Rapport SGC 223

ComfortPower

Design, construction and evaluation of a combined fuel-cell and heat pump system.

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Summary

Catator AB has constructed, commissioned and evaluated a combined fuel-cell and heat-pump system (ComfortPower). The project was co-financed by a number of partners: Swedish Energy Agency through Swedish Gas Centre (SGC), Catator, Alfa Laval, Nibe, Skanska and Swedish Defence Materiel Administration (FMV).

The basic idea behind the project was to demonstrate the possibility to achieve ultrahigh thermal efficiencies when combining fuel-cell technologies and heat pumps. Moreover, the system should provide a great flexibility with respect to the fuel mix and should in addition to heat provide surplus electricity and cooling.

The system was built on a HT-PEM platform (high temperature polymer electrolyte fuel cell from Serenergy a/s), which was operated by Catators proprietary Optiformer technology. The power generator was combined with a heat pump module (F1145-5, 230 V), supplied by Nibe. The system was packaged into a cabinet (1.65 x 0.6 x 0.6 m) comprising the power module, the heat pump, all necessary balance-of-plant components and the control system. The power output from the fuel-cell system was around 1.35 kW, which enabled operation of the heat pump compressor. By utilizing surplus heat energy from the fuel cell it was possible to achieve a favourable operation point in the heat pump system, resulting in a high overall COP (coefficient of performance). The heat output from the system was as high as 10 kW whereas 6 kW cooling could be provided. The thermal efficiencies measured in experiments were normally around 200%, calculated on the lower heating value of the fuel.

A number of fuels have been investigated in the fuel cell system, including both gaseous (natural gas/LPG) and liquid fuels (alcohols and kerosene). Indeed, the system has a wide fuel flexibility, which opens up for a variety of applications in campus villages and buildings.

This study has demonstrated the possibility to reduce the carbon dioxide footprint by a factor of 2 over conventional boilers in heating applications. In addition the unit can be operated on a variety of fuels and can produce cooling and electricity in addition to heat. A fully working system has been designed, packaged and fitted with an advanced control system.

The addressable market for the system is huge in countries where fuel gases are used for heating, which indeed is the normal case. In countries like Sweden, where the electricity grid is relatively much more developed than the gas distribution grid, the market potentials are less favourable. A simple energy analysis, however, indicate a higher global thermal efficiency when using distributed heat production (ComfortPower) compared to a normal heat pump utility using electricity from the grid produced at an overall moderate efficiency (normally 30-40%) in a central power plant. The reason for this finding is that the residual heat from the power plants cannot be used in distributed heat pump utilities. The large-scale similarity would be to combine district heating with heat pumps. This would, however, demand a duplicate infrastructure, which is uncommon – at least outside Sweden.

Continued work should be directed to a careful optimization of the system to gain additional efficiency. Minor system modifications involving balance-of-plant components should also be undertaken. The thermal efficiency in the system is expected to reach 225-250% following such measures. In addition to these efforts a long-term test should be performed to gain information on reliability and system stability. This test should preferably be performed with biogas as the fuel.

By exchanging the HT-PEM with a SOFC (Solid Oxide Fuel Cell) it would be possible to reach thermal efficiencies close to 300%. This potential achievement is explained by a relatively higher electric efficiency in a SOFC-system (around 50% instead of 30%). The SOFC-technology is less mature than the PEM-technology even if improvements are made rapidly. The continued work should also address the choice of fuel cell from a theoretic viewpoint as an addition to the system related studies proposed on the existing system.

Sammanfattning

Catator AB har designat, driftsatt och utvärderat ett system bestående av bränslecellsaggregat och värmepump (ComfortPower).. Projektet delfinansierades av en rad företag: Energimyndigheten via Svenskt Gastekniskt Center (SGC), Catator, Alfa Laval, Nibe, Skanska och Försvarets Materielverk (FMV).

Den grundläggande idén bakom projektet var att demonstrera möjligheterna att uppnå mycket höga termiska verkningsgrader då man kombinerar bränslecells- och värmepumpsteknik. Vidare var avsikten att påvisa bränsleflexibilitet och möjligheterna att samtidigt kunna generera kraft och kyla.

Systemet baserades på en HT-PEM-stack (högtemperaturpolymerbränslecell från Serenergy a/s), som försörjdes med reformatgas från Catators Optiformer system. Kraftenheten kombinerades med en värmepumpsmodul (F1145-5, 230 V) från Nibe och samtliga systemkomponenter paketerades i en enhet med yttermåtten 1.65 x 0.6 x 0.6 m. Enheten kunde producera ca 1.35 kW el, vilket var tillräckligt för att driva värmepumpssystemets kompressorenhet. Genom att utnyttja restvärmen från kraftenheten, kunde en fördelaktig driftpunkt uppnås i värmepumpsystemet, vilket medförde höga prestanda (ökat COP-värde). Experimenten visade att enheten kunde leverera drygt 10 kW värme och ca 6 kW kyla. Den termiska verkningsgraden för systemet uppmättes till värden kring 200%, beräknat på bränslets effektiva värmevärde.

Ett antal olika bränslen har studerats i kraftenheten, bl.a. energigaser såsom naturgas och gasol samt vätskeformiga bränslen såsom alkoholer och fotogen. Systemet har en stor bränsleflexibilitet, vilket öppnar upp för många tillämpningar inom fastighetsuppvärmning samt i tälttillämpningar.

Studien visar att koldioxidavtrycket kan minskas till hälften genom att använda ComfortPower i stället för konventionella pannor. Dessutom kan enheten drivas med ett stort antal olika bränslen samt genererar förutom värme även kyla och kraft. I denna studie har ett komplett och paketerat system involverande ett avancerat kontrollsystem designats, byggts och utvärderats.

The adresserbara marknaden för ComfortPower är enorm i länder där energigaser används för uppvärmning, vilket är den normala situationen. I vissa glest befolkade länder (t.ex. i Sverige), där kraftnätet är mer utbyggt än gasnätet är marknadsituationen mindre gynnsam. En energianalys visar att det är mer fördelaktigt med decentralicerad kraft- och värmeproduktion (ComfortPower) i förhållande till värmepumpsystem som drivs via elnätet där elen producerats i centrala anläggningar med medelmåttig verkningsgrad (typiskt 30-40%). Anledningen till detta är att restvärmen som produceras vid elgenereringen inte går förlorad i ComfortPower utan används till att optimera värmepumpsystemets prestanda. En storskalig analogi skulle vara att nyttja värmepumpsaggragat i kombination med fjärrvärme men detta förutsätter en relativt ovanlig och komplicerad infrastruktur – åtminstone utanför Sverige.

Fortsatt arbete bör inriktas på en omsorgsfull optimering av systemet för att öka verkningsgraden. Mindre systemmodifieringar innefattande utbyte av vissa delkomponenter bör också genomföras. Den termiska verkningsgraden förväntas nå 225 - 250% efter dessa åtgärder. Förutom denna optimering bör långtidsutvärderingar genomföras för att få

ytterligare information om tillförlitlighet och stabilitet hos systemet. Långtidstestet kan lämpligtvis utföras med biogas som bränsle.

Genom att byta HT-PEM-stacken mot en SOFC-stack (fastoxidbränslecell) så kan den termiska verkningsgraden ökas till nästan 300%. Denna ökning förklaras av att SOFC-tekniken möjliggör högre elektriska verkningsgrader (ca 50% I stället för ca 30% hos HT-PEM). SOFC-tekniken är mer omogen är PEM-tekniken, även om framsteg sker snabbt. En teoretisk studie bör dock genomföras för att i detalj undersöka effekterna av ett byte av bränslecellsteknik.

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1. Introduction

The industrialisation process was initiated some centuries ago and led to the evolution of the industrialised part of the world. This process has gone hand in hand with increasing energy consumption and environmental pollution. The developing economies will most probably increase their energy consumption rapidly during the next few centuries in order to enhance the social welfare of their societies. The increasing consumption of fossil fuels together with a inadequate thermal efficiency in most existing thermal processes will lead to extensive pollution problems and to a drain of existing fossil energy resources. This leaves us with a devastating scenario concerning global energy supply and environmental pollution.

There is a growing international consensus that the existing methods of power and heat generation need to be improved to enable the evolution of an ecologically sustainable global society. The long-term solution will include a variety of efficient energy production methods based on renewable sources.

The building sector alone stands for 25-30% of the energy consumption [1] and hence it is extremely important to address this market with technologies capable of reducing the energy waste. Energy conservation, smart buildings with passive heating, improved insulation will help us to decrease the energy consumption. In parallel it is equally important to address new and improved methods to produce heat in an economic and environmentally friendly way.

The fuel cell technology might be one important ingredient in the future energy system, enabling us to reach higher conversion efficiencies in the conversion of fuel energy into electricity. Indeed, there are a number of impressive programs running involving fuel-cell systems in combined heat and power systems (e.g. in Japan, Germany, UK and Denmark) [2,3]. All these programs focus on decentralized production of electricity. The rational is to achieve a better balance in the grid and to increase the flexibility. Most units are powered by fuel gas even if the Japanese program also involves units operated by kerosene. The units are typically around 1 kW in electricity, suitable for an ordinary household.

Sweden has no comprehensive national fuel cell program and the efforts in this field have merely been directed to theoretical paper studies and technology reviews. There are a number of companies in Sweden, which are involved in the international fuel-cell industry and may contribute to the Swedish technology export even if the domestic fuel-cell industry is expected to remain small.

Swedish heat-pump industry is world leading, which might be explained by the fact that electricity is readily available within Sweden. Heat pumps for heating purposes is more common in countries were the electricity grid dominates over the gas distribution system. On the contrary, combined heat-and power is believed to play a significant role in countries with a poor electricity grid and an established gas distribution system. The latter situation is most common from an international perspective.

By combining fuel cell systems with heat pumps it is possible to achieve peak performance with respect to efficiencies in heat production. When electricity is produced in ordinary power plants (nuclear, gas, oil, coal), 60 – 70% of the fuel energy is lost in the condenser. The remaining part is converted into electricity. In hydroelectric power (common only in a few countries), the efficiency in electricity production is very high. Large-scale combined heat-and power systems (district heating) is also a way to reduce the losses from energy conversion since the heat produced can be used for heating purposes.

A system involving a fuel-cell system and a heat pump will provide a unique synergy since the residual heat produced by the fuel-cell system can be used in the heat pump to improve the operating point, i.e. the coefficient of performance (COP). The result is a system that produces electricity with a high efficiency and where the residual heat is used to improve the capability of the heat pump to collect additional heat from the environment. The thermal efficiency might be between 200 and 300% depending on the choice of fuel cell technology and system layout. Indeed, it should be possible to reduce the carbon dioxide footprint by a factor 2-3 by replacing conventional boilers with fuel cell/heat pump hybrids.

