Rapport SGC 251

ComfortPower

System improvements and long-term evaluation

ComfortPower powered by 1 kW$_e$ HT-PEM

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November 2011

Rapport SGC 251 • 1102-7371 • ISRN SGC-R-251-SE

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Summary

Catator has previously developed a novel heating system abbreviated ComfortPower in a R&D-programme supported by Catator, Swedish Gas Centre (SGC), Swedish Defence Materiel Administration (FMV), Skanska, Nibe and Alfa Laval. The ComfortPower unit comprises a multi fuel reformer system tied to a high-temperature polymer electrolyte fuel cell (HT-PEM) and a heat pump system.

Since the residual heat from the fuel cell system can be utilized in a very effective way, it is possible to reach high thermal efficiencies. Indeed, the thermal efficiency in the unit has previously been shown to reach values as high as 175 – 200% based on the lower heating value of the fuel [1]. In addition to heat, ComfortPower can supply comfort cooling and surplus electricity.

This project phase has focused on the following elements:
- System improvements to further enhance the efficiency with existing fuel cell (HT-PEM)
- System simplifications (e.g. DC-compressor system) to manage issues with start-up currents
- Tests with biogas qualities (various levels of CO_2) and biogas/air
- Long-term test with biogas quality (upgraded biogas)
- Additional tests with liquid fuels (alcohols and diesel)
- Map the need for cooling and heating in various applications
- Investigate how ComfortPower can reduce the primary energy consumption and reduce the environmental impact
- Study the possibility with a SOFC-based system with internal reforming

It was found that the Optiformer technology [2] can be used to derive a suitable reformate gas for the HT-PEM unit from a wide range of fuels. Even if operation with fuel gases is the natural choice in most cases, it is possible also to use alcohols and other liquid fuels (e.g. in Campus applications). The heat pump system was equipped with a 24 V DC-compressor provided by Nibe. The compressor could be directly powered by the accumulator system and start-up currents, harmful to the inverter, could be avoided. Some improvements were made on the thermal design of the unit to further increase the COP-value of the heat-pump system.

Extended tests with various biogas qualities indicated a minor drop in cell voltage as the CO_2-concentration increased. This drop is connected to the relative dilution of hydrogen once the concentrations of balancing gases increase (predicted by Nernst equation). It was also possible to use biogas/air in the Optiformer/fuel cell system without any problems.

Mapping of the overall thermal efficiency of the ComfortPower indicated an increase over figures obtained in the previous configuration [1]. Indeed, the efficiency of the heat pump system was boosted by 20% through the improved thermal design and the absence of some parasitic losses in the inverter system. However, since we obtained some problems in the sealing of the fuel cell (internal gaskets), the efficiency of the fuel cell gradually deteriorated. Efforts are directed to find the failure mechanism, which most probably are connected to the pre tension of the cell stack.

The study includes a survey of the heating- and cooling need in various applications. In addition, a theoretic study has been included concerning the possibilities connected to other methods for power generation in the ComfortPower.

From an environmental perspective it is clear that the ComfortPower technology would contribute to a lower consumption of primary energy wherever it is used. In parallel to this we shall see a dramatic reduction of the emissions of greenhouse gases and nitrogen oxides. The study indicates a potential annual reduction of 750 TWh and a reduction of 150 Mt of CO_2-emissions following a substantial ramp-up of the technology. Today the addressable market is about 7 million units/a in Europe (the boiler market). If the market penetration is similar to when the condensing boilers replaced the atmospheric boilers (turning of the 20th century), we shall see a gradual shift from condensing boilers to hybridized systems involving heat pumps during the next decade.

However, the fuel cell technology will compete with other available technologies for power generation (e.g. internal and external combustion engines) and issues with cost, reliability and system complexity are lurking in the background even if such systems might be one ingredient to a more sustainable society. Indeed, most boiler manufacturers are currently evaluating systems to become the next generation of boilers. It is likely that these boilers will include modules for small-scale power generation and various heat-pump systems.

Sammanfattning

Catator har utvecklat ett sofistikerat uppvärmningssystem (ComfortPower) i ett forsknings- och utvecklingsprojekt finansierat av Catator, Svenskt Gastekniskt Center (SGC), Försvarets Materielverk (FMV), Skanska, Nibe och AlfaLaval. ComfortPower består av ett reformersystem som sammankopplats med en högtemperaturpolymerbränslecell (HT-PEM) och ett värmepumpsystem.

Eftersom överskottsvärmen från bränslecellssystemet kan användas på ett mycket effektivt sätt blir det möjligt att uppnå höga totala värmeverkningsgrader för systemet. I experimentella försök har totalverkningsgrader på 175 – 200% uppnåtts (räknat på det effektiva värmevärdet[1]) . ComfortPower kan dessutom leverera komfortkyla samt kraft.

Detta projekt har fokuserat på följande områden:
- Systemförbättringar för att öka värmeverkningsgraden ytterligare
- Systemförenklingar (t.ex. nyttjande av DC-kompressor) för att undvika problem med höga startströmmar
- Tester med olika biogaskvaliteter (olika halter av CO_2) respektive biogas/luft
- Långtidstest med uppgraderad biogas
- Ytterligare tester med vätskeformiga bränslen (bl.a. alkoholer och diesel)
- Utreda behovet av värmning och kylning i olika applikationer
- Undersöka hur ComfortPower kan minska den primära energiförbrukningen samt reducera de miljöskadliga utsläppen
- Undersöka möjligheterna att nyttja SOFC-baserade system med intern reformering

Optiformertekniken [2] kan användas för att producera en lämplig reformatgas för en HT-PEM stack med utgångspunkt från ett stort antal bränslen. Även om huvuddelen av systemen kommer att använda bränslegaser som naturgas och biogas är det också möjligt att använda vätskeformiga bränslen (t.ex. alkoholer, fotogen och diesel), vilket är av intresse i exempelvis Campus-applikationer. Enheten utrustades med ett 24 VDC kompressorsystem (genom Nibe), som kunde försörjas med ström direkt från ackumulatorn. Härigenom undviks problem med höga startströmmar som kan ge problem i invertersystemet, samtidigt som de parasitiska förlusterna kan reduceras. Vissa förbättringar infördes i den termiska designen, varvid värmepumpens COP-värde kunde ökas.

Omfattande försök med olika biogaskvaliteter utfördes och resultaten indikerade en viss (dock betydelselös) minskning av cellspänningen vid förhöjd CO_2-halt. Denna minskning är kopplad till utspädningseffekter och beskrivs av Nernst ekvation. Det visade sig även möjligt att använda biogas/luft i systemet. Denna gaskvalitet förekommer i Stockholm och används som stadsgasersättning.

Kartläggningen av totala värmeverkningsrader påvisade en förbättring (ca 20%) relativt jämförbara resultat erhållna i den tidigare konfigurationen. Detta beror på en förbättrad termisk integration och minskade parasitiska förluster. Under långtidsförsöket erhölls en successiv prestandaförlust hos bränslecellen, vilket sannolikt beror på läckage (bristfällig tätning) till följd av problem med förspänningen av stacken (fjäderbelastade skruvar).

Studien beskriver hur kyl- och värmebehovet ser ut i vissa typiska applikationer. Rapporten innehåller också en analys avseende hur andra kraftgenereringsmetoder skulle kunna användas i ComfortPower.

Från ett miljömässigt perspektiv är det tydligt att ComfortPower skulle bidra till att minska den primära energiförbrukningen (uppvärmning med gas) i Europa med upp till 750 TWh/år (motsvarar ca. 2 ggr Sveriges årliga energiförbrukning). Dessutom skulle en massiv introduktion av denna teknik medföra substantiella minskningar av utsläppen av CO_2 (motsvarande 150 Mton) och kväveoxider. Idag uppgår den adresserbara marknaden till 7 miljoner enheter per år i Europa (pannsegmentet). Om marknadspenetrationen kommer att likna det paradigmskifte som skedde när äldre pannor ersattes med kondenserande pannor för ca 10 år sedan, så bör tekniken få en god spridning på ytterligare 10 års sikt.

Bränslecellsystemen kommer dock att konkurrera med andra tillgängliga tekniker för kraftproduktion (t.ex. interna och externa förbränningsmotorer) och problem med kostnad, tillförlitlighet och systemkomplexitet kan fördröja/förhindra marknadsetableringen. De flesta panntillverkare utvärderar för närvarande innovativa systemlösningar som kommer att ingå i nästa generations pannor. Det är sannolikt att dessa pannor kommer att innefatta såväl moduler för småskalig kraftgenerering samt olika typer av värmepumpsystem.

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1. Background

During the last few years a lot of attention has been devoted to energy conservation and effective energy conversion. Condensing boilers have replaced traditional systems based on non-condensing boilers and atmospheric burners. Production and distribution of electricity is in focus and decentralized heat-and power generation has come on the agenda. A number of companies are today developing small-scale combined heat- and power units (micro CHP, μCHP) based on various technologies, e.g. internal and external combustion engines and fuel cells.

Some researchers/companies have tried to include heat pumps into their μCHP-systems in order to further boost the heating efficiency [e.g. 3-6]. From a macro perspective such systems can reduce the overall losses in production and distribution of energy.

There exist a widespread infrastructure for gas distribution in most countries whereas electricity production normally is centralized to a minor number of big power plants (condensing power, nuclear power or hydroelectric power) connected to a relatively poor power distribution system with respect to its capacity. In such cases it is of importance to achieve local power production adjacent to heat production with a high overall efficiency. A normal condensing boiler will give heating efficiencies of around 105% (based on the efficient heating value of the fuel). This figure is close to a situation where a heat pump is used to produce heat from electricity derived from condensing power units. In these cases, 60 – 70% of the total energy is rejected as low quality heat. In addition there are losses in the transmission of electricity, normally 5 – 10%.

In a combined μCHP-unit/heat pump, it is possible to recover the residual heat and to optimize the operation conditions in the heat pump by shifting the condensation and evaporation temperatures in the system. Depending on the split between power and heat, which will depend on the technology used, the overall heating efficiency can vary. If the electric efficiency in the system is around 30%, overall heating efficiencies of around 200% can be reached.

Figure 1 below explains the differences between centralized power generation and operation of heat pumps and similar decentralized systems.

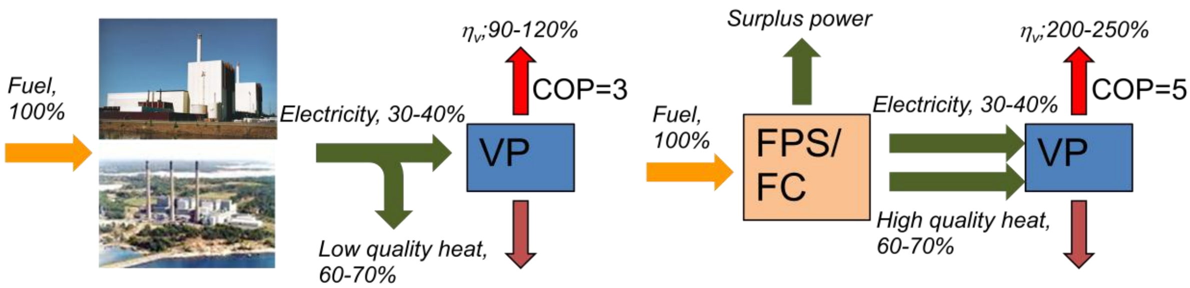

Figure 1 Comparison of a traditional heat pump system and the ComfortPower system

There exists a number of technologies for small-scale power generation. Figure 2 below shows the most relevant options together with typical electric efficiencies. Some commercial and pre commercial units are highlighted in the figure. Technologies based on internal or external combustion engines usually give electric efficiencies between 20 and 30% in the power window of interest (0.5 – 5 kW_e). Fuel cell systems including fuel processing usually give efficiencies between 30 and 40% whereas SOFC systems using internal reforming might boost the electric efficiency to 50% or even higher.

