)
E.Process control unit
F.Auxiliary burner
G.DC/AC inverter
H.Desulphurisation unit
I. Exhaust line

Figure 11 SOFC stack assembly (one cell shown).



The stack.
This consists of several fuel cell elements connected in series. They generate 1 kW of electrical power, which covers the basic power requirements of a single-family home (operated parallel to the grid).

Figure 12 Schematic Sulzer HXS 1000 Premiere system.

Natural gas is desulphurised and mixed with deionized and vaporized water. The natural gas/steam mixture is than internally reformed to reformate (i.e. fuel consisting of carbon monoxide and rich in hydrogen). The hydrogen and carbon monoxide are consumed (i.e. oxidized) in the anode compartment of the SOFC stack, operating at 900 ^{0}C. Air is supplied to the cathode compartment of the SOFC stack and the cathode exhaust air is mixed with the anode off gas which contains some water vapour and carbon dioxide which is combusted with the cathode exhaust, providing sensible heat to the heat storage vessel via heat exchanger C. The flue gas then leaves the system through exhaust pipe I.

The system is designed to produce 1 kW AC electricity, together with maximal 2.5 kW of thermal power (tap water @ 65 ^{0}C). The system is equipped with a 22 kW heater to take care of the peak demands of heat.

The system at ECN (figure 13) is equipped with a PC based control & data acquisition system. The system is also connected via a modem to Sulzer Hexis in Winterthur and can be monitored and operated from there as well.

Figure 13 Sulzer HXS 1000 Premiere system at ECN, NL.

4.2. Operational results

The HXS 1000 Premiere system was operated in a heat following mode. The initial system electrical efficiency, expressed as AC power produced vs. LHV of fuel was found to be 25-32 % at full load .The thermal efficiency of the system was found to be around 60-53 % on LHV basis and the total efficiency is therefore 85 %.

It was found a decease in electrical efficiency does occur over time , but that this decrease is highly dependant on the way of operation of the system. A strongly dynamic operation of the system will decrease the system efficiency rather fast, a gentle and steady state operation of the system is beneficial to a modest decrease in efficiency.

5. CONCLUSIONS

Review of market considerations, together with development of PEMFC and SOFC technologies for residential micro-CHP application is an important step towards realization of further cost-effective improvements in energy efficiency and emission reductions to meet the end-users growing demand for reliable heat and power supply.

A prototype PEMFC system with a Johnson Mathey P3 reformer and an ECN PEMFC stack was successfully operated for an extended period of time. The gross electrical efficiency of this system of 28 % has potential to increase to 35 % by adopting a dedicated reformer size and optimizing the stack performance. The PEMFC system is capable to operate in a dynamic mode of operation.

A pre-commercial residential SOFC system was tested in a heat following mode. The gross electrical efficiency of 32-35 % can only be maintained with a steady state operation of the system and as few disturbances as possible. The system is less suitable to operate in a dynamic mode of operation. Further developments in stack technology have the potential to increase efficiencies to above 40 % and a higher degree of robustness.

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