In addition to heating these units will provide cooling and surplus electricity. By using suitable technologies in the fuel processing it is also possible to add fuel flexibility, which decreases the vulnerability in the society.

Catator has been working with small-scale fuel processing and fuel cell systems during the last decade. A number of complete fuel cell systems have been designed and evaluated over the years. Based on these systems, a lot of experience and knowledge has been developed, which can now be exploited in this project. The aim with this project is to design, construct and evaluate a combined fuel cell- and heat pump system.

2. Background

The focus on environmentally friendly fuels and effective energy conversion has increased during recent years. Great progresses have been accomplished in the field of biogas and increasing amounts of this renewable fuel is now supplied to the Swedish gas distribution system [4]. In parallel increasing attention has been paid to gasification and production of synthetic energy gases and fuels. In the long term renewable fuels are expected to replace large quantities of the fossil fuels. During this transition period it important to design fuel flexible energy systems. The biogas potential in Sweden is believed to be close to 20 TWh/a [5].

The second corner stone in a sustainable energy system is to provide technologies with peak efficiency in the energy conversion. This aspect will be applicable both in both power- and heat generation. Small scale heat- and power production is possible via a number of technologies like heat engines, fuel cells and solar cells but large-scale implementation is currently hindered by cost aspects. Decentralized heat-and power generation will in addition provide less vulnerability in the energy system, a lesson learned following natural disasters like the hurricane Gudrun in 2005.

During recent years, Catator has developed a number of reactor systems for small-scale production of hydrogen rich gases from various renewable and fossil gaseous and liquid fuels. During 2007/08, the Optiformer concept was developed [6] as a compact and lightweight thermo-mechanic stable and fuel flexible reformer system. The unit can be operated at atmospheric conditions but might also be pressurized in applications including reformate purification with pressure-swing adsorption or membrane technologies.

In parallel activities in the reformer area, Catator has conducted extensive studies on complete fuel-cell systems, including various fuel cell technologies on the request on the Defence Materiel Administration (FMV). During this program it was realized that it should be possible to develop an efficient and fuel flexible power unit based on Catators proprietary reformer technology in combination with a HT-PEM fuel cell. This fuel cell concept offers advantages with respect to variations in the gas quality and provides a simple, reliable and highly controllable unit on a system level. The electric efficiency (from fuel to electricity) can be as high as 35%, even if it is more realistic to expect values between 25 and 30% in the field.

The heat pump industry in Sweden is world leading and developing rather rapidly. A normal heat pump is powered by electricity and heat is taken from various sources like air, water or from the soil. The performance of the heat pump system will depend on the temperatures in the pressurized circuit. Indeed, the smaller the temperature difference is, the higher will the coefficient of performance (COP) become. In a normal heat pump system we often see limitation with too low temperatures in the evaporator and too high temperatures in the condenser, which will lead to moderate COP-values – normally around 3 on a yearly basis. If it were possible to add heat to the heat pump, the operation point of the heat engine can be improved to yield higher COP-values. Indeed, the exhausts from the fuel cell system might be used for peak heating purposes and to increase the temperature on the cold side in the pressurized circuit (residual heat and water condensing). The water, which can be collected on the cold side, will make the fuel cell system independent in water supply. It is realistic to achieve average COP-values of about 5 in a combined heat-pump/fuel cell system.

Figure 1 below is a schematic representation of the normal case for a heat pump and the combined heat pump/fuel cell system. In the normal case, fuel is supplied to a central power plant, producing 30 – 40% of electricity from the fuel. The residual heat, which is recovered in the condenser, is normally a waste except when district heating systems are available. If this electricity is used for heat production in a heat pump system the efficiencies are between 90 and 120% calculated on the lower heating value of the fuel. Moreover, the conventional way of producing electricity from fuels is via solid fuels like coal or brown coal. This technology results in excessive emissions of greenhouse gases.

In the combined system we can use the heat to provide a better operation point for the heat pump and simultaneously utilize the heat generated in the fuel cell system. With a COP of 5, we can rather easily achieve efficiencies between 200 and 250% bases on the lower heating value of the fuel. Indeed, by using the optimal fuel-cell technology (SOFC with internal reforming), it should be possible to reach efficiencies around 300%. This approach is currently somewhat more immature than the PEM-technology but progresses are made quickly.

Of course, this picture can be discussed, at least in Sweden, where we produce a lot of electricity from hydroelectric facilities and where we use a lot of district heating. In most other countries, however, this picture is indeed extremely valid.

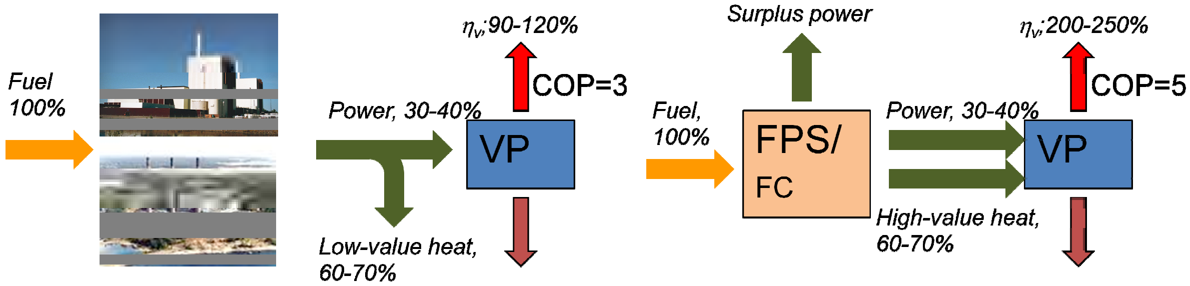

Figure 1 Thermodynamics of ComfortPower

The pie diagram in Figure 2 is a breakdown of the energy consumption in various sectors, both in Sweden and within EU [7]. The transportation sector in this case is not restricted to road transportation but includes rail-, air -and sea transportation.

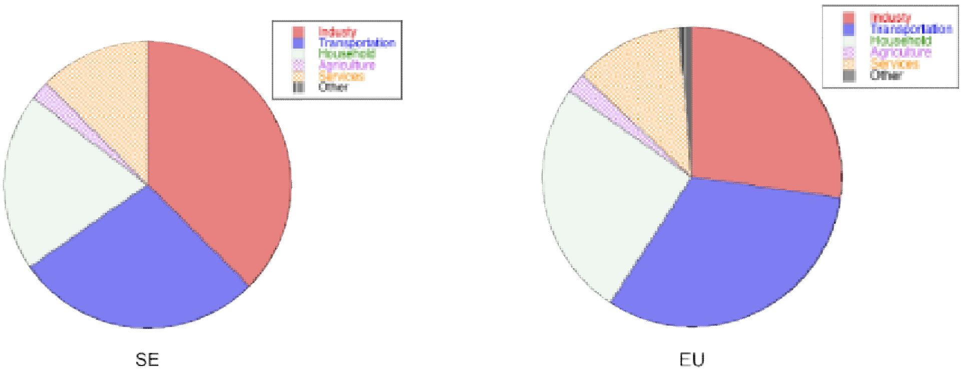

Figure 2 *Pie diagram of energy consumption within Sweden and EU. Total consumption, EU: 1160 Mtoe/a, SE: 32 Mtoe/a (2008) [7]. 1 toe=42 GJ.*

The breakdown shows some differences between Sweden and EU (27 countries). In this kind of statistics there always is a degree of uncertainty about how different segments are defined. Industries use relatively more energy in Sweden as compared to EU whereas the household part in Sweden is a bit smaller than in EU.

Electricity is a common energy source to heat houses in Sweden, which is in contrast to the situation in most other countries [8]. In Sweden about 50% of the energy consumption in houses is provided as electricity whereas the same figure within EU (27 countries) is less than 25% [8]. The normal way of heating houses (and buildings in general) in most countries is with gas boilers. The total consumption of natural gas for heating purposes (about 30% of the total gas consumption) within EU (27 countries) is about 1,500 TWh/a [9].

If modern boilers working at an average efficiency of 100% related to the lower heating value were replaced by the ComfortPower technology it should be possible to reduce the primary energy consumption (and carbon dioxide emissions) by at least 50%. This corresponds to 750 TWh and 150 Gkg of CO_2. The energy related challenges within EU is divided into the following areas [10]:
- Climate change
- Increase of emissions
- Growing dependence on imported fossil fuels
- Increasing energy costs
- Falling competitiveness

The ECO directive will put commercial light on energy efficiency in the energy conversion (high efficiency) and reduced carbon dioxide footprint (less emissions) [10]. Apart from legislative advantages resulting in top positioning (energy and comfort rating), the ComfortPower concept will offer advantages to the user with respect to fuel flexibility (renewable option) and by its output flexibility (heat, cooling or power).

3. Aims and objectives

The overarching objective is to design, construct and evaluate a combined power-and heat unit, which can be combined with a heat pump system for achieving peak thermal efficiencies. The system is expected to give the following maximum output capacities:

- heat, 10 kW
- cooling, 6 kW
- power, 1.5 kW

The study is divided into four consecutive phases according to:

1) System design and choice of components
2) Construction and packaging
3) Implementation of control system
4) Verification tests with gaseous and liquid fuels

The following results can be derived from this study:

a) Design principle for the complete system and expected performance data
b) A packaged system including power unit, heat pump, balance-of-plant system and control logics
c) Experimental data from verification tests with the power unit and the complete system
d) Suggestions concerning improvements and continued activities

The project is conducted during the period 2010/Q1 – 2010/Q3.

4. System description

The ultimate solution would be to go directly from chemical energy to electric energy without generating heat. In reality, however, production of electricity always result in energy losses. The most common way to produce electricity is via thermal cycles, either in large power plants or in heat engines. The efficiency will depend on the thermal cycle and any losses in the process. Small-scale production of electricity can be realized in small heat engines equipped with generator systems. Larger units (>5 kW) based on heat engines may give reasonable electric efficiencies (normally above 30% under optimal conditions). Downsizing such systems will, however, lead to poor efficiencies due to increasingly severe effects of internal friction in moving parts and thermal losses. At power outputs around 1 kW, it is unlikely to find commercial systems based on heat engines that provide higher efficiencies than about 15%.

The efficiency in heat engine powered systems is also highly depending on the load condition; at part load the efficiency is only a fraction of the value at optimal conditions.

The power generation in a fuel cell relies on electrochemistry and ion transport through membranes. A fuel cell contains no moving parts and hence no friction losses are possible. This opens up for small systems with reasonable high efficiencies and a wide turndown ratio. Indeed, it is possible to reach electric efficiencies as high as 50% in units as small as 1 kW.