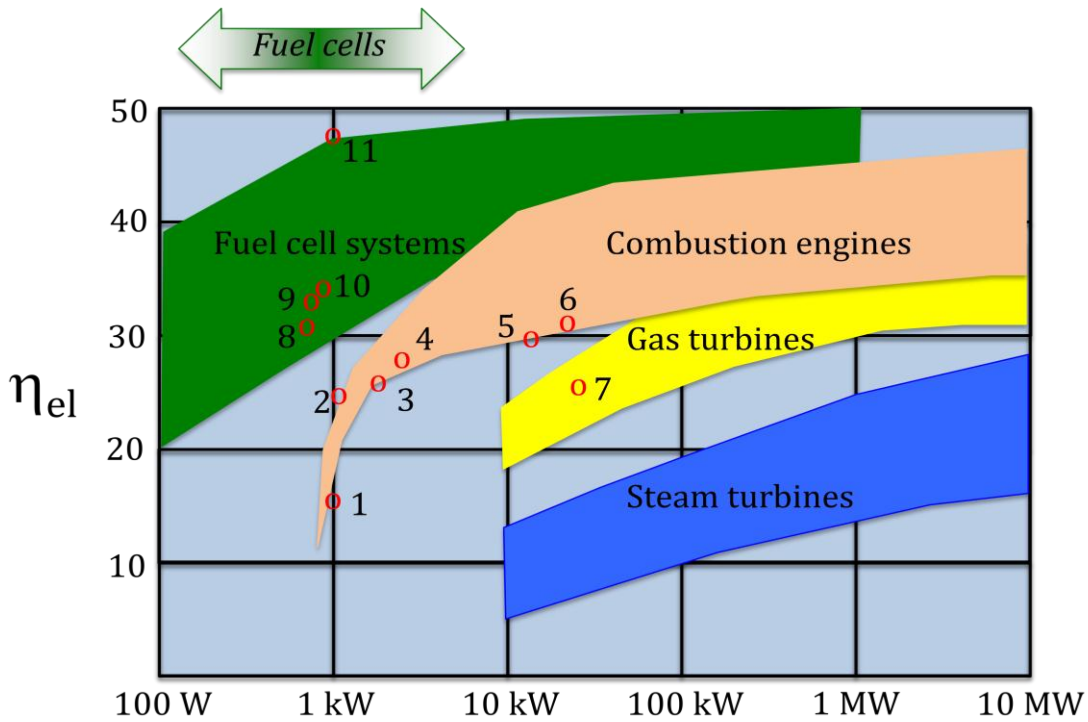

Figure 2 Typical electric efficiencies found in different energy conversion devices with natural gas as fuel [7,8].
1=Dachs/stirling 1 kW_e, 2=Vaillant EcoPOWER1.0, 3=Vaillant EcoPOWER 3.0, 4=Dachs G 5.5, 5=EC-Power XRGI 15, 6=Viessmann Vitobloc 200 EM-20/39, 7=Capstone C30 micro turbine, 8=ComfortPower (HT-PEM), 9=EneFarm (LT-PEM),10=CeresPower (SOFC), 11=TOFC/CFCL (SOFC+internal reforming)

It is obvious that the fuel cell technology will give the highest electric efficiencies for power outputs of around 1 kW_e. The fuel cell technology offers a number of advantages over conventional technologies based on combustion engines, which can be seen in Figure 3 below. It is possible to build extremely compact systems, which are silent, clean and efficient. The fuel cell technology also gives a multi fuel possibility. Indeed the ComfortPower unit can use a number of gaseous and liquid fuels.

Unfortunately there are also a number of hurdles, which need to be removed before a massive market introduction is possible. The technology is immature, which means that reliability and longevity are not proven yet. In addition the cost is far too high as a result of the R&D-nature of the fuel-cell area.

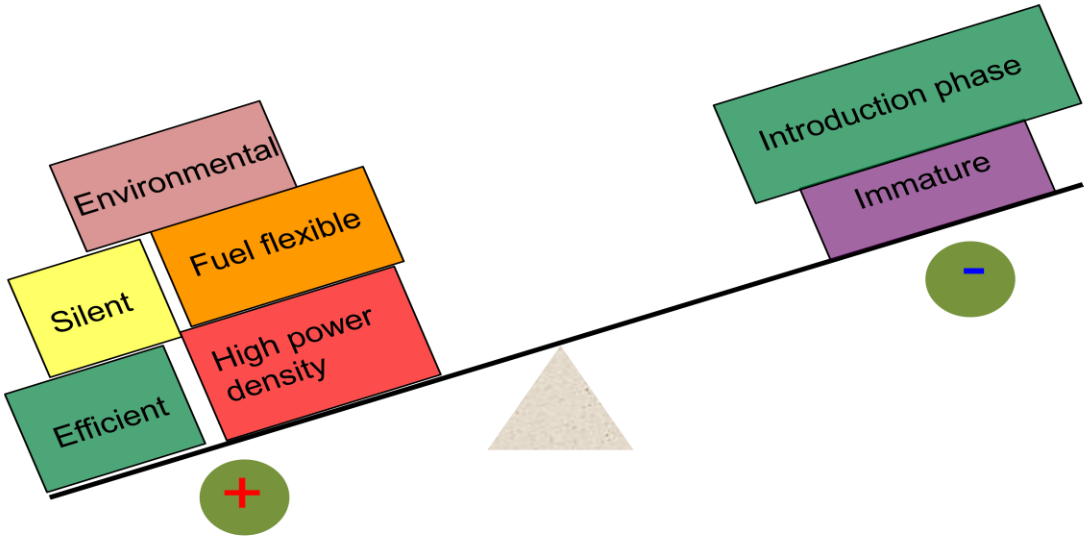

Figure 3 Advantages and disadvantages with the fuel cell technology

Figure 4 below summarizes the important areas, which need to be addressed further in the fuel cell area. The fuel cell technology has made a number of important progresses in recent years when it comes to reliability and robustness. It is important to stress that fuel cells rely on complex catalytic and electrochemical processes, which might be affected by a number of more or less understood parameters. Indeed, the inherent complexity in fuel cell systems is much more pronounced than in combustion engines. In order to reach targeted lifetimes of 40,000 – 80,000 hrs, it is extremely important to control the process parameters and the quality of fuel, water and air. Any shortcomings here will result in a dramatic decrease of the lifetime over the expected.

The Japanese fuel cell programme has shown that it is possible to come down to acceptable failure rates for systems based on steam reforming and LT-PEM [8]. For fuel cells operating at higher temperatures (HT-PEM and especially SOFC) there still are some question marks even if encouraging results have been achieved in single cell testing. Combustion engines will generally need relatively more maintenance than fuel cell systems provided that the lifetime demands can be reached for the fuel cell system.

From a performance perspective, it is reasonable to believe that fuel cell systems can compete with systems based on internal combustion engines.

The second most important problem to address with fuel cell system is associated with the cost (or price). Since the technology is in an introduction phase, it relies on subsidies and tax reductions in various ways. It is probably possible to price fuel cell systems somewhat higher than systems based on internal combustion engines, provided that high reliability and maintenance free operation can be demonstrated.

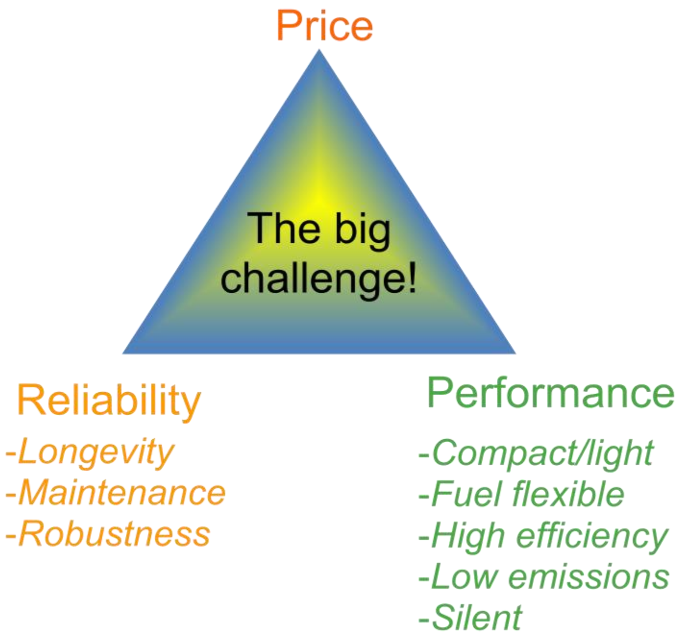

Figure 4 Important hurdles for the fuel cell technology

Even if the high thermal efficiencies found in the ComfortPower unit might be somewhat jeopardized by replacing the fuel cell system with a combustion engine, the reliability and robustness might well be improved. Indeed, reliability, robustness and cost issues will always be central when replacing a working technology with a new concept in an existing technology field.

The combination of μCHP units and heat pumps will probably materialize on the market but the question is related to the choice of power generation system.

2. Objectives

The principle of the ComfortPower was demonstrated and confirmed in the previous project phase [1]. This project phase focuses on measures to optimize the system and to extend the experience concerning fuel flexibility and long-term stability. Various applications for the ComfortPower technology are discussed and the savings with respect to energy consumption and emissions are highlighted. Different ways for power generation in the ComfortPower unit are also addressed.

In conclusion the following items are included in this project phase:
- System improvements to further enhance the efficiency with existing fuel cell (HT-PEM)
- System simplifications (e.g. DC-compressor system) to manage issues with start-up currents

- Tests with biogas qualities (various levels of CO_2) and biogas/air
- Long-term test with biogas quality (upgraded biogas)
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3. System optimization

A number of improvements were suggested for the existing ComfortPower unit. The most important ingredient in these efforts was to replace the 230 VAC compressor with a 24 VDV compressor. It was very difficult to find commercial available alternatives, which were appropriately sealed for maximum heat performance. In addition it was not possible to find a compressor with the same capacity as in the previous study.

Nibe assisted Catator in finding a Chinese compressor unit (Zhejiang XB135Z24) with an input power ranging from 500 to 700 W_e, depending on the operation conditions. This in turn led to a requirement to replace also the heat exchangers in the system to get a balanced unit. Preliminary mapping of the performance showed a close correlation with data obtained from the supplier (Zhejiang).

Even if the fuel cell in the system can give a power output in the neighbourhood of 1 kW_e, only a part of this capacity is required to run the heat pump system. Consequently it was decided to run the long-term stability test at around 700 W_e.

Figure 5 below shows the results from the mapping of the heat pump system. It is obvious that the COP-value obtained, will depend on both the evaporation and the condensation temperatures. By shifting the temperatures in the heat pump system by utilization of residual heat from the fuel cell system, it is possible to improve the COP-values over a conventional unit. In addition, any waste heat produced in the fuel cell system can be readily recovered in the heat pump system. Figure 6 below shows how the temperature levels in the heat pump system are shifted in the phase diagram due to the thermal integration with the fuel cell system. The phase diagram has been generated from data presented by NIST Chemistry WebBook [9].

The performance of the 24 DC-system with respect to COP-values is similar to the 230 VAC-case, previously studied [1].

Calculations show that a suitable evaporation point is around 5-10°C and a suitable condensation temperature could be between 30 and 45°C, depending on operation mode (floor heating and tap-water heating respectively). The exhausts from the fuel-cell system will add about 15°C to the outlet temperature from the heat pump. The evaporation temperature can be increased by 2 – 5°C by utilizing the residual heat from the cathode side in combination with the latent heat of the exhausts (water condensation). A cycle where the temperature levels are 10°C and 35°C respectively will result in COP-values of around 6, indeed very high.

An approximate correlation between COP-values and temperature levels for the studied system can be expressed as:

$\Delta COP = -0.13\ \Delta T_{cond} + 0.25\ \Delta T_{evap}$, where:

ΔCOP= Change in COP value when temperature levels are changed
ΔT_{cond} = condensation temperature (°C)
ΔT_{evap} = evaporation temperature (°C)

If the condensation temperature is decreased by 10°C and the evaporation temperature is increased by 5°C, this will result in an increase of the COP-value by approximately 2.5.

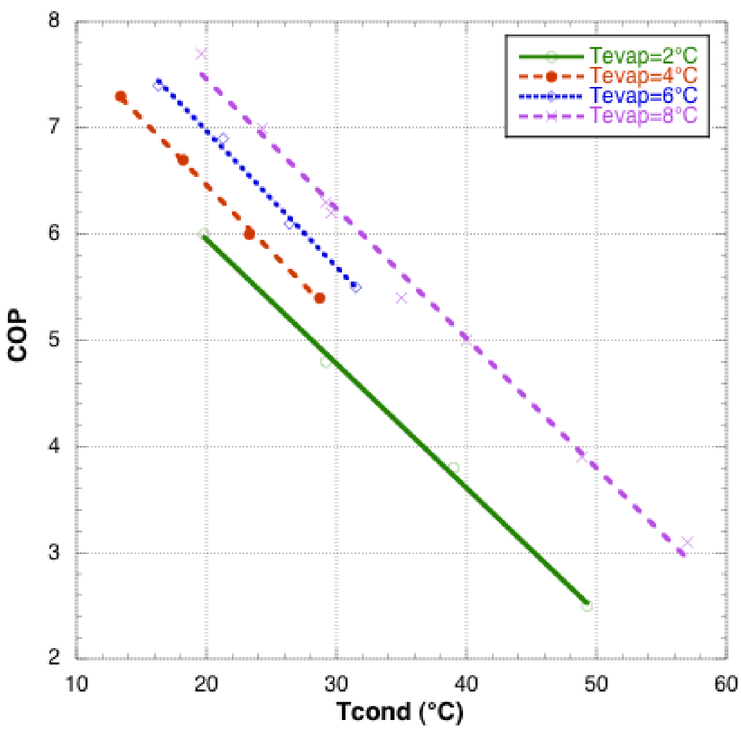

Figure 5 Measured COP-values in the heat pump system (compressor: Zhejiang XB135Z24, coolant:R134a) at various temperature levels.