Fuel cells normally demand hydrogen as a fuel even if some fuel cells can use carbon monoxide and some simple fuels like methane and methanol. A logistic fuel consequently needs to be transformed into a hydrogen rich gas in a fuel processor. Apart from hydrogen, the reformate gas from the fuel processor will also contain various amounts of different species, some of which might act as poisons in the fuel cell. Such species need to be removed upstream the fuel cell in a purification device.

Figure 3 shows a block diagram including the most important steps when producing electricity in a fuel cell system. The key elements are the reformer and the fuel cell itself. Depending on fuel choice and fuel cell type, the demand on sulphur- and CO removal will vary. The amount of heat exchange will also vary depending on the fuel-cell technology.

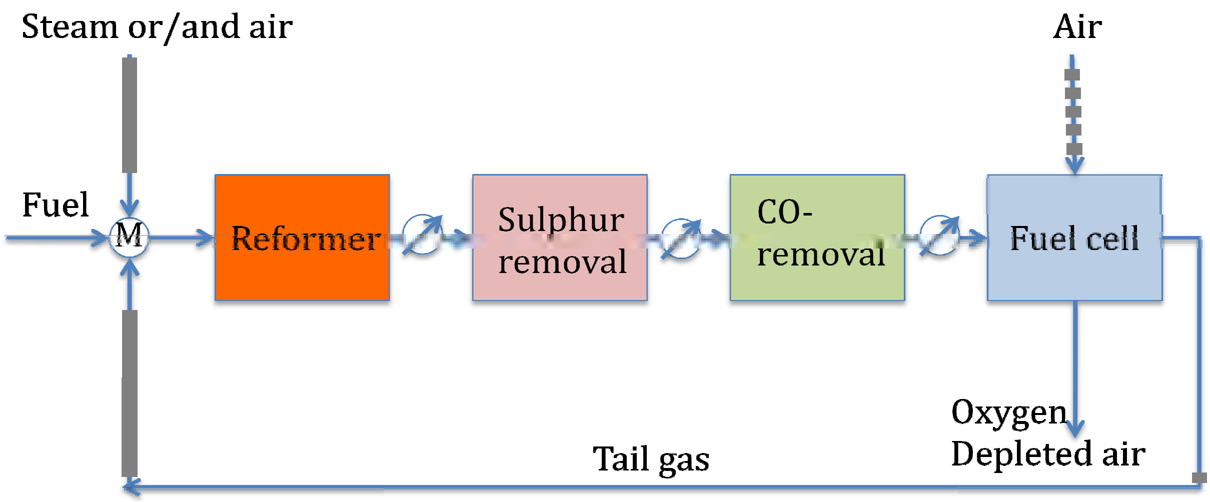

Figure 3 Block diagram, fuel to electricity
Gas purification and degree of heat exchange will depend on fuel choice and fuel-cell technology

A number of reformer technologies are available, giving different efficiencies in the conversion between fuel energy and hydrogen energy. Steam reforming is the most novel form of fuel processing giving high hydrogen yields and high efficiencies. Such devices are relatively more complicated and bulky than simpler devices for auto-thermal reforming or catalytic partial oxidation. Figure 4 below show the differences between the different technologies available. In auto-thermal reforming and catalytic partial oxidation, air is used in the reactor system and the reformate will contain nitrogen. Small amounts of ammonia might be formed, which act as a severe poison on some fuel cells (polymer electrolyte fuel cells).

There also exist non-catalytic partial oxidizers based on thermal oxidation or plasma supported thermal oxidation.

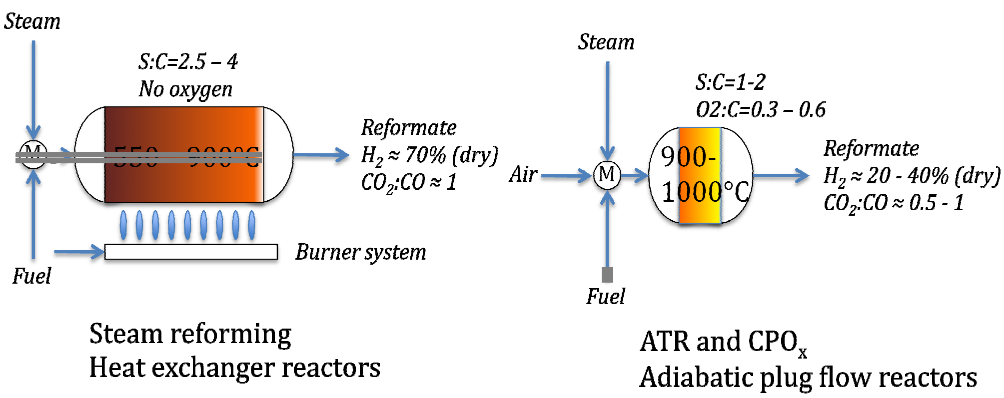

Figure 4 Various reformer technologies

There are also a number of fuel-cell technologies available on the market. They operate at various temperatures and are constructed from various materials. The most common types of fuel cells are abbreviated SOFC (Solid Oxide Fuel Cells) and PEM (Polymer Electrolyte Fuel cell). Other types of fuel cells are Alkaline Fuel Cells (AFC) and Molten Carbonate Fuel Cells (MCFC). Figure 5 below summarizes some characteristics for the various fuel cells.

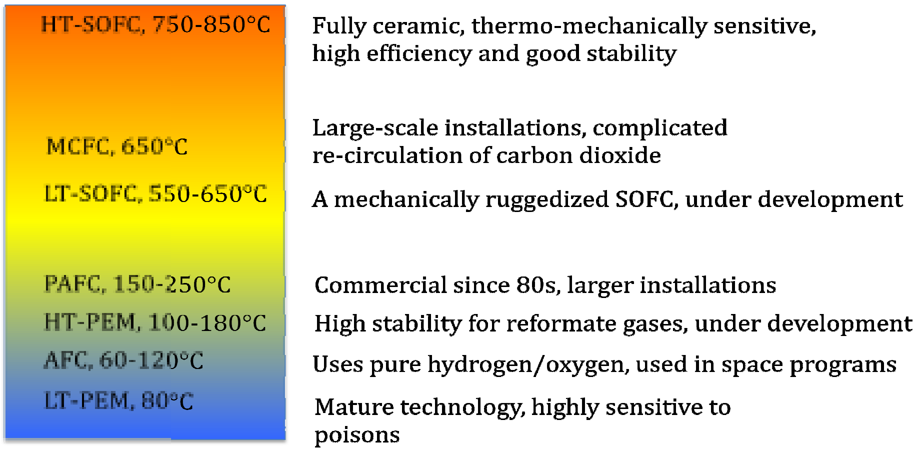

*Figure 5 Different fuel cell technologies
SOFC=solid oxide fuel cell, MCFC=molten carbonate fuel cell, PAFC=phosphorus acid fuel cell, PEM=polymer electrolyte fuel cell, AFC= alkaline fuel cell.*

High-temperature alternatives will offer electrochemical advantages (high efficiencies and insensitivity to poisons) but suffer from material problems. The HT-PEM concept is a compromise between efficiency, insensitivity to poisons and mechanical robustness.

Even if the conversion efficiency between fuel energy and electricity can be high in a fuel cell system, a lot of residual heat will be produced. In most combined heat- and power units, the focus has been on power generation and little attention has been paid to an efficient use of the residual heat. By combining the fuel-cell system with a heat pump system, the efficiency in heat recovery can be very high. The ratio between the output of the power module (fuel cell system) and the electricity consumption of the compressor system may be tailored according to the application. In some cases the unit is grid connected and in some cases the unit shall operate independently of the electric grid. In some cases power production is in focus and in other cases heat- and cooling are in focus. Figure 6 shows the thermal efficiency of various heating devices.

Traditional non-condensing boilers generally had a poor thermal efficiency, typically 60 – 70%. During the last decade there has been a paradigm shift from non-condensing to condensing boilers and efficiencies are generally around 105% today, calculated on the lower heating value.

New trends include hybridization of condensing boiler swith solar energy and heat pump devices, which has the potential of improving the thermal efficiencies further. Combined heat- and power, which might include small heat engines (preferably Stirling engines) or fuel cells, will improve the energy efficiency further. The ComfortPower technology will add significant improvements to the primary energy efficiency, when implemented into the market.

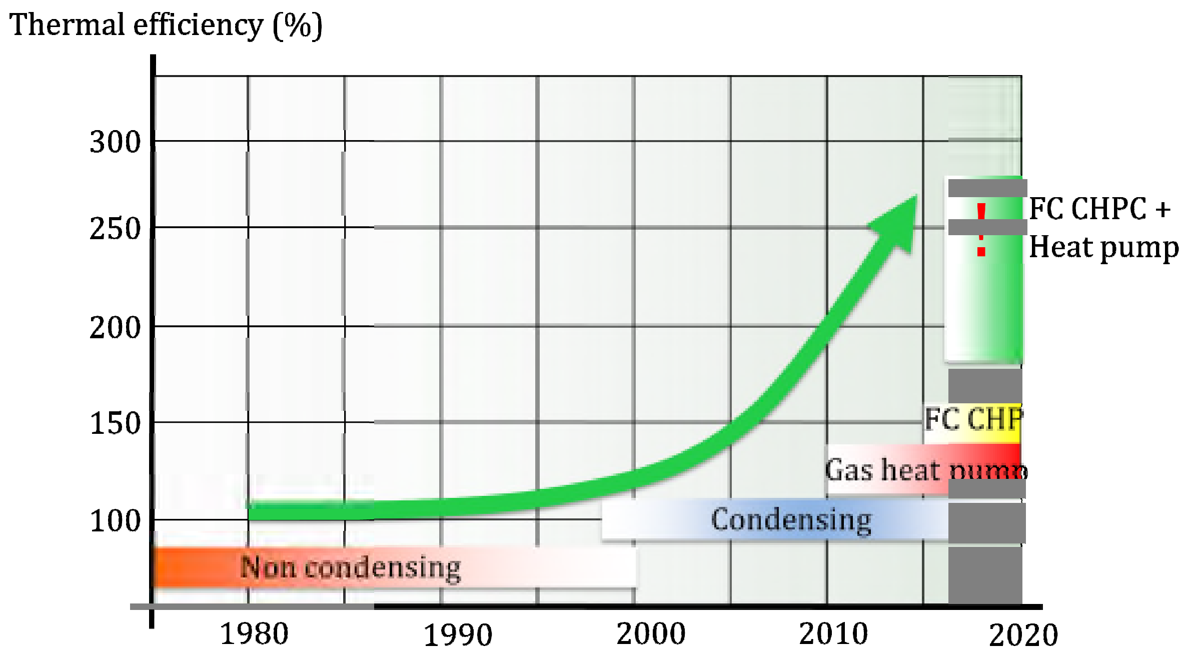

Figure 6 *Efficiencies and trends in the European boiler market [ref]. Credit for power supply from CHP.*

It is quite clear that the combination of fuel cells and heat pumps is a way to reach peak performance with respect to thermal efficiencies. Every year between 6 and 7 million of boilers are sold within EU, about 30 million worldwide. A modern condensing boiler will enable a thermal efficiency slightly above 100% calculated on the lower heating value of the fuel. The ComfortPower technology should enable a dramatic decrease in fuel consumption and greenhouse emissions, if widely implemented.

5. Fuel processing

As discussed previously one could distinguish between steam reforming (SREF), auto-thermal reforming (ATR) and catalytic partial oxidation (CPOx). In choosing between the operation principles it is of importance to take system complexity and efficiency into consideration.

SREF will give the highest efficiency and relates to a coupling between an exothermic reaction and an endothermic reforming reaction in a heat exchanger reactor. Catator has previously designed and evaluated SREF-units equipped with gas purification (Ultraformer and Optiformer) [11]. The Optiformer concept has been validated for jet fuel containing up to about 300 ppmw S with low reformate concentrations of olefins/aromatics. By utilizing tail gas from the fuel cell on the exothermic side of the heat exchanger it is possible to reach efficiencies close to 100% on a reformer system level. The drawback of SREF is is directed to the inherent complexity of such systems with integral burners, evaporators, coolers etc. Furthermore, such systems are difficult to design as “water-free” systems, even if some water can be recovered from the fuel cell outlets. Another problem is associated with thermo-mechanical issues (crack formation) during rapid cycling at extremely high temperatures (900°C+). The Optiformer concept is however much more reliable than the Ultraformer concept in this sense.

Auto-thermal reforming is an intermediate between SREF and CPOx and will give efficiencies as high as 80% with appropriate heat recovery and possibly tail gas re-circulation. In ATR, steam, air and fuel are mixed up-stream a catalytic step. The exothermic oxidation is balanced by the endothermic reformation and inlets-and outlet temperatures are rather equal. The reactor design is very simple and problems associated with thermo-mechanical issues can be avoided.

Catalytic partial oxidation is probably the easiest way to produce reformate, but unfortunately at a low efficiency (typically below 60%). One way to improve the efficiency and widen the window of operation is to re-cycle tail gas to the inlet. By utilizing tail gas re-circulation, it is possible to avoid coke formation and to reduce the risk of catalyst overheating. The reactor design is similar to the ATR-case.

CATs ATR/CPOx-technology is abbreviated Multiformer since it characterized by fuel flexibility. It can run as a pure CPOx-unit with/without tail gas recirculation or as a ATR-unit with external steam/water-supply. It consists of two catalytic zones and one insulated gas volume (hot spot). The basic idea is to initiate and complete the combustion process in the first catalytic section and then to generate a peak temperature in the gas volume. The majority of the reforming reactions are then conducted in the second catalyst bed. The peak temperature varies with the fuel quality but could be as high as 1000°C+, measured in the hot-spot section. The Multiformer is equipped with a low-pressure atomizer and mixer located upstream the first catalytic section. The reactor has an internal insulation and a fully ceramic lining in the hot spot section. The unit has an air jacket for reducing the skin temperature and increasing the inlet air temperature. The fuel inlet line is cooled to avoid gum- and coke formation in the delivery line. Figure 7 presents Catators different fuel processors.

When using fuels with an extremely high sulphur level (500 ppmw+), the performance can be improved by installing a 2nd reactor with a separate air inlet downstream the main reactor. This will add one mixing step and one supplementary catalyst section.

The hexiformer concept is based on plates coated with catalyst and assembled into a plate-type device. It is possible to add heat on one side of the plate via combustion end extract the heat from the other side via an endothermic reaction. Such plate-type reformers can be used in- low and medium temperature applications, where possible issues with thermo-mechanic failures can be handled. The may typically be used in reforming of alcohols and low-sulphur kerosene.

The reactor is constructed from high-temperature stable alloys whereas the catalytic wire meshes are base on FeCrAlloy or similar materials.

Figure 7 *Fuel processor types provided by Catator*
Optiformer – SREF/WGS, thermo-mechanical ruggedized
Hexiformer – plate type catalytic reactor
Multiformer – ATR and/or CPOx

Figure 8 shows the reformate compositions when steam reforming different gaseous and liquid fuels. The natural gas contained 89% methane, 9.9% higher hydrocarbons and about 1% inert components.

The kerosene used in the study was obtained from Japan. Light kerosene contains about 7% aromatic compounds whereas heavy kerosene contains about 22%, mainly as complex aromatics. The sulphur contents were in all cases (except for the jet fuel, which contained 280 ppmw sulphur) less than 10 ppmw, corresponding to less than 1 ppmv of H_2S in the gas-phase.

No heavy hydrocarbons could be detected in reformate from natural gas and methanol. In diesel and kerosene reforming, minor amounts of unsaturated and aromatic hydrocarbons were formed. The amount of such components will increase with sulphur level in the liquid fuel, i.e. jet fuel gave more heavy hydrocarbons than sulphur free kerosene.

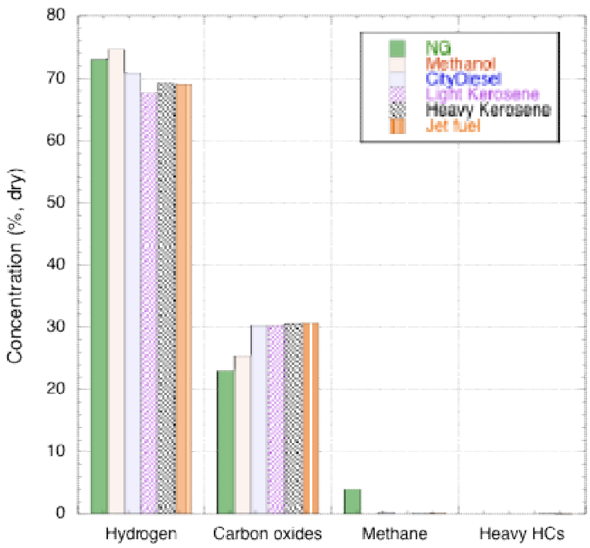

Figure 8 *Typical performances in steam reforming of various fuels.*
Heavy HCs less than 0.1 % in all cases.

Depending on the choice of fuel cell technology different measures are necessary to purify the reformate gas, especially with respect to sulphur.

6. Fuel-cell system

There are in reality two types of fuel cells available for the ComfortPower system, i.e. HT-PEM and SOFC. It were in principle also possible to use the low-temperature version of the PEM-technology, but this would require a relatively more complicated system architecture with extensive gas purification.

The basic difference between the PEM and the SOFC is associated with the transport mechanism across the electrolyte. Hence, in the PEM, hydrogen ions (protons) are transported whereas oxygen ions are transported in the SOFC. As a consequence, all reducing gases are in principle fuels in a SOFC whereas only hydrogen will work as a fuel in the PEM. Indeed, it is well known that CO is a fuel in SOFC. A number of researchers have tried to use hydrocarbon directly in the fuel cell with poor results. Coke will form by decomposition of any hydrocarbon at temperatures prevailing in the SOFC, eventually coating all metallic surfaces and clogging the system. If enough steam is supplied together with the hydrocarbon, steam reforming will proceed in parallel to the electrochemical process. Steam reforming will decompose the hydrocarbons into hydrogen and carbon oxides and simultaneously provide some cooling of the stack. The presence of sulphur will, however, effectively inhibit the reforming reactions while leaving the electrochemical processes unaffected.

Nernst equation is the basis in modelling a fuel cell. For the electrochemistry we can write:

$E=-\Delta G/(n \times F) + R \times T/(n \times F) \times \ln (\{O_2\}^{0.5} \times \{H_2\}/\{H_2O\})$, where

E = Electrode potential (V)
ΔG = Gibbs free energy (J/mol)
F=Faradays constant
R=Gas constant
n=number of electrons involved
{specie}=activity, in this case pressure (atm)

Nernst equation describes the reversible energy in an electrochemical reaction. The reversible energy may be taken out as electricity whereas the irreversible part will result in heat. The ratio between the reversible and the total energy is the electric efficiency. Moreover, the electrochemical reactions are complicated by activation-, polarization- and diffusion phenomena, which will influence on the activity of the reacting components in Nernst equation. Such phenomena are influenced by the reaction rate and the mass-transfer characteristics in the system.

Figure 9a a and b shows the transport processes in the different fuel cell types.

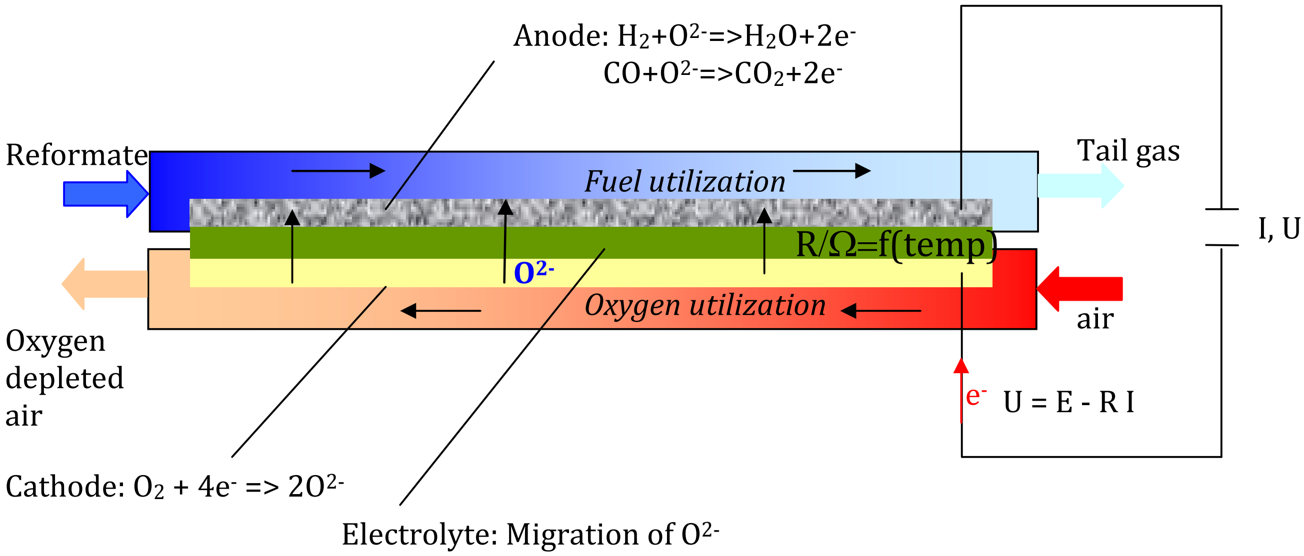

Figure 9a, Solid Oxide Fuel Cell

When the SOFC is subjected to load (current is increased), we shall se a consumption of hydrogen/carbon monoxide, thus lowering the cell potential according to Nernst equation. Simultaneously, a resistance (Ohmic) will emerge in the SOFC, which will further decrease the cell potential depending on load and temperature conditions. The overall relative fuel consumption is called fuel utilization and shall preferably be around 70-80%.