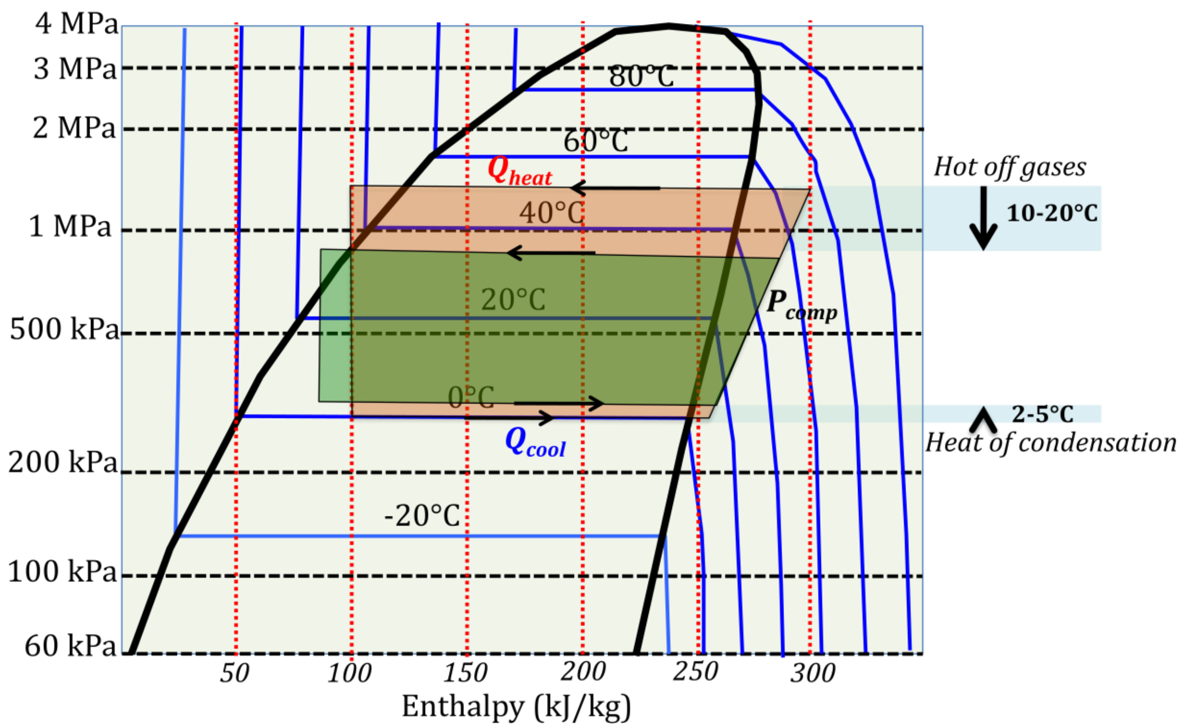

Figure 6 Effects of the thermal integration on the cycle diagram (R134a). Red rectangle=before thermal integration, green rectangle following integration.

Since the fuel cell is operated at part load, also the fuel processor (Optiformer) needs to be turned down during the tests, approximately to 40% of full load. The relative heat losses will unfortunately also increase by turning down the load. Ideally, the fuel-cell system should operate at its design load to minimize any such losses.

Figure 7 below shows the revised system layout with revisions marked in red. Due to the new compressor unit, no power conditioning is necessary anymore. In addition, we have eliminated any problems with start currents, which tended to dark out the inverter. The new heat exchanger will increase the evaporation temperature and hence improve the COP-value somewhat.

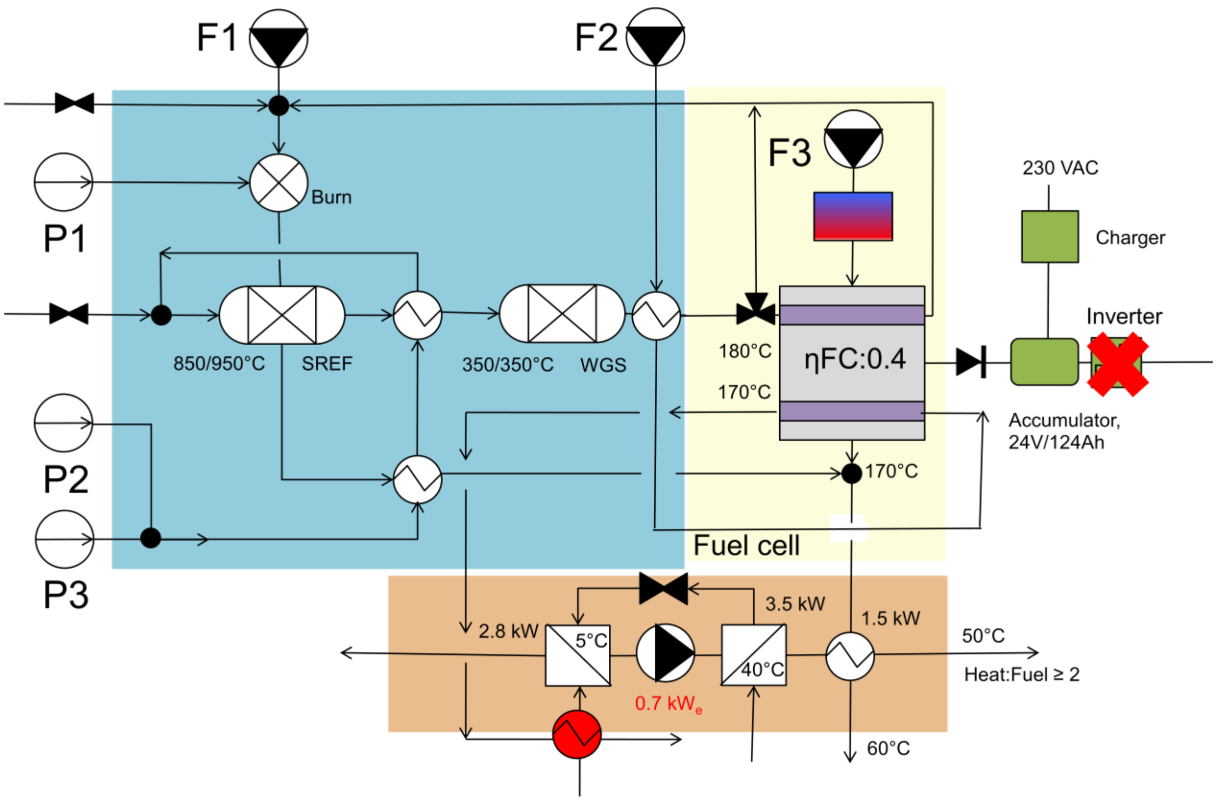

Figure 7 Revised system layout with revised settings
The Compressor is operated directly from the FC/accumulator.
The condensation heat is recovered in the heat pump system.

Since no power conversion is needed in the system for operation of the heat pump, the parasitic losses can be reduced. Previously, a power conversion device comprising one DC/DC-converter and one DC/AC-converter with an overall efficiency of about 90% was used.

In order to improve the performance and to reduce the parasitic losses further it were possible to reduce the pressure drop in the system and especially so over the fuel cell unit. By doing this, the high-performance fans in the system can be replaced with ordinary fans with less power consumption. This would, however, demand a completely new design and architecture of the fuel cell interiors, which is outside the scope of this project.

The Optiformer unit was modified to enable a simpler and more reliable supply of liquid fuels. One task is to further investigate the utilization of liquid fuels in the Optiformer system even if short-term tests already have been performed with some fuels, e.g. kerosene. A number of tests with various fuels will be presented as a part of this study and these results are of importance if the unit shall be operated in Campus applications. FMV is currently investigating the possibilities to further explore the technology both together with Swedish armed forces (Försvarsmakten) but also together with foreign authorities. Indeed, such applications could be a unique opportunity to further develop the ComfortPower concept and to improve the TRL-level (TRL=technology readiness level).

During the long-term test, focus was on the fuel cell system since the heat pump reliability is well proven. Tests with the complete system were performed mainly to study the total system efficiency.

Figure 8 below shows the expected increase in performance, due to a closer thermal coupling and less parasitic losses. The parameters, which mainly influence the performance, are linked to the fuel cell and fuel cell system efficiencies. As stated earlier it is important to try to maximize the efficiency in the fuel cell system. As previously shown, the fuel cell system efficiency is around 30% in a HT-PEM based system [1]. It is possible to yield higher efficiencies by choosing other fuel cell technologies, but the system complexity is expected to increase. The SOFC-option with internal reforming is interesting in applications where methane is used as fuel. In this case, however, we like to build a fuel flexible system and consequently a fuel processing system is required. This will in turn reduce the system efficiency somewhat. A detailed survey of SOFC + internal reforming is given later in this report. From the Figure it is obvious that the heating efficiencies are expected to increase by approximately 20%.

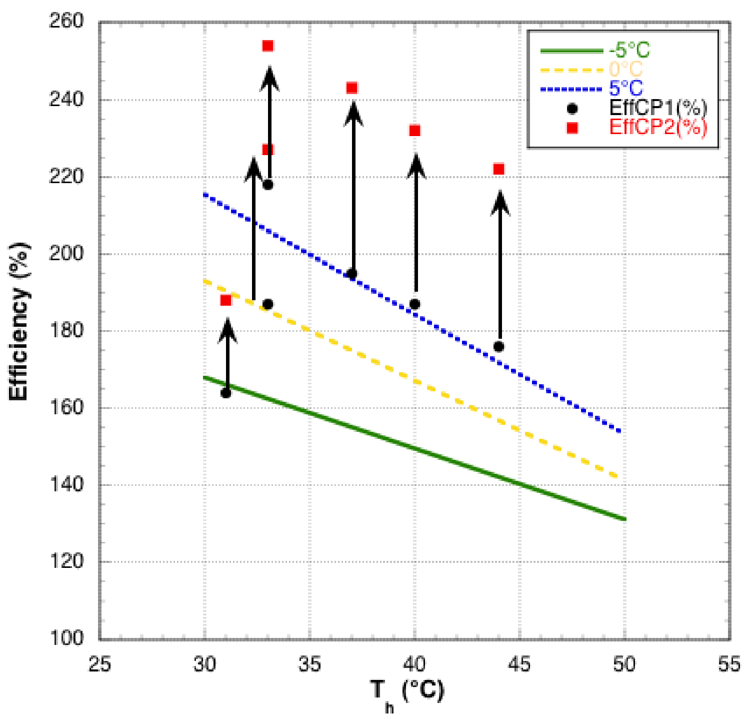

Figure 8 Plot showing expected increase in performance
Calculations made for the experimental data presented in [1]. CP1=ComfortPower 1 , CP2=ComfortPower 2, Data for various temperatures on the hot and the cold side.

4. Fuel compatibility

A number of fuels can be used in the ComfortPower-unit, ranging from gaseous energy gases to liquid fuels. The choice of fuel will depend on the application. In normal applications, the ComfortPower unit will be connected to the grid and natural gas or biogas will be logical fuel choices. In campus applications, however, it is important to decrease the logistic burden and hence to choose a fuel with high volumetric and gravimetric heat content.

In military applications (FMV), the ultimate fuel choices are diesel and kerosene (jet fuel). These fuels have high energy densities and are logistically available. Figure 9 below shows the heat densities of various fuels. Liquid fuels like diesel and kerosene have merits in comparison to alcohols and liquefied fuel gases (LPG, LNG).

However, different fuels show different advantages and disadvantages in fuel cell systems. The advantages and disadvantages with various fuels and some experimental results are discussed below. It can also be concluded from the figure that battery is a very bulky and heavy way to provide power in the field.