In the PEM, similar physical phenomena msut be taken into consideration with the clear difference that hydrogen ions are transported instead of oxygen ions. The ion conductivity of the membrane is much higher than in the SOFC-case and the window of operability ranges from about 100 to 170ºC. Hydrogen is the only usable fuel in this kind of fuel cell and all other fuel molecules are left unconverted.

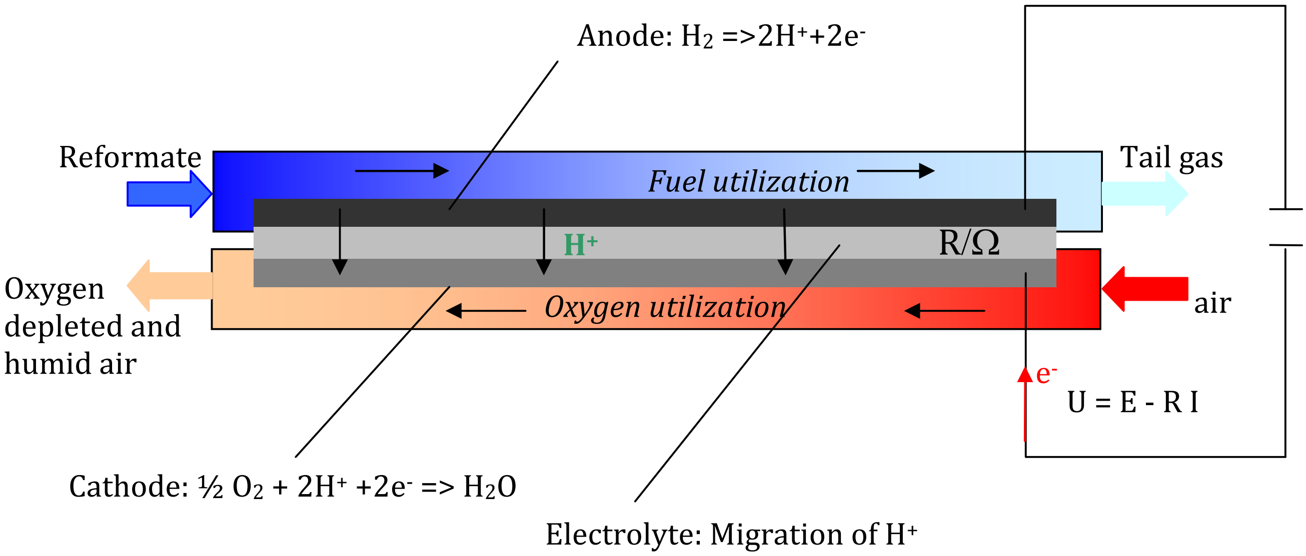

Figure 9b, Polymer Electrolyte Fuel Cell

Table 1 and 2 summarizes the specification and our observations and expectations for the SOFC and HT-PEM-stacks.

Table 1 SOFC-characteristics

Parameter	*Recommendation*	*Experience*
Gas on anode side	<250°C, no CO allowed >250°C, reducing cond.	OK OK
Air quality	No moisture allowed	OK
Heating conditions	10° C/min <150°C gradient within SOFC <800°C maximum	OK OK
Impurities	No S <10 ppmv total HC C_1 allowed	50-100 ppmv S demonstrated >100 ppmv aromatics demonstrated >100 ppmv olefins demonstarted Paraffinic HC is a fuel
Operation	Fuel starvation serious OCP under protective gas	OK Cathodic protection?

As can be seen, different gas qualities need to be supplied to the SOFC depending on the operation mode. The temperature raise rate and the maximum temperature gradients must be controlled in a narrow window. Fuel starvation is a serious mode of operation, which might lead to rapid deactivation (minute scale). Fuel starvation occurs when load is supplied to the fuel cell with no or too little fuel available. A simple measurement of the cell voltage will enable us to avoid such detrimental conditions however. If the fuel supply is cut it is important to go to OCP (open cell potential) and to supply a protective gas (containing hydrogen). Important to note is also the dramatic discrepancy between the specification and practical experiences concerning tolerances respect to sulphur, aromatics and olefins.

Table 2 HT-PEM-characteristics

Parameter	*Recommendation*	*Experience*
Gas on anode side	Reformate with up to 2% CO	OK
Air quality	No impurities allowed	OK
Heating conditions	Max 180º, preferably 160ºC	OK
Impurities	5 ppmv S (possibly 20 ppmv) No HC>C_1	Tests up to 100 ppmv have been performed in this study with good results. No problems with HCs have been detected.
Operation	Fuel starvation serious OCP not allowed	OK OK

The HT-PEM is not sensitive to thermo-mechanical issues but might well be overheated and destroyed (polymer membranes). The maximum continuous operation temperature is set to about 170°C (180ºC) but the lifetime is dramatically improved if this value is reduced by 20-30ºC. The CO- and (most probably) S-tolerances will increase with the temperature and we thus have a sensitive trade-off between lifetime- and tolerance issues. The HT PEM will suffer from fuel starvation in a similar way as the SOFC. In addition to this, the HT-PEM will also be harmed by OCP-conditions due to over potential. It is thus essential to control over- as well as under voltages. A HT-PEM will manage 1.5 – 2% CO continuously and peaks as high as 5% for a short while. S-tolerance is reported at 10-20 ppmv continuously and 35 ppmv+ intermittently.

No moisture control in the membrane is necessary in contrast to a low-temperature PEM (LT-PEM). Flooding conditions may lead to acid leakage from the membranes with corrosion issues and accelerated deactivation. During shutoff it is thus essential to avoid condensation in the fuel cell. Cathode deactivation is probably possible in the presence of a number of air impurities but no such systematic studies have been conducted yet.

Figure 10 shows the cell voltage of a typical SOFC and HT-PEM cell versus current density. It is clear that the SOFC-technology offers higher cell potentials and higher stack efficiencies. A stack will contain a number of individual cells, which are parallel in flow but serial in electric current. The minimum cell voltage of a SOFC-cell is usually set to 0.65-0.7 V whereas corresponding values for the HT-PEM cell is about 0.5 V. In the latter case there also exists a maximum cell voltage, 0.7 V.

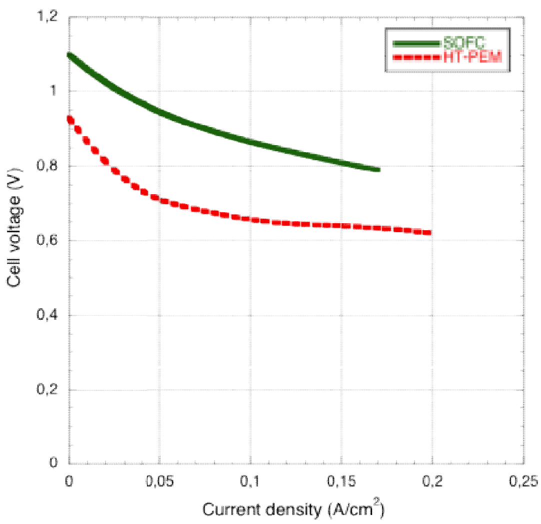

Figure 10 Fuel cell characteristics with reference gas (H_2/N_2-mixture) at 70% fuel utilization.

A number of tests have been performed to map the sensitivity of SOFCs and HT-PEMs to sulphur. Carbon monoxide is normally considered to be a fuel in a SOFC whereas the CO-tolerance of a HT-PEM stack is high. The reformate gas may contain 1-2% of CO without serious performance drop, which opens up for a simplified gas purification system.

Catator has previously demonstrated SOFC-operation at high concentrations of sulphur [12, 13] without any significant power penalties or degradation. It was found that addition of H_2S in the ppm-level completely inhibited the internal reforming of methane whereas the effects on the electrochemical oxidation of hydrogen were too small to be detected in the experimental set-up used in that study. Based on these findings, a number of activities were initiated at Topsøe Fuel Cell a/s (TOFC) and Risø National Laboratories (Risø) with the firm aim to grasp the sulphur effect on SOFC-anodes comprising nickel. Indeed, Hansen was successful in describing the sulphur effect based on traditional adsorption isotherms for nickel surfaces [14]. Hansen correlated a vast number of literature data to this correlation and found a clear relationship between the sulphur coverage and the power penalty found in the SOFC [14]. Surprisingly enough, however, the intercept with the abscissa was shifted to a sulphur coverage of about 50%, i.e. at a coverage below 50% no power penalty could be detected. This phenomenon is at the moment not well understood. Complementary investigations performed at Catator also reveal that the internal water-gas-shift reaction normally occurring on the SOFC-anode might be affected by the presence of sulphur. This will result in a poor utilization of CO present in the gas mixture, sine the consumption of CO is believed to proceed via the WGS-reaction in parallel to electrochemical oxidation of hydrogen. Direct oxidation of CO is much slower than oxidation of hydrogen.

Figure 11 indicates experimental data obtained for the SOFC-and HT-PEM stack together with the predictions provided by Hansen [14].

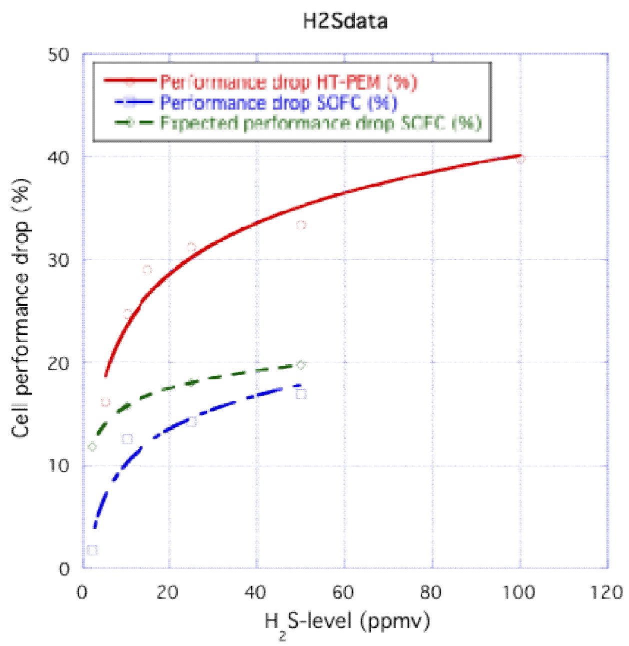

Figure 11 S-sensitivity for HT-PEM- and SOFC cells. Tests performed at 170°C (HT-PEM) and 825°C (SOFC) with H_2S-additiuon to a CPO gas containing ca 20% H2. Expected performance drop according to Hansen for the SOFC-cell [14] enclosed.