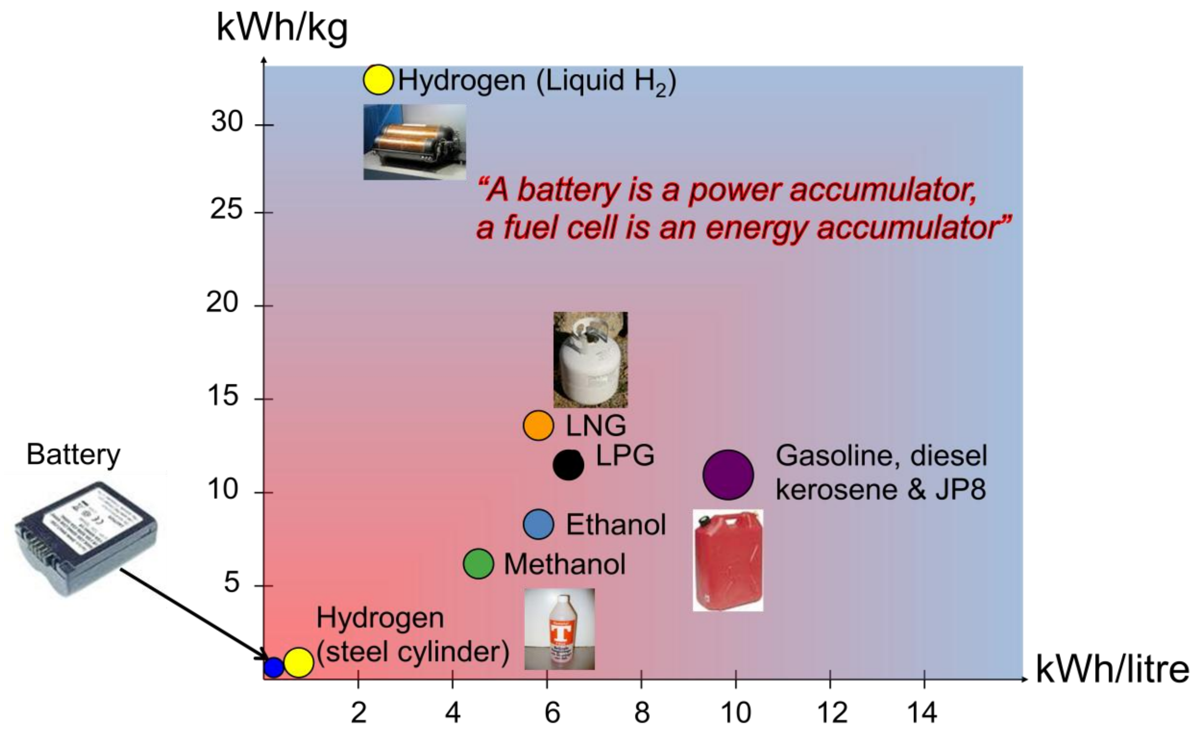

Figure 9 Logistic efficiency among various fuels.

Alcohols like methanol and ethanol can be mixed with water, which means that the fuel- and water supply can be simplified. Methanol is perhaps the easiest fuel to reform and is readily processed into a mixture between hydrogen and carbon oxides already at modest temperature levels, typically below 500°C.

Ethanol demands a relatively high reforming temperature (typically 600 – 700°C) since low processing temperatures might result in formation of acetaldehyde. Too high temperature levels, however, can result in increased concentrations of ethylene [18].

Other relevant liquid fuels include kerosene and diesel. Such fuels contain sulphur compounds in addition to heavier hydrocarbons. For successful operation of the fuel cell it is mandatory to use qualities with low sulphur levels or to install a sulphur trap downstream the fuel processing device. Indeed, it is normally possible to process high-sulphur containing logistic fuels like jet fuel but a sulphur trap needs to be installed to protect the fuel cell.

This study has focused on operation with biogas qualities. Upgraded biogas, which is the normal quality found in the gas grid contains methane and some smaller amounts of carbon dioxide (typically 2 – 3%). Minor amounts of higher hydrocarbons (normally propane) are added to increase the heating value of the gas.

The effect of an increased concentration of carbon dioxide has also been evaluated in this study. Indeed biogas from digestion might contain 30 – 40% of carbon dioxide and various trace components in small concentrations (e.g. hydrogen sulphide) [10]. Consequently, it is also of interest to study the sensitivity to sulphur in the system.

In the city of Stockholm, a mixture between biogas (upgraded) and air is distributed. The idea is to give the gas a similar Wobbe index as the previously distributed town gas had (a low BTU-gas). The various biogas qualities including biogas/air are shown in Table 1 below. It is important to remove impurities like siloxanes and excessive amounts of H_2S upstream the fuel cell system. Such compounds might be found in raw biogas in various concentrations [11].

Table 1 Biogas qualities
Sulphur added as odorant, usually around 5 ppm(v).
Natural gas (Danish gas quality as reference)

Natural gas	*Biogas (from digestion)*	*Upgraded biogas*	*Biogas/air*
89.6% methane 5.9% ethane 2.4% propane 0.9% butane 0.2% pentane 0.1% hexane 0.3% nitrogen 0.7% carbon dioxide 5 ppm(v) sulphur	60 – 70% methane 30 – 40% carbon dioxide 0.2% nitrogen up to 1,000 ppm H_2S	97.5% methane 2.5% carbon dioxide 5 ppm(v) sulphur	51% methane 1% carbon dioxide 10% oxygen 38% nitrogen 5 ppm(v) sulphur

Figure 4 below shows typical reformer gas compositions found in steam reforming of various fuels in the Optiformer unit. Especially in the case of diesel, there are a number of relevant qualities on the market involving various biodiesel mixtures. At low operation temperatures there might be issues with very high fluid viscosities giving rise to problems with supply/atomization and mixing. Analysis have been performed with

NDIR (CO, CO_2, total-HC), FID (total-HC), gas chromatography (hydrocarbons), PID (H_2S, hydrocarbons) and TCD (H_2).

All fuels are readily processed into a mixture of hydrogen and carbon oxides. Normally, the mixture contains various amounts of methane and higher hydrocarbons in addition to these components. The amount of higher hydrocarbons will depend on a number of parameters like operation temperature, residence time and steam-to carbon ratio. Normally, we do not see any issues with these components as long as condensation can be avoided and coke formation can be prevented. Very sticky components (sulphur compounds, carbon monoxide and some oxygenated hydrocarbons) might, however, reduce the availability of free sites for hydrogen decomposition in the fuel cell. It is well known from DMFC-applications (DMFC= direct methanol fuel cell) that strong adsorption might lead to cross over of this component, which affects the performance of the fuel cell.

Figure 10 shows measured reformate gas compositions in tests with different fuels in ComfortPower.

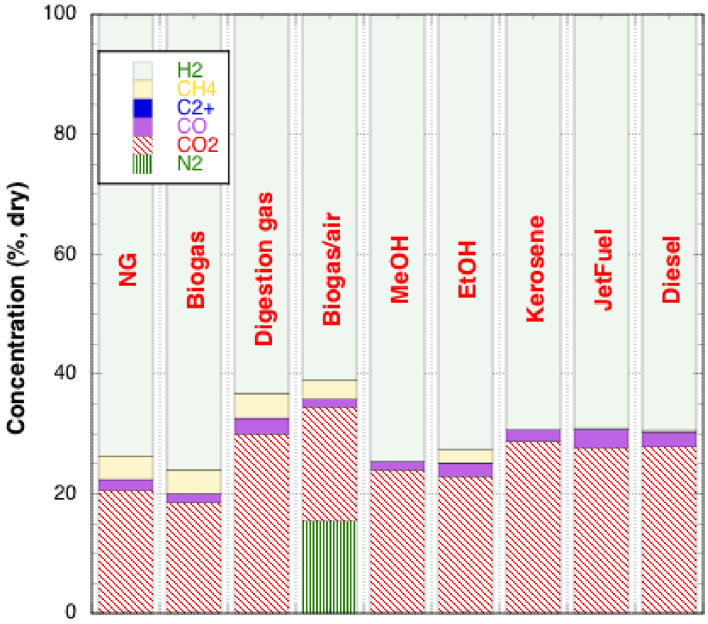

Figure 10 Reformate gas compositions (dry conditions)
Natural gas, upgraded biogas, digestion gas, biogas/air, Methanol, Ethanol, Kerosene, Jetfuel and Citydiesel.

The fuel cell performance depended merely on the hydrogen concentration according to Nernst equation for similar hydrogen utilization degrees. 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)

The stack potential (55 cells, OCP) will decrease only by 0.5 V at 160°C if the hydrogen concentration (wet conditions) is reduced from ca. 50% (upgraded biogas) to ca. 40% (digestion gas). Depending on varying CO-concentrations and the presence of H_2S in some cases it was, however, not possible to verify this effect quantitatively in the experiments.

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.

In summary, the experimental work, verified the great range of fuel flexibility for the power unit in ComfortPower. Moreover, there are no effects on the reforming process when the concentration of carbon dioxide is increased. Indeed, carbon dioxide can assist or replace steam in the reforming process and the process where steam is replaced by carbon monoxide is called dry reforming [19]. If air is added to the biogas composition, less heat needs to be supplied to the burner; the process is in between ordinary steam reforming and auto thermal reforming.

One potential hazard is that small amounts of ammonia might be formed in the reactor and this component is known to be a strong poison in PEM fuel cells since the acidic environment in the membrane is neutralized. This effect could, however, not be detected during the tests with biogas/air.

Figure 11 shows the effects of an increased CO_2-level in the reformate gas. Indeed, the only effect is that hydrogen will be diluted and hence the cell potential will be lower according the Nernst equation. Addition of air has a similar effect and will in addition to dilution also result is the consumption of some hydrogen (combustion).

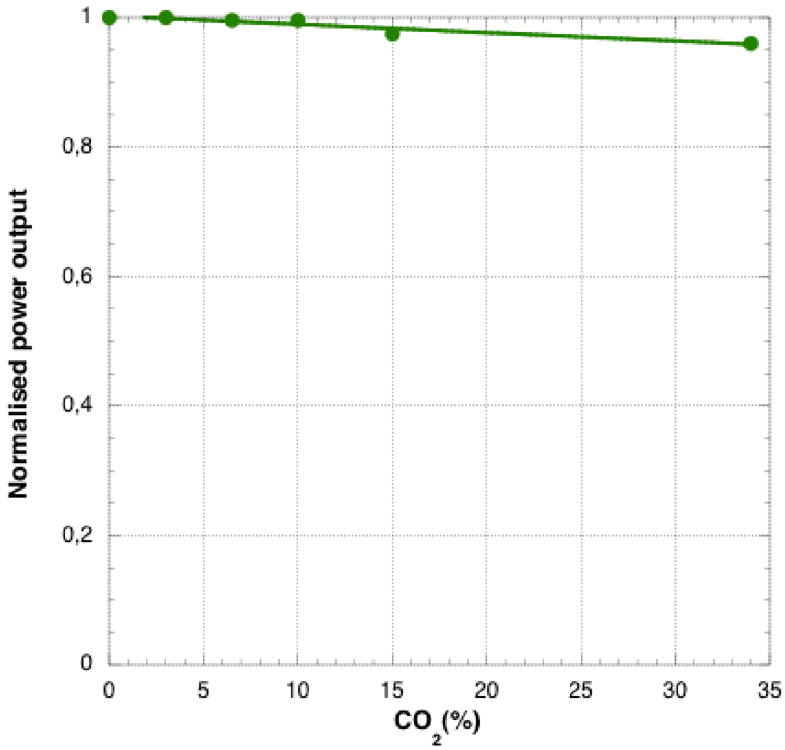

Figure 11 Fuel cell performance - effect of CO_2-concentration in mixtures between methane and CO_2.

Based on information from BASF, considering the membrane, small amounts of sulphur is acceptable. The odorant, normally present in natural gas or biogas will be converted into hydrogen sulphide but the concentration is too small to cause any detrimental effects. Figure 12 shows the performance drop versus the concentration of hydrogen sulphide (resulting H_2S-levels for various fuels are shown). Fuels like methanol and ethanol are normally completely sulphur free. Most logistic fuels will give rise to rather small performance penalties whereas some fuels like raw biogas and jet fuel will cause significant performance drops and hence desulphurization is strongly recommended for those cases. The effect of H_2S was reversible. Following a short period of purge with pure hydrogen, the capacity was recovered.