From these results it is obvious that fuels containing up to about 500 ppmw of sulphur can be used without severe performance penalties. At still higher sulphur levels upstream desulphurization is recommended. As a rule of thumb, 10 ppmw of sulphur will result in ca. 1 ppmv of H_2S in the reformate gas. At H_2S-levels exceeding about 50 ppmv, there is a risk of formation of bulk nickel sulphide in the SOFC, which might give rise to issues with the electric conductivity and structural damages.

To summarize the fuel cell status, the SOFC-concept is believed to cause more operation- and system related problems. Simultaneously, the SOFC is however less sensitive to impurities and shows a better capability with difficult fuels as jet fuel. Rather much concerning deactivation phenomena is still unknown or poorly understood. Extremely conservative approaches, which might prove not necessary, are taken to protect the units from issues, which might be only theoretically derived. A more pragmatic approach is desired in this area, even if this in some cases may lead to fuel cell failures.

Depending on expected issues with thermo-mechanical failures, the HT-PEM-concept has been chosen for this initial study. The HT-PEM stack is supplied by Serenergy a/s, and consists of 55 plates, with an expected power output around 1.5 kW_e.

7. Heat pump

The heat pump basically includes a compressor, an expander valve and two heat exchangers. The idea is to evaporate a certain cooling agent (normally R407C or R410A) in the cold heat exchanger. The evaporation process demands external energy, which is taken from the environment. The cold gas is then compressed and condensed in the hot heat exchanger, leaving heat energy to the environment.

The temperature levels in the system will affect the performance factor (coefficient of performance, COP). The COP-factor relates the heat output from the heat pump to the compressor power necessary. The smaller the temperature difference is, the higher will the COP-factor become. In ordinary systems, the seasonal average COP-factor (SCOP) is normally around 3. A similar COP-value can also be defined for the cooling cycle, which is then one unit less than for the heating cycle. The measured COP-value will vary depending on the temperature levels, which in turn are govern by the application.

A typical scenario concerning the temperature dependence of a state-of-the art compressor is given in Figure 11 below [15]. For floor heating, the normal maximum water temperature is about 35°C (low-temperature heat pump) whereas in old houses (old radiators) a typical water temperature might be 60 – 65°C (high-temperature heat pump). In new buildings the water temperature for radiator heating can be decreased to about 50°C (medium-temperature heat pump). The evaporator temperature is highly variable in air-to water systems and is dependant on climate zones and meteorological data. Typically, we can see variations between -30 and 10°C. In ground to water systems (soil or bed rock) the evaporation temperature is more stable, typically between -10 and 0°C. Each degree rise in evaporation temperature or fall in condensation temperature will typically give 2-3% improvement of the COP-value.

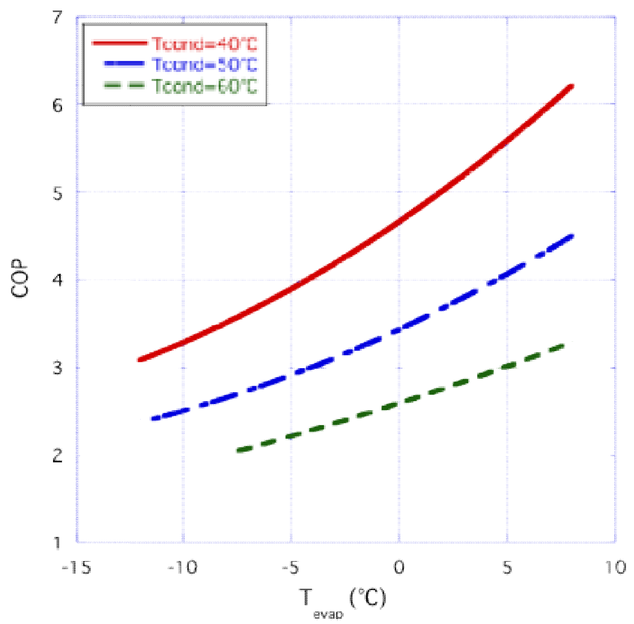

Figure 11 Typical temperature dependency of COP-values [ref] Cooling media: R 407C.

Nibe has supplied the heat pump module (F1145-5, 230 V) in this project. The detailed information concerning capacity data is confidential and only general data are thus discussed in this report. The unit is a COTS-device and no measures have been taken to optimize the unit for the operation conditions in the fuel-cell system.

If it were possible to reduce the working temperature difference in the heat pump system, it should be possible to increase the COP-factor. Since the fuel cell system will emit about 60-70% of the fuel energy as heat, it is possible to shift the operation point in the heat pump system to yield higher COP-values. The flue gases from the fuel-cell system also carry a lot of water, which can be condensed to yield a higher operation temperature in the evaporator.
The consequence is that extremely high thermal efficiencies can be reached related to the lower heating value of the fuel. Figure 12 below gives a schematic representation of this effect.

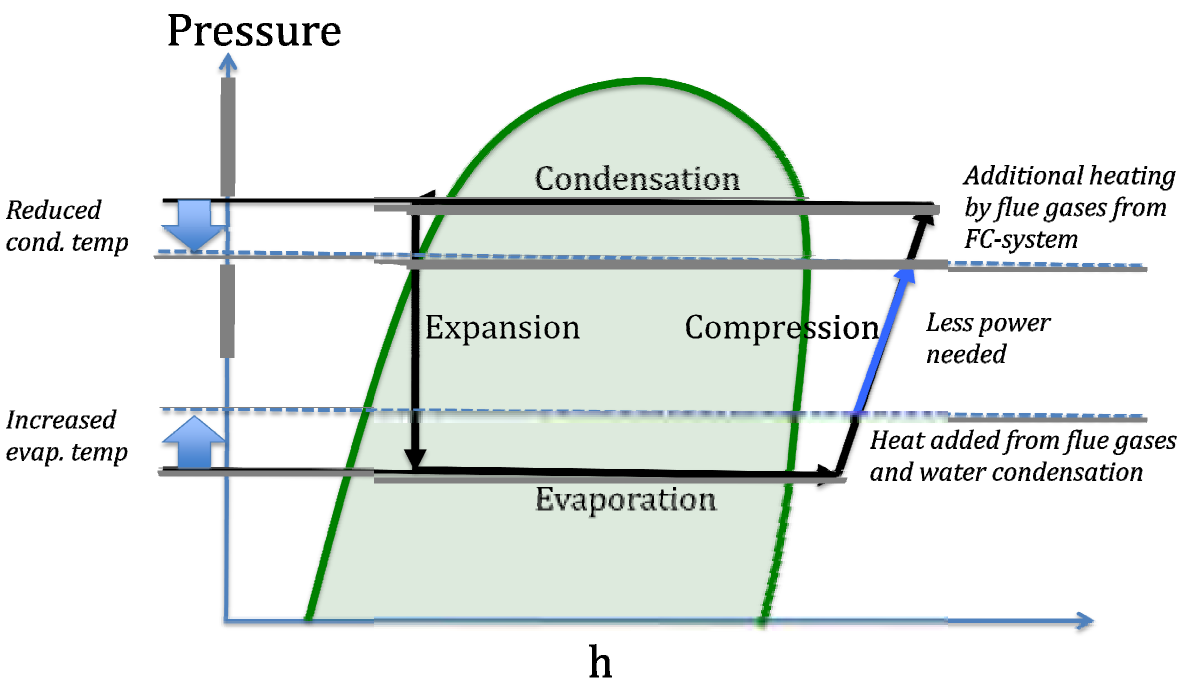

Figure 12 How we can shift COP to higher values

The most important factors for achieving peak performances are associated with the following parameters:
- The electric efficiency of the fuel cell system
- The temperature of the hot gases leaving the fuel cell system
- The amount of water, which can be condensed in the cold heat exchanger

Table 3 below summarizes the possibility to reach peak performances with various system combinations and system modifications.

Table 3 Expected performance in various fuel cell/heat pump systems Evaporation @0°C, Condensation @ 40°C. COP≈4.6 (Figure 11) Thermal efficiency calculated on the lower heating value of the fuel.

Fuel cell	*Reformer tech.*	*Application*	*Electric eff. (%) Power module*	*Thermal eff. (%) System*
HT-PEM	*ATR/CPOx*	*Mobile, Campus*	*25%*	*190*
HT-PEM	*SREF*	*Buildings, Campus*	*30%*	*208*
SOFC	*ATR/CPOx*	*Campus*	*35%*	*226*
SOFC	*SREF*	*Buildings*	*40%*	*244*
SOFC	*Internal reforming*	*Buildings*	*50%*	*280*

Indeed, in a carefully optimized system including a SOFC-unit, the thermal efficiency might be as high as 300%. For the combined fuel cell and heat pump system investigated in this study, the thermal efficiency is expected to reach values slightly above 200%, calculated on the lower heating value of the fuel.

8. P/I-diagram + expected performances

The complete system contains four main modules; fuel processor system, fuel cell, heat pump and power electronics.

The system is designed to enable fuel flexibility, i.d. both gaseous and liquid fuels can be used in the system. Fuel processing is performed in the Optiformer unit comprising steam-reformer, water-gas shifter, catalytic burner and steam generator. The reformate gas is led to the anode side of the HT-PEM and about 75% of the hydrogen flow is consumed under normal operation. Residual gases are then fed back to the catalytic burner in the Optiformer unit.

The fuel-cell consists of a HT-PEM module supplied by Serenergy a/s. The fuel cell contains 55 plates and produces 1.5 kW_e under optimum conditions with respect to gas composition, temperature conditions and flow conditions. It is electrically connected to the accumulator to achieve a stable system without heavy transients. A DC/AC-converter is installed to enable 230 VAC to the compressor system. Exhausts from the catalytic burner, the cooling air and the depleted air from the fuel cell cathode are den supplied to the heat pump system.

The heat pump module has been supplied by Nibe (F1145-5, 230 V) and will give a COP-value around 5 under normal operation together with the fuel-cell system.

The fuel cell is expected to deliver around 1.5 kW_e at a stack efficiency of about 40%. The voltage is expected to vary between 25 and 40V, depending on the load situation. Fuel utilization should be around 75%, hopefully somewhat higher following optimization.

The exhausts will leave the ComfortPower unit at a temperature of about 60°C. A system schematic is shown in Figure 13 below. The overall ratio between heat recovered and heat of fuel supplied (lower heating value) is expected to be around 2, even it somewhat higher values should be possible following careful optimization and some system improvements.