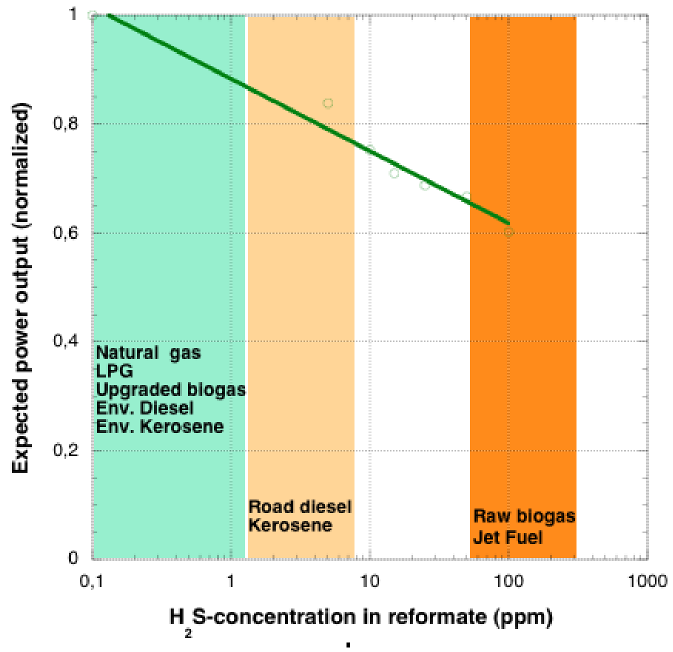

Figure 12 Performance drop due to the presence of H_2S
Data obtained following 8 hrs of stable operation at a certain H_2S-concentration.

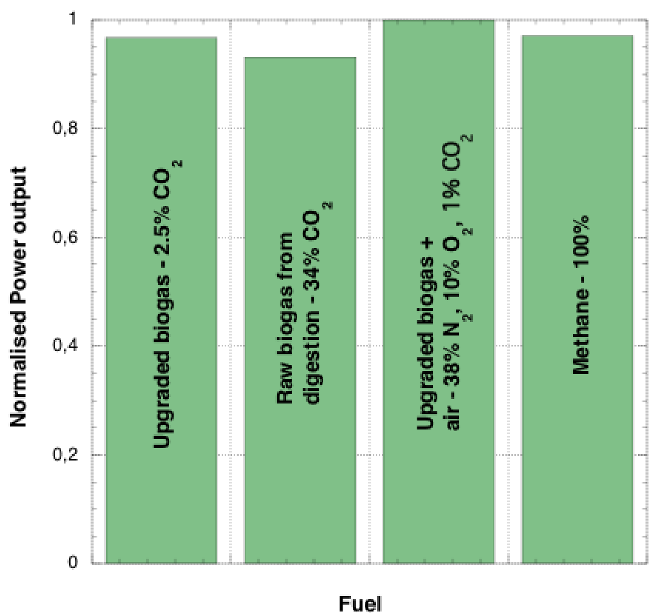

Figure 13 Tests performed with various biogas qualities in the fuel cell system

5. Long-term stability

The fuel cell system was operated at reduced capacity (ca 600 – 700 W_e) in order to fit the power consumption of the compressor unit.

Before starting the tests in this study a status check was performed on the fuel cell, which had been on the shelf for about 9 months. It was found that the capacity of the fuel cell had decreased somewhat during the storage. During identical conditions, it was only possible to drag 30 – 35 amperes from the stack (at 25 – 27 VDC), i.e. 750 – 900 W_e. It is clear that the internal resistance in the stack has increased to some extent but the mechanism is not known. Humid conditions can result in leaching of phosphorous acid from the membranes, thus reducing the electric conductivity over the membrane. In addition, phosphorous acid might lead to catalyst deactivation since phosphorous is a well-known catalyst poison [20].

Since the stack is operated at 25 – 27 VDC (cell voltage of around 0.5 V), the stack efficiency will be around 40%. A synthetic upgraded biogas (methane + carbon dioxide) was used during the long-term test. A number of start/stops were performed during the test, in total ca. 10. According to BASF, the supplier of the membrane, the membrane should show a very low deactivation rate (5 - 20 μV/h per unit cell, depending on operation temperature) in operation with methane based reformate [16]. Even if the reported deactivation rate is about twice as high as for a corresponding LT-PEM membrane, the expected deactivation during a 200 – 250 hr test should stay below 5 mV per cell, i.e. 0.3 V in total (55 cells in total). At a constant current of 30 amperes this would correspond to 9 W_e or about 1%.

Figure 14 below shows the relative power loss at constant voltage during the long-term test. Indeed, the loss over the period is about 15 times higher than expected or about 15%. Two regions can be spotted, at operation times less than 50 hrs, the relative loss is relatively insignificant. At times beyond 70 hrs, we again see rather stable conditions with a relatively low continuous loss. The stepwise decrease between 50 and 60 hrs might be due to increased leakages from the stack causing local hot spots and perhaps a mixed potential phenomenon. Indeed, a sealing test indicated gas leakage from the cell stack. The pre tension of the stack might have been too low and a test with increasing the pre tension was made, but only a minor recovery of the power output could be detected. Consequently it is believed that the leakage might have damaged some of the membranes in the fuel cell stack.

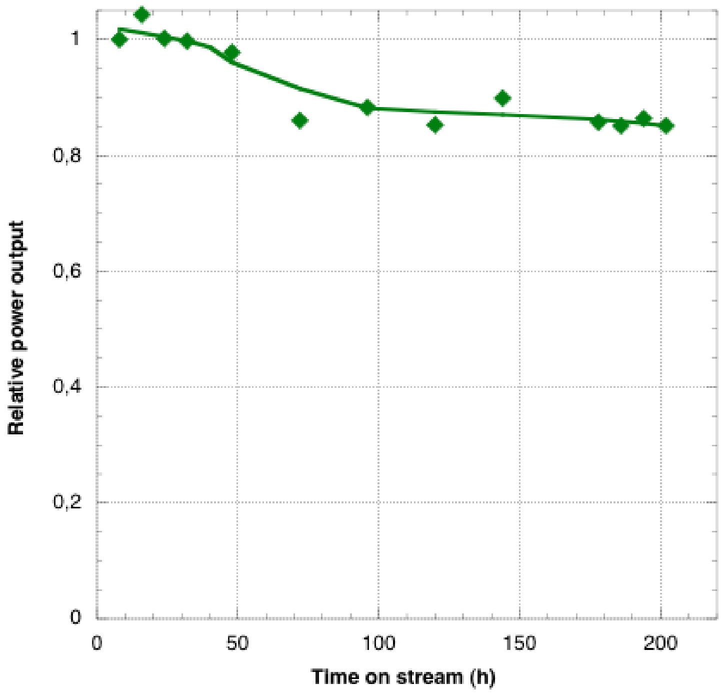

Figure 14 Relative power loss during the long-term test.
Operated at constant voltage, ca 26 – 27 VDC.

Figure 15 below shows how the concentration of methane and carbon oxides varied during the test. It is normal that the methane concentration increases by a few % during the initial phase when the effects of thermal sintering and sulphur poisoning level out. Similar trend were obtained in tests with the Ultraformer-unit [21]. Following a period of approximately 50 – 100 hrs on stream the gas compositions becomes stable.

Calculations indicate that a CH_4-concentration of around 5% is rather optimal for the operation of the burner in the Optiformer. If the conversion gets too high, the exhaust from the fuel cell anode becomes too fuel lean and additional methane must be supplied upstream the burner.

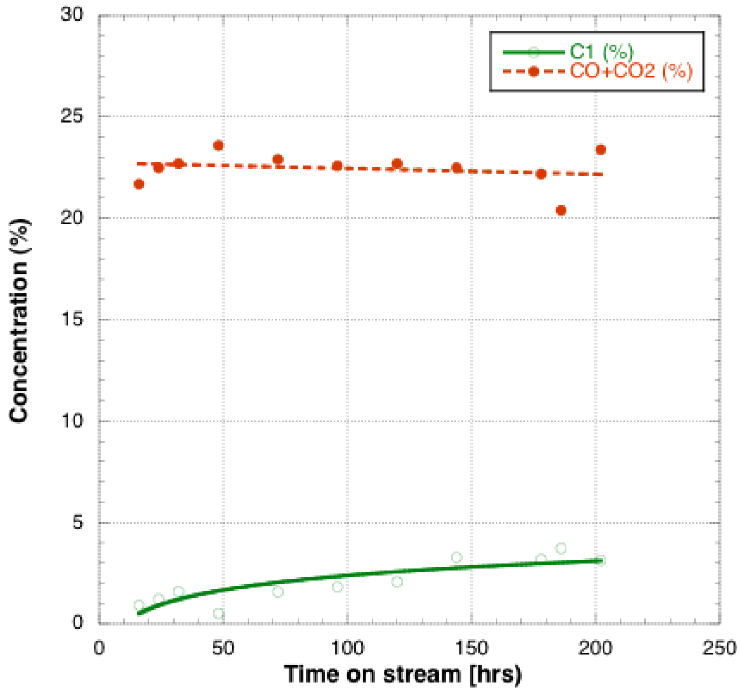

Figure 15 Concentration of methane and carbon oxides as a function of the time

6. Efficiency evaluations

The fuel cell efficiency is easily derived from the cell voltage and corresponds to the product between the cell voltage and 0.8. This means that a cell voltage of 0.5 will give a cell efficiency of 40%. This value is then multiplied by the utilization factor, which normally is around 0.7. The overall fuel cell system efficiency then corresponds to the stack efficiency multiplied by the reformer system efficiency. Normally the excess fuel originating from the stack is enough to run the process.

On top of this we have some parasitic power losses in fans, pumps, power electronics etc. Hence, it is important to reduce the pressure drop in the system and to avoid/minimize power conversion.

Various fuel cell systems will give different overall efficiencies, see figure 16 below. Indeed, if a solid oxide fuel cell is used with internal reforming, it is possible to reach overall electric efficiencies above 50%.

In this case we have used the Optiformer together with a HT-PEM stack, which gives us efficiencies according to Figure 17 (mapped in the previous project [1]). If the utilization factor is above 0.7, it is normally necessary to add extra fuel to the Optiformer burner to heat the reactor. At utilization factors of around 0.7 the system becomes self-sustainable.

At still lower utilization factors, it is necessary to increase the air supply in order to avoid overheating of the Optiformer. The fuel cell system will consequently give efficiencies slightly less than 30% (raw electricity). In situations where power conversion is needed (DC/DC-conversion and DC/AC-converison), this figure will decrease by a few%.

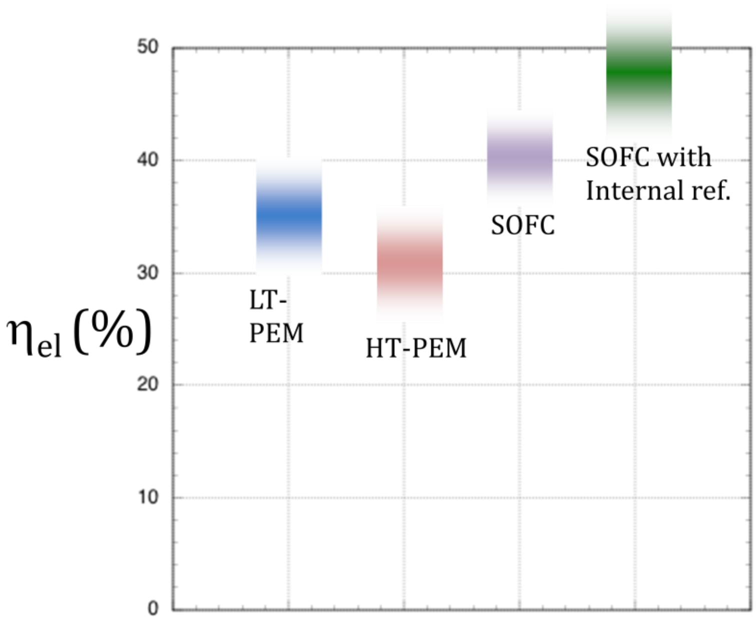

Figure 16 Fuel cell system efficiencies, bar diagram
LT-PEM=low temperature polymer electrolyte fuel cell
HT-PEM=high temperature polymer electrolyte fuel cell
SOFC=solid oxide fuel cell

The DC/DC-DC/AC-device used in ComfortPower 1 showed an overall efficiency of 90%, which means that the total efficiency from fuel to 230 VAC was around 27%.

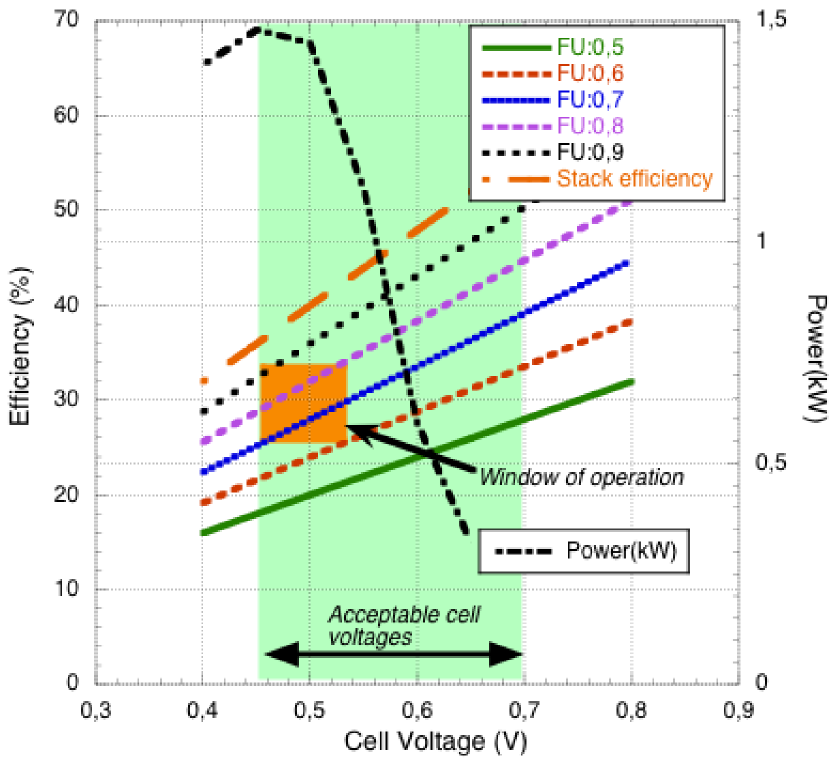

Figure 17 Fuel cell system efficiencies vs cell voltage and utilization factors [1].

Based on the mapping of the heat pump system and data from the fuel cell system, a numeric model was derived to calculate and analyze heating efficiencies in the modified ComfortPower for various system temperature levels. The generated data were compared with data previously obtained for ComfortPower 1 and the agreement between experimental and calculated data is very good.

From figure 18 below, it is clear that the heating efficiency has increased by approximately 15 - 20% through the modifications and the optimization. In order to further improve the heating efficiency, it is necessary to change the fuel cell technology from PEM to SOFC, preferably with internal reforming.

In the experimental evaluations, the cold and the hot sides were connected to plate-type heat exchangers and the temperature differences over the heat exchangers were measured. The flow rates through the heat exchangers were measured by carefully calibrated flow meters. Furthermore it was possible to vary the inlet temperature on the hot side by using an additional electric water heater in that circuit. The set-up enabled us to vary flow rates, temperature differences and inlet temperatures.

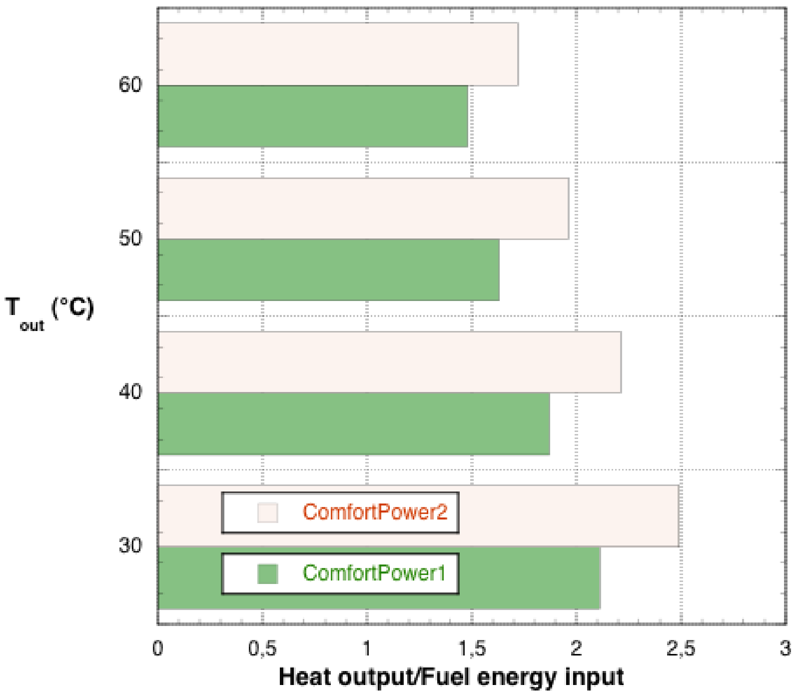

Figure 18 System efficiencies, ComfortPower 1 and 2
Evaporation temperature: ca 5°C, heating from 10°C to T_{out}.
Fuel cell system efficiency: 30%, DC/AC-efficiency:90% in ComfortPower1, 100% in ComfortPower2.

7. Operation profiles

The temperature levels in the ComfortPower system will depend on the application. In general there are a number of possible cases, which must be covered [22]:

- Domestic applications
    - Floor heating
    - Heating with radiators
    - Heating with convective elements
    - Hot tap water production
    - Comfort cooling

- Campus applications
    - Heating with convective elements
    - Comfort cooling

In floor heating the normal delivery temperature is 30 - 45°C whereas heating with radiators or convective elements will demand higher delivery temperatures, normally 45 – 55°C. Hot tap water is normally delivered at temperatures of around 55°C and would require operation at even higher condensation temperature or peak heating with electricity (or hot flue gases). The tap water must sometimes be heated to higher temperatures to avoid problems with Legionella. This is usually accomplished via electric heating.

In comfort cooling by circulating water, the minimum water temperature should be limited to about 18°C to avoid problems with condensation.

The normal heating source for a heat pump is either air or water. If air is used, the evaporation temperature in the heat pump might vary depending on the season whereas water (especially ground water) gives a more stable (and usually higher) evaporation temperature. The evaporation temperature in air-source heat pumps could vary between 10°C or higher down to -20°C or less. In water-source heat pumps the span of evaporation temperatures could be limited to about 0 – 10°C.

Figure 19 below shows the thermal setup of the ComfortPower unit. The heat pump is supplied with ambient air or water on the heat-source side. This stream is preheated with the humid cathode stream and sensible as well as latent heat can be recovered to increase the heat input. On the condensation side, the residual thermal energy from the fuel cell system is recovered. Due to the thermal integration, the temperature lift in the heat pump system can be reduced by 15 – 20°C, which favours the thermal efficiency, see Figure 20. The temperature difference over the evaporator is normally limited to about 5°C

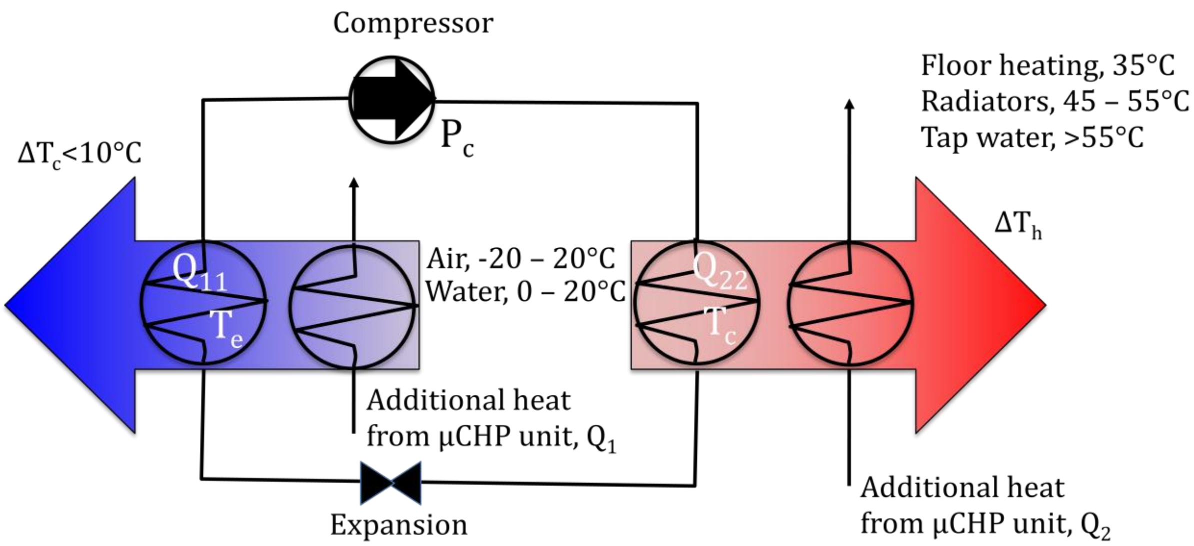

Figure 19 Thermal setup in ComfortPower
Q_1 and Q_2 are additional heats supplied by the fuel cell system.

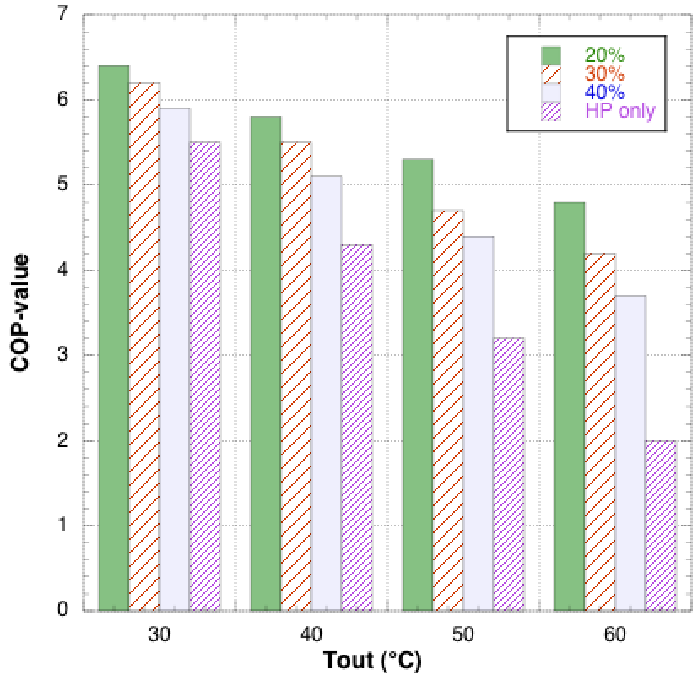

Figure 20 Shift in heat pump COP-values due to the thermal integration with a µCHP-unit.
Obtained at different values for electric efficiency, evaporation temperature was set to 5°C and the overall heat efficiency to 90%.

When hot water is delivered at 60°C, the corresponding COP-value is around 2 when only the electric compressor is used. The temperature lift in the heat pump system can be decreased when utilizing the excess heat from the fuel cell system. This results in higher COP-values, especially at high water outlet temperatures.

Figure 21 shows the expected performance of ComfortPower 2 in various applications. Evaporation- and condensation temperatures, differential temperatures and the power generation efficiency will influence on the performance. The efficiency will normally vary between 150 and 200% in these applications.

In campus applications, convective elements are normally used to supply heat (and cooling). The delivery temperature on the hot side will depend on the dimensioning of the convective element (the smaller the higher temperature) but is normally between 45 and 55°C. The same situation is valid on the cold side; if small elements are use the temperature difference needs to be higher. In order to avoid condensation problems, the outlet temperature on the cold side should stay around 18°C.

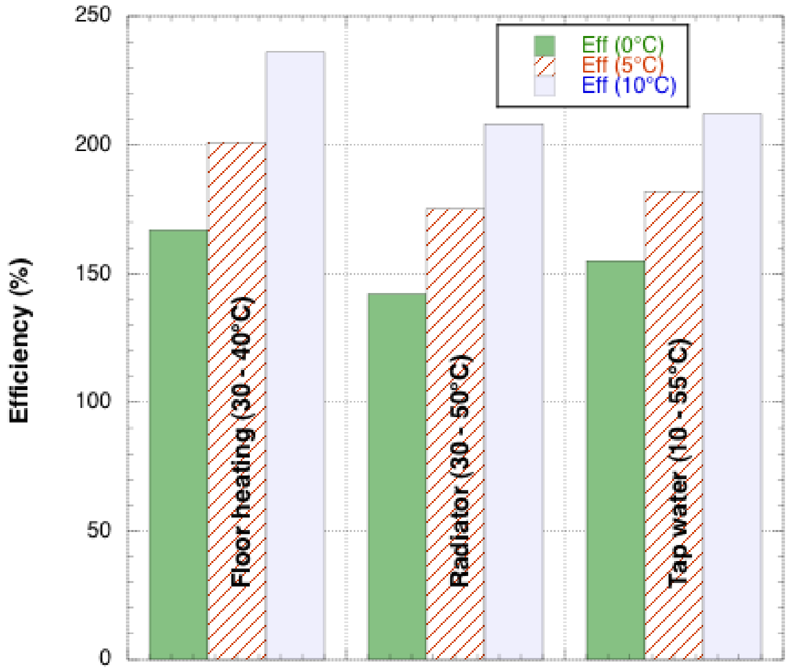

Figure 21 Expected thermal efficiencies in various applications. Calculated for various evaporation temperatures.