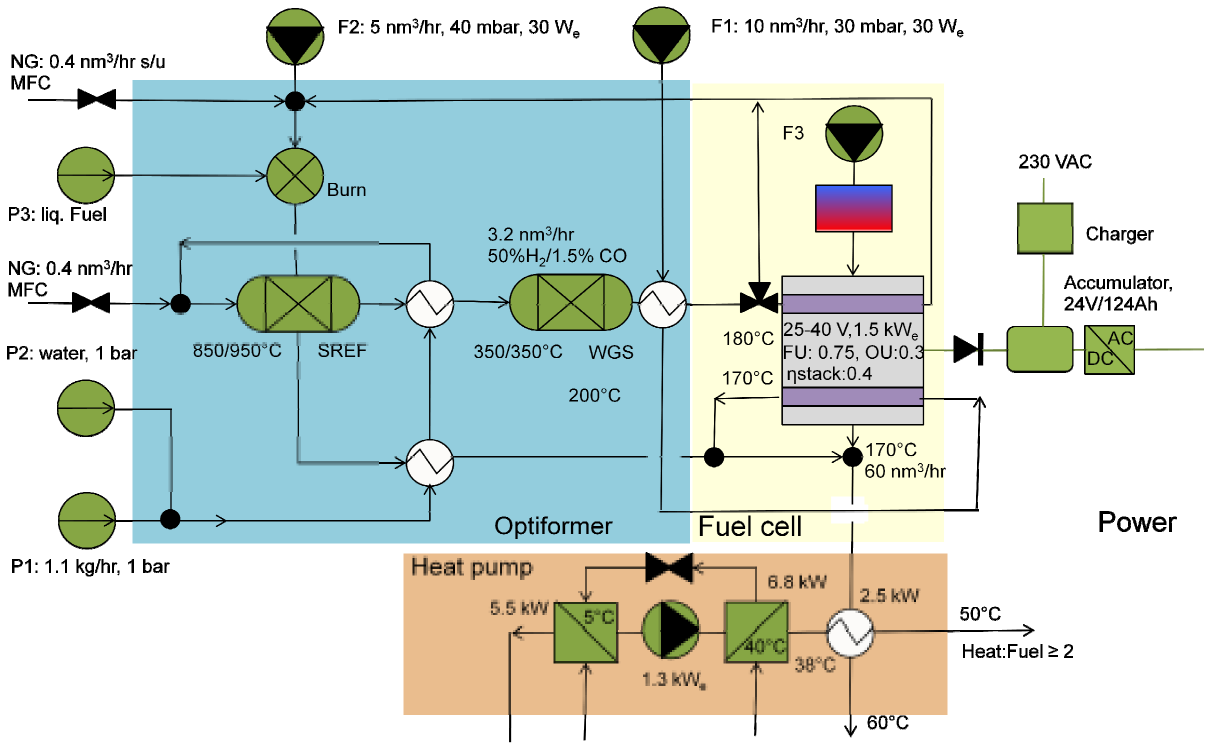

Figure 13 *System lay-out and calculated data. Optiformer – proprietary reformer technology to Catator, HT-PEM delivered by Serenergy a/s, Heat pump supplied by Nibe. Heat exchangers supplied by AlfaLaval.*

The total parasitic losses are expected to be less than 150 W_e and are associated with pumps, fans, internal electronics. The conversion efficiency in the DC/AC-unit is slightly above 90%. The DC/AC-converter can be removed if a 24 DC-compressor system could be found.

9. Packaging

The unit is packaged in a standard cabinet for heat pump systems, supplied by Qvantum AB. The heat pump system is located in the top of the cabinet, whereas the power module is located directly below the heat pump. The power electronics and the accumulators are located in the bottom section of the cabinet.

The overall size of the unit is 1.65 x 0.6 x 0.6 m and the weight is about 240 kg, with the following approximate breakdown:

- Cabinet, 50 kg
- Heat pump, 70 kg
- Power module, 40 kg
- Power electronics including accumulators, 80 kg

The pictures below show various views of the unit together with an internal view. All connectors for the heating and cooling agent are readily accessible from the outside. The control system is located on the top of the unit (black box).

Figure 14 *ComfortPower, front, side and internals*
From top: Control system, heat pump module, power module and power electronics.

The size of the unit is very compact taking the complexity and the number of components into consideration. Some efforts could be directed to find components with less weight. The power module, however, is relatively light and can probably not be optimized much further.

The system has a very low sound impact on the environment, which opens up for domestic applications. Heating and cooling is in this case distributed via conventional convector elements.

10. Results, system demonstration

A number of validation tests have been performed on the ComfortPower unit according to:
- Verification of heat pump system
- Tests with the power module (reformer system + fuel cell)
- Test with the complete system including power module and heat pump

A large number of experimental data have been collected and this report summarizes some important findings.

A numerical model has been developed to analyze the collected data and to allow further evaluations. The power module has been evaluated with a number of gaseous and liquid fuels, preferably however with natural gas and methanol. Table 4 summarizes data from tests with various fuels. The expected thermal efficiencies have been calculated for temperatures according to: inlet temperature cold side, 5°C, outlet temperature on the hot side, 40°C.

The fuel-cell temperature was kept constant at 160 – 170°C during the tests in order to give insensitivity to 1-2% of carbon monoxide. The Optifomer unit (fuel processor) was operated on tail gas from the fuel-cell system and no additional fuel was supplied in the data points presented in Table 4. The efficiencies found for the various fuels will depend on how the operation conditions are optimized. Following careful optimization, the differences between fuels should be very small.

The exhaust temperature (from the power module) was measured and the flue-gas emissions were mapped (NDIR). The concentration of nitrogen oxides is generally below 2-3 ppm, which is 10 times less than from ordinary boilers based on premixed burners.

A lambda sensor was installed in the Optiformer´s exhaust channel to enable carful burner control with respect to the air supply. No desulphurization was implemented and the reformate gas will consequently contain about 1 ppmv of H_2S. According to previous data, this will give rise to a performance drop of a few%. It should be possible to increase the performance slightly by installing a sulphur trap but this would make the system more complicated and the demands on maintenance would increase. It is wiser to overdesign the fuel cell slightly than to increase the complexity. At very high sulphur levels (jet fuel) the performance drop is more than 20% and under such conditions it might be favourable to install a sulphur trap (adsorber cartridge) upstream the fuel cell to avoid excessive overdesign of the fuel cell.

Start-up of the system is via combustion of the fuel itself. The reformate gas is then re-circulated to the burner and used as a fuel during the warm-up phase (typically 15 minutes). When the fuel cell starts to produce electricity, the reformate is depleted in hydrogen and the air flow needs to be adjusted to give reasonable temperatures. The fan control system includes temperature- and lambda sensors. Once in tail-gas mode, the system is extremely stable and the fuel cell is prevented from rapid electric transients by the accumulators. The flue-gas emissions in tail-gas mode are extremely low, less than 1 ppmv NO_x and only a few ppmv of CO.

The parasitic losses found in the system varied between 90 and 160 W depending on load condition and temperatures. The fuel-cell blowers (cooling fans) stand for 50% of the parasitic losses.

Table 4 Experimental data NG, Methanol, Kerosene (low sulphur) Tcin≈5°C, Thout≈40°C

Fuel	*Fuel consumption @ ca 1.3 kW_e*	*Water consumption (kg/h)*	*Electric eff. (%) Power module*	*Thermal eff. (%) System*
Natural gas	*0.4 nm^3/hr*	*1.1 - 1.2*	*28 - 32*	*200-220*
Methanol	*0.75 kg/hr*	*Ca. 1.1*	*25 - 31*	*170-210*
Kerosene	*0.4 kg/hr*	*1.3 - 1.5*	*Ca. 27*	*Ca 190*

If the data concerning stack- and system efficiencies are plotted in a probability graph, we obtain a good picture of the performance of the unit. From Figure 15, it is obvious that the data scatter around ca. 40% for the stack efficiency and 29% for the power module efficiency. Following careful optimization, we should be able to reach about 35% for the power module efficiency.

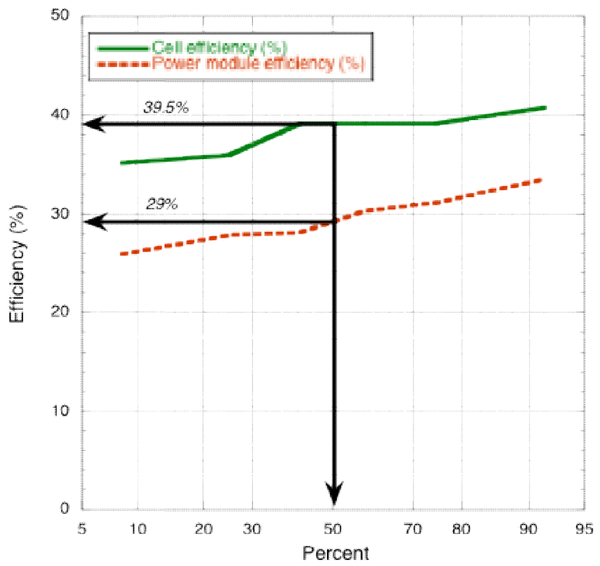

Figure 15 Measured efficiencies in the power module on stack- and system level.

From a theoretical viewpoint, the system efficiency will depend on the stack efficiency, the fuel utilization, the reformer efficiency and possible parasitic losses. Since the off gas from the fuel cell is used to power the reformer system, the maximum fuel utilization possible is set by the thermal heat needed in the reformer. Increasing the fuel utilization beyond this value will demand additional fuel supply to the reformer. The balancing fuel utilization will depend on the fuel, but is usually between 70 and 80%.

Figure 16 shows how the efficiency of the power module will depend on the cell voltage and the fuel utilization. The power output during fair conditions with respect to the CO-level (less than 1.5% CO at inlet) is also plotted versus the cell voltage. At a certain cell voltage, we reach a maximum power production. At still lower cell potentials relatively more heat than power is produced.

The HT-PEM cell shall be operated between 0.45 and 0.7 V (green area in the diagram), preferably above 0.5 V to achieve acceptable stack efficiencies. In the tests performed, the cell voltage has varied between 0.45 and 0.5 V at stationary conditions. The reason for this is found in the hybridization with accumulators, where the fuel cell will charge the 24 V lead accumulator at a certain over voltage. Following deep discharge, however, the voltage may drop to values between 0.45 and 0.5 V/cell during recharge.

The hybridization creates a lot of technical advantages by providing a relatively stable voltage in the system where the fuel cell does not need to be subjected to heavy load transients causing degradation.

The normal window of operation is also shown in the Figure. This window corresponds to a cell voltage between 0.45 and 0.55 V and corresponding fuel utilization between 70 and 80%. The full stack contains 55 cells so the output voltage from the stack may vary between 25 and 30 V under operation.