8. Systems based on other fuel-cell types and engines

As previously stated, there a number of technologies to produce power in small systems. We have various types of fuel cell systems, combustion engines (internal and external combustion), organic Rankie cycle (ORC) and micro turbines.

Fuel cells can deliver electricity at a high efficiency and also show high turn-down efficiencies. Combustion engines and turbines give lower electric efficiencies and generally poor turn-down efficiencies.

Fuel cell systems normally require complicated and ineffective power conversion whereas combustion engines normally are directly tied to a generator system, which delivers 230 VAC.

Systems based on combustion engines are normally relatively simpler and constitute few components whereas the need for maintenance might be higher. Fuel cell system are said (at least in the future) to show a very long lifetime without excessive need for service measures.

Fuel cell systems can be built for a wide range of fuel flexibility and so might combustion engine solutions based on external combustion or gas turbines. Figure 22 shows a

ComfortPower system based on SOFC with internal reforming. This kind of system is expected to show electric efficiencies in the high 40s or the low 50s. The system schematic is rather simple if it is compared with the one showing ComfortPower 2.

Since this concept relies on reforming adjacent to the electrochemical process, it is mandatory to de sulphurize the fuel to avoid poisoning of the nickel catalyst in the fuel cell. Already sub ppm-levels of H_2S will destroy the reforming capacity on the anode side.

A SOFC-system is operated at high temperatures, normally well above 600°C. This also means that the heat quality of the excess heat leaving the system is very high. Consequently, the heat recovery in the system can be very effective.

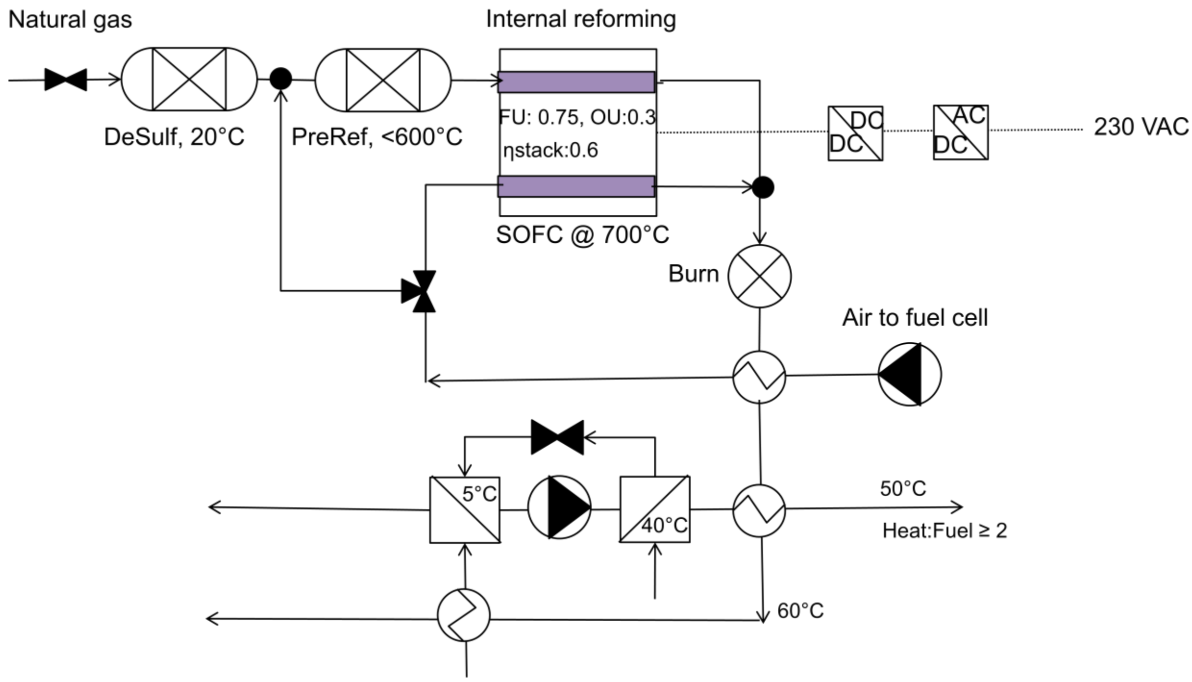

Figure 22 ComfortPower based on SOFC with internal reforming, schematic diagram

Figure 23 shows a general schematic of a system involving a Stirling Engine, which also shows a high degree of fuel flexibility. The system is very simple and no fuel purification is normally required. The electric efficiency is expected to be around 15% even if some producers/researchers claim efficiencies between 20 and 25% down to very small sizes (a few 100 W_e) [17]. The burner in the Stirling engine is normally recuperated, which means that the flue gases leaving the unit are relatively cold. The idea is to use the exhausts to increase the evaporation temperature and the coolant circuit to boost the outlet temperature on the hot side of the heat pump.

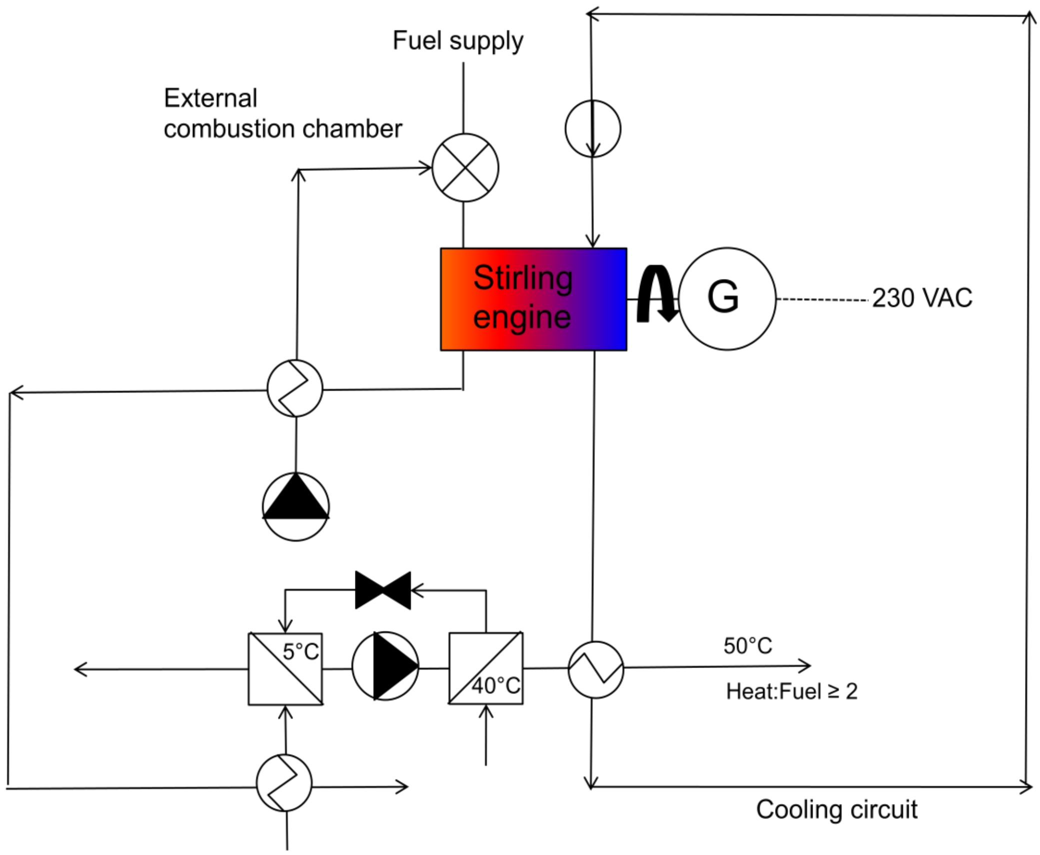

Figure 23 ComfortPower based on Stirling Engine, Schematic diagram

When analyzing various sources for power generation and grid related electricity (produced at 30% overall efficiency), it stands clear that a unit comprising a SOFC with internal reforming would be the best alternative from a heating efficiency point of view.

Also power generation operating at low electric efficiencies will give a clear advantage over systems operating on grid related electricity. Renewable sources for electricity (hydroelectric power, wind and solar) will give much higher grid related efficiencies (85 – 90%) but such sources are not readily availably in most countries (Norway and Sweden are exceptions though).

Figure 24 compares various technologies with respect to heating efficiencies. Even if SOFC/Internal reforming gives the highest efficiency it is also important to take practical aspects (maintenance and robustness) as well as the cost into consideration. Consequently, combustion engines are in favour of fuel-cell systems based on these aspects for the time being. Stirling engines are relatively more expensive than internal combustion engines but show a much higher degree of fuel flexibility. The Stirling technology is consequently a candidate technology for these systems, especially if the electric efficiency can be improved.

Figure 25 summarizes the split between electrically generated heat (heat pump) and the sensible heat provided by combustion/exhausts at various electrical efficiencies (various power generation systems). It is thus important to match the power of the compressor to the electric efficiency of the power generation system for a certain heat output. If the heat is generated via a stand-alone heat pump, working at an outlet temperature of 50°C, the overall efficiency will be slightly less than 1 (grid electricity is assumed to be produced at 30% fuel efficiency). A condensing boiler will typically give efficiencies in the neighbourhood of 100 – 105% under these conditions. The µCHP/HP-systems will generally give efficiencies between 150 and 250% under these circumstances. The higher the electric efficiency is, the lower will the contribution from the fuel cell system be to the total heat recovered. The efficiency in heat recovery will depend on the thermal quality of the exhaust, which will increase with the temperature. Hence the heat in exhausts from a SOFC-system is recovered more readily than the heat in exhausts from a LT-PEM-system. If the temperature difference on the hot side is substantial and the outlet temperature is high (tap water), it is favourable to have relatively more heat coming from the fuel cell system since the COP-values in the heat pump become poor at high condensation temperatures. If the outlet temperature is low and the temperature difference is small (e.g. floor heating), relatively more heat should come from the heat pump system.

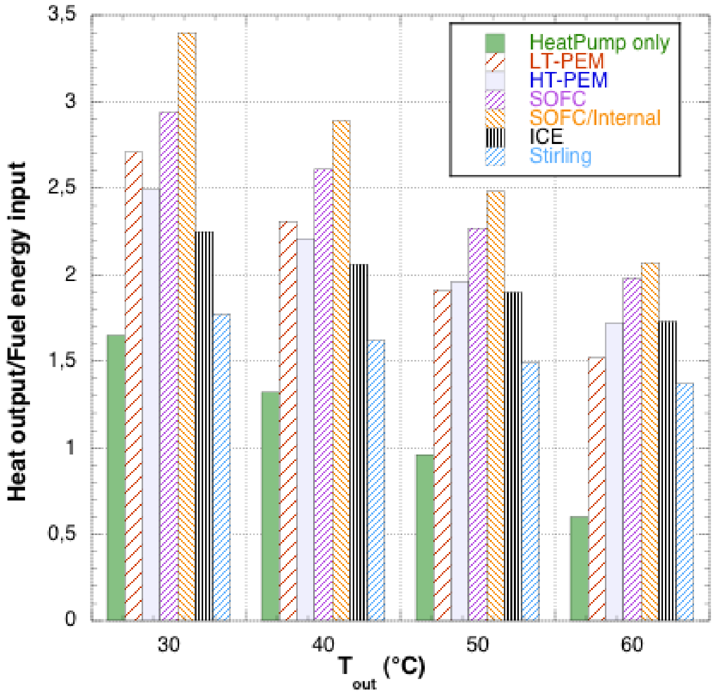

Figure 24 Expected performances for various systems at different outlet temperatures.
η_{el}: From grid (30%), LT-PEM (35%), HT-PEM (30%), SOFC (40%), SOFC/Internal (50%), ICI (25%), Stirling (15%)
Evaporation temperature, 5°C

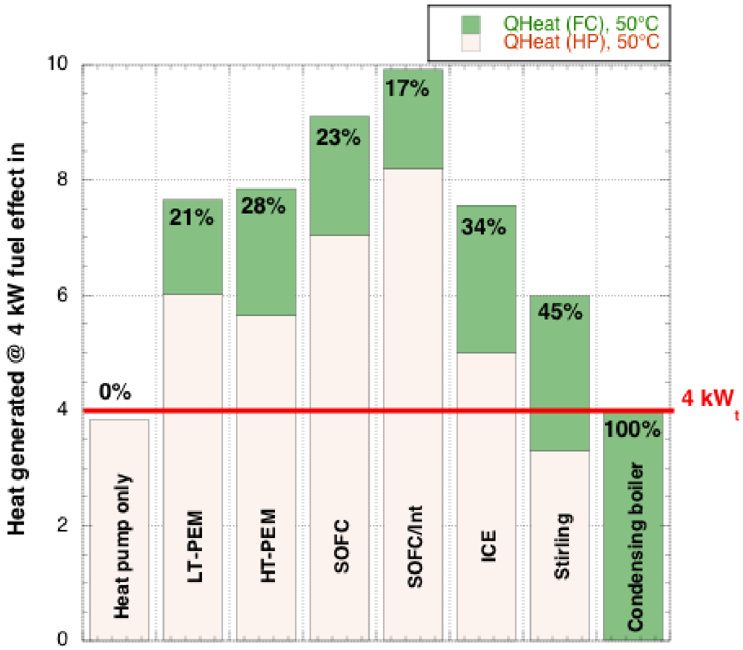

Figure 25 Split between electrically derived heat, QHeat(HP) and sensible heat, QHeat(FC) in a ComfortPower unit. 4 kW_t fuel in, T_{out}=50°C, Grid electricity obtained at 30% fuel efficiency.

The cooling efficiency of a ComfortPower unit will correspond to the efficiency found in a stand-alone heat pump system, i.e. the COP-value will typically vary between 2.5 and 3. In the cooling mode there is no use for the additional heat generated by the fuel cell system (except possibly for simultaneous hot tap water production).

9. Environmental savings

The primary business area for ComfortPower is domestic heating where the unit will replace ordinary wall mounted boiler systems. In addition to a much higher heating efficiency the ComfortPower unit will provide surplus electricity and the possibility of comfort cooling.

The environmental savings are totally associated with decreased primary energy consumption and consequently a smaller carbon dioxide footprint. The emissions of CO, unconverted hydrocarbons and nitrogen oxides are low but not necessarily lower than from modern wall mounted boilers.

Every year about 7 million wall mounted boilers are sold in Europe and the expected lifetime is about 10 – 15 years. A paradigm shift in technology will obviously take some time even if all technical and economical expectations can be met.

It is assumed that the technology can get 30% of the market share for new boilers within 15 – 20 years. Today the total CO_2-emissions are around 3,500 Mt per year in the EU-27 zone [11]. The analysis shows that it is possible to decrease these emissions by about 1% following a considerable ramp-up of the technology. Simultaneously, the primary energy consumption will decrease by a few percent. Thus, the overall environmental impact will still be rather small.

Natural gas stands for about 30% of the total fossil fuel consumption and most of the gas is used for heating purposes (household sector in the pie diagram below) [12].

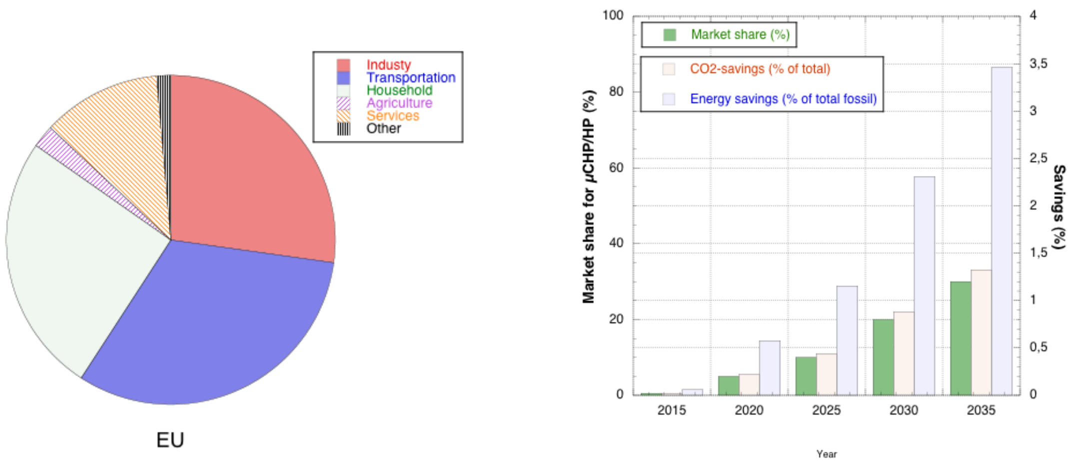

Figure 25 Energy consumption per sector within EU (27) and possible savings with the µCHP/HP-technology.
Total energy consumption: ca 1160 Mtoe.

It is of interest to investigate how a µCHP/HP-system (µCHP= small scale heat and power, HP=heat pump)can compete with pure HP-systems from an environmental perspective. Figure 26 shows how the CO_2-savings will depend on the grid carbon intensity and the COP-factor in the HP-system. In Sweden, the grid carbon intensity is below 20 g/kWh$_e$. This means that is always will be a poor choice to replace a pure HP-system with systems using fossil fuels here from a CO_2-perspective, even if the efficiency is extremely high.

In continental Europe and especially in some countries worldwide (like Poland, China, Australia etc) the situation is quite different with grid carbon intensities of between 500 and 1,000 g/kWh$_e$ [13]. Under such conditions a pure HP-installation cannot even compete with a traditional condensing boiler. Implementation of the µCHP/HP-technology here would dramatically reduce the CO_2-impact on the environment.

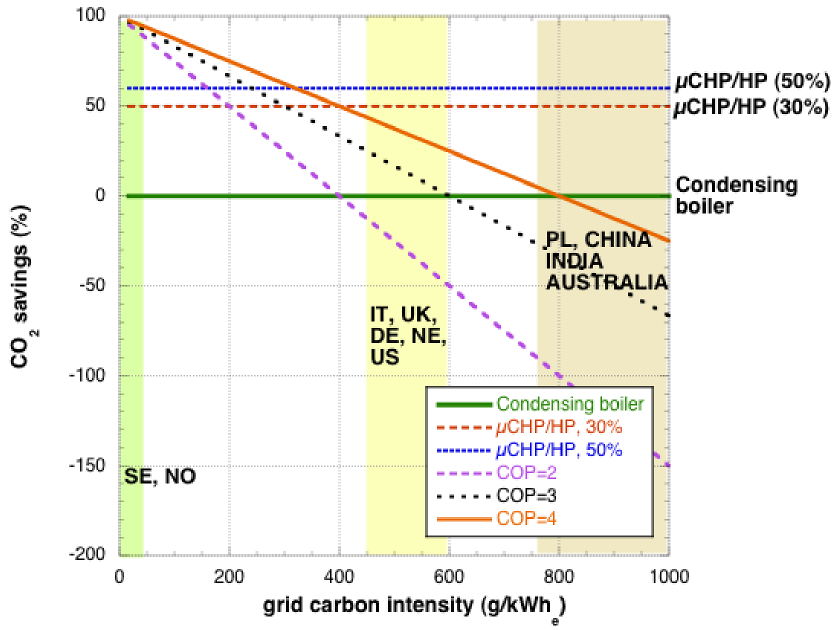

Figure 26 CO_2-savings when installing a heat pump powered by Grid electricity.

Data given for heat pumps operating at different COP-values. Base line (0%) correspond to a condensing boiler @ 200 g CO_2/kW_t. μCHP/HP-units working at 30 and 50% electric efficiency shown in the same diagram.

The ComfortPower-unit will of course be more expensive than a traditional wall mounted boiler. Studies indicate that the price for a μCHP-unit will be about 7,000 – 10,000 Eur per unit (1 kW_e-systems) once in volume production [8]. These figures are valid for combustion engine based systems as well as systems based on fuel cells. Depending on the gas price and the energy consumption (energy cost), the pay off time will vary according to Figure 27 below. A number of analysis indicate that the gas price will increase in the future, which would make this technology more interesting. In addition to this, it might be possible to achieve tax reductions since this technology is environmentally friendly.

The pay-off time must probably be below 5 years (expected lifetime of a condensing boiler is currently 12 – 15 years) for attracting enough interest on the market. A typical gas price of 600 SEK/MWh [23] and an annual consumption of 15 MWh will result in a energy price of 9,000 SEK/a. Under such conditions the added values with ComfortPower would correspond to about 25,000 SEK, see Figure 27 below. High gas consumptions and increasing gas prices will of course change this picture completely.

It is reasonable to believe that the price difference between a ComfortPower unit and a conventional gas fired condensing boiler will reach levels well above 50,000 SEK. In order to justify the investment in a ComfortPower unit will then mean that the current energy cost must be above approximately 20,000 SEK per year.

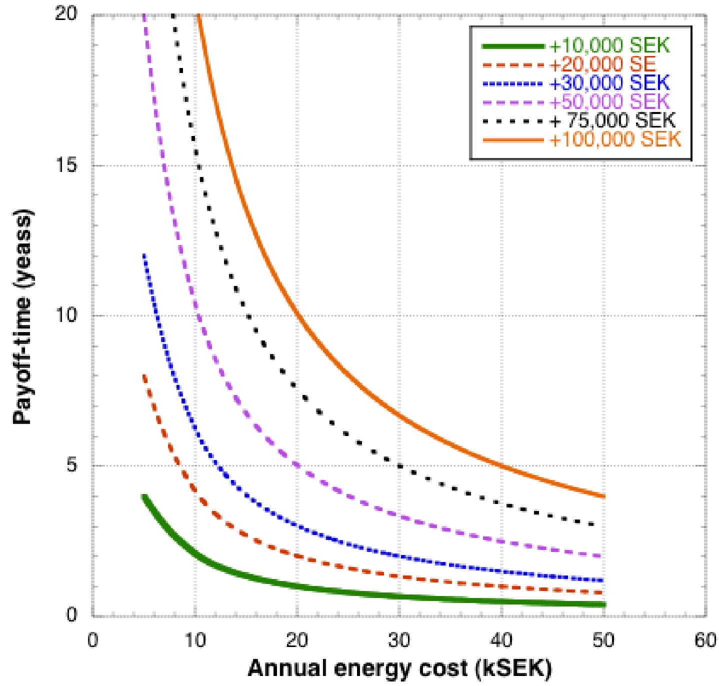

Figure 27 Pay off time as a function of the annual energy cost in a household at various differential costs for the ComfortPower over a conventional condensing boiler. Assumed thermal efficiency of ComfortPower:200%. Annual energy cost with a condensing boiler (i.e. before installation of ComfortPower).

The ComfortPower unit will contribute with other advantages over a conventional boiler, which are difficult to price, e.g. comfort cooling, power generation possibility and multi fuel operation. Such additional advantages might favour the situation to some extent.

From the section it is obvious that the potential of the technology will vary depending on the energy situation in a certain region (e.g. the carbon grid intensity, the tax system, the availability of different fuels etc). A realistic ramp-up of the technology would show some miner impacts on the total carbon dioxide emissions and the total energy consumption. Increased gas prices will promote the introduction of this technology as and so will possible tax reductions and subsidies.

10. Conclusions

The ComfortPower unit has been improved and simplified by a number of actions. The original 230 VAC compressor was replaced by a 24 VDC compressor in order to achieve a direct coupling between the fuel cell stack and the battery. Through this modification, it was possible to remove the inverter system, which contributed with some parasitic losses.

A number of experimental evaluations have been performed during this project phase:

- Mapping of the heat pump system following modifications of the thermal integration
- Tests with liquid fuels in the fuel cell system
- Tests with various biogas qualities and biogas – air mixture
- Long term evaluation with upgraded biogas

The thermal integration of the unit was improved by separating the air streams from stack cooling and cathode air. The sensible and latent heat in the cathode off gas was recovered on the cold side of the heat pump, thus enabling us to increase the evaporation temperature by 2 – 5°C. The normal COP-value for heating is between 5 and 6 as a result of the shift in evaporation and condensation temperatures. Since it was possible to remove the inverter in the modified 24 VDC-configuration, the efficient COP-value (raw electricity to heat) increased by about 0.5 units.

A number of gaseous and liquid fuels have been tested in the fuel cell system. The power output is correlated to the hydrogen concentration (via Nernst equation) and the utilization factors. In addition, the CO-concentration will influence on the performance, the higher the CO-concentration is the higher must the operation temperature be. The fuel cell temperature is limited to 160°C (short peaks are allowed up to 170°C). The sulphur content of the fuels studied varied between 0 and 10 ppm(w), which resulted in H_2S-concentrations of about 1 ppm(v) in the reformate. Such low levels will not influence the performance of the HT-PEM stack. In a previous test, the reformer system has been operated with jet fuel without problems even if the reformer temperature needs to be increased. Jet fuel will give too high H_2S concentrations even for a HT-PEM stack and hence desulphurization upstream the fuel cell stack is recommended.

Biogas qualities could be readily reformed and the resulting reformate could be used in the fuel cell without problems. Even raw biogas (from digestion) could be used following purification from excessive sulphur. Blends of upgraded biogas and