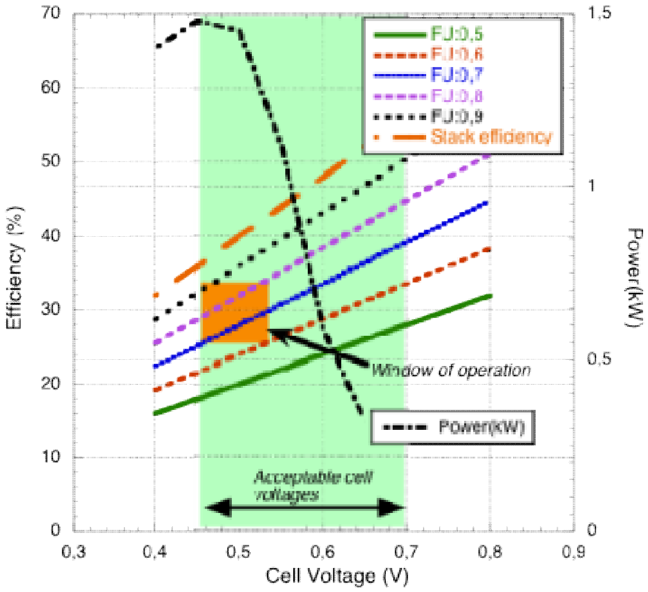

Figure 16 Efficiency of power module at different values of the cell voltage and fuel utilization. Power production versus cell voltage is given in the same diagram.

The ComfortPower unit was connected to convective elements for heating and cooling. The flow rates and temperatures were measured to enable a detailed mapping of the energy balances. The flow rates could be adjusted by increasing/decreasing the speed of the circulation pumps.

The exhaust gas temperature was measured in order to determine the flue-gas losses. No efforts were made to use the exhausts to improve the operation point on the cold side in this project. By implementing this feature, the operation point in the cold heat exchanger can be increased by approximately 5°C. Simultaneously, it will be possible to recover water for the steam reforming process.

The thermal efficiency of the system was calculated from efficiency data obtained for the power module, the compressor effect needed and the heat supplied via the convector element. Figure 17 shows predicted values for the thermal efficiency versus the temperatures in the system. The efficiency will depend on the electric efficiency obtained in the power module. Typically, an increase in the electric efficiency by 5% will increase the thermal efficiency by 40%. Consequently, to arrive at peak performances with respect to thermal efficiencies it is of paramount importance to improve the electric efficiency in the power generation.

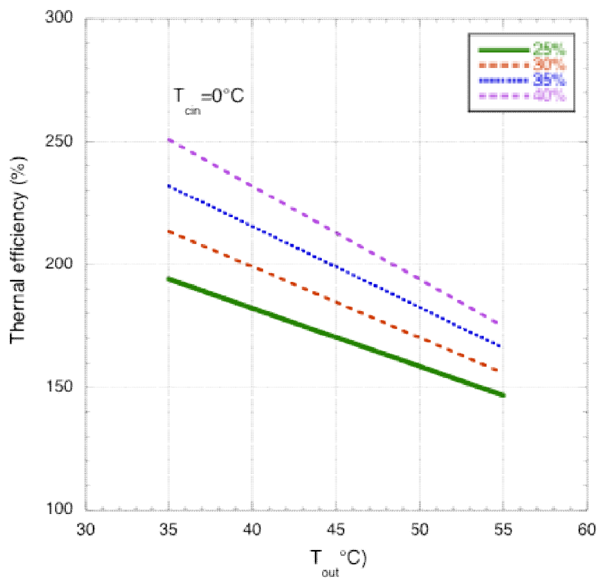

Figure 17 *Thermal efficiency vs. the efficiency of the power module. T_{out} is the outlet temperature from the system.*

Figure 18 shows an efficiency plot for an electric efficiency of 29% (the average efficiency obtained in the tests). Data points for efficiencies obtained in different operation points are also given. The data verifies previous calculations, and it can be concluded that thermal efficiencies between 170 and 220% can be obtained in the standing system.

Depending on the temperatures needed in a specific application, the achievable thermal efficiency will vary.

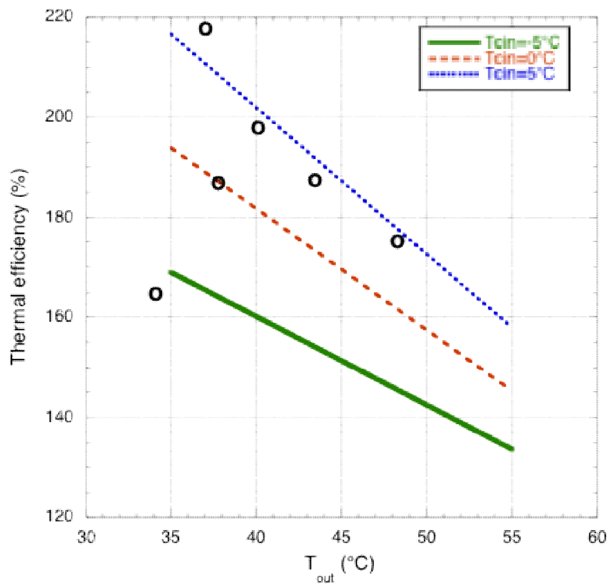

Figure 18 *Thermal efficiency as a function of temperature levels for the evaluated system. Experimental points shown in the figure.*

11. Possible system improvements

Even if the standing system performs as expected, we foresee a number of improvements, which could increase the efficiency further.

The voltage output from the fuel cell is generally between 24 and 30 VDC and power conversion is necessary to operate the compressor. If it were possible to find a heat pump compressor powered by a 24 DC electric motor, it should be possible to reduce the losses in the power transformation.

It is also important to optimize the number of plates in the fuel cell to avoid losses in DC/DC-conversion and to enable optimal operation of the fuel cell. The electric efficiency of the fuel cell will decrease with a decreasing cell voltage and for the HT-PEM stack, the cell voltage should preferably be kept above 0.5 V. In a SOFC, the cell voltage is as high as 0.7-0.8 V, thus giving a higher electric efficiency.

In this system we have used COTS (commercial of the shelf) power electronics. It is possible to find more efficient power electronics, usually giving efficiencies as high as 92-94%, but the price is too high in low volumes.

The number of electric components like pumps and fans should be reduced to minimize the parasitic losses and to reduce the cost. The system pressure drop can be reduced to further minimize electricity consumption in the blowers.

The thermal integration and insulation can be improved to some extent resulting in a slightly higher electric efficiency (a few%).

As previously discussed, the electric efficiency was around 29% in the existing system, slightly less than expected (about 30%). By implementing the relatively minor technical modifications proposed in combination with an optimization of the operation, the electric efficiency is expected to reach the targeted values. By replacing the 230 VAC compressor with a 24 VDC compressor, we will also avoid any problems arising from peak currents during start-up. In the system studied, it was necessary to start the compressor at a lower voltage (by using a AC/AC-converter) to avoid such problems.

The existing ComfortPower reached an overall thermal efficiency between 170 and 220% depending on the operation conditions. By analysing the expected performance improvements the thermal efficiency should reach the window 225 – 250%. Further improvements in the electric efficiency are possible by replacing the HT-PEM with a SOFC. Indeed, our analysis indicates thermal efficiencies as high as 250 - 300% in careful optimized SOFC/heat pump systems.

12. Future outlook and continued system development

This study covers the first tests conducted with the ComfortPower system. Following careful optimization and implementation of the improvements proposed, the expected thermal efficiency is expected to be as high as 225-250% related to the efficient heating value of the fuel supplied.

As discussed before, there are a number of important milestones before prototype series of the ComfortPower are produced. These milestones will address the following aspects:

1) Technical system freeze
2) Reliability studies and long term tests
3) Certification work
4) Continued long-term test on real site
5) alpha-prototype series (typically 10 units in field)
6) beta-prototype series (typically 100 units in field)
7) gamma-prototype series (typically 1,000 units in field)
8) Market introduction

Milestones 1 through 4 are associated with system development and system studies whereas milestones 5 through 8 are more commercial achievements associated with building reliability, decreasing production cost and creating an infrastructure for production, distribution and maintenance.

The total time frame for the program is at least 5 years. This time frame is necessary to get enough feedback from the various prototype series.

The first milestone involves a technical system freeze, which means that the system and the major components shall be defined. One important task is to decide on the choice of fuel-cell technology. The HT-PEM technology offers simplicity and flexibility whereas the SOFC-technology could add superior efficiency and perhaps better lifetime if operated continuously.

It is very difficult to indicate an acceptable price label for ComfortPower since external factors like gas price, electricity price and legislation will have a substantial impact. In many countries, small-scale power generation is subsidised and any such initiatives are likely to affect the economic trade-off greatly.

It is realistic to believe that the market price of a CHP-unit in the 1 kW_e-class is 2,000 – 3,000 Eur. The sale of a CHP-unit is normally embedded with a number of legislative measures to reduce the impact of the investment cost [eg. 16]. A typical payoff time for a CHP-unit is 2-3 years when taking such measures into consideration.

In this case we also add the heat pump module, so the price label should be higher for this kind of system. Energy savings is expected to be around 1,000-1,200 Eur/a for a typical consumer (20 MWh/a consumption @ 10 cEur/kWh). If this kind of system is subsidised due to its extremely high environmental rating, the market situation will be greatly improved. Also, increasing fuel prices will favour the market situation significantly.

The biggest barrier to reach such price levels in volume production today is the fuel cell itself. We now see a shift from research and development to commercialisation in the fuel-cell business and this change is necessary to bring down the cost. From a material viewpoint, the fuel-cell cost should be able to reach fundamentally acceptable values.

13. Possible achievements

The ComfortPower technology provides a combined heating, cooling and power unit with peak performance. Already without extensive optimization and system tuning, the thermal efficiencies reach 200% calculated on the lower heating value of the fuel supplied. In addition to heating, the unit can provide cooling with a high efficiency. When no heat or cooling is needed, electricity can be delivered to the grid or consumed internally.

The ComfortPower technology will enable a decrease in the carbon footprint by 50 – 70% over conventional boilers. Moreover, the unit provides extensive fuel flexibility, which becomes increasingly important due to environmental aspects. Depending on substantial energy savings, the pay-off time on the investment is reasonable. If the fuel price continues to increase, which is likely, the investment will be even more favourable.

The unit is compact and easy to transport, which together with the built-in fuel flexibility opens up for campus applications. The technology is easy to scale for higher demands on the effect output.

ComfortPower represents a new type of green boiler technology available for buildings and campus applications where flexibility, energy savings and environmental concern are in focus. Catator is committed to bring this technology to further refinement and to reduce any barriers preventing commercialisation.

14. Literature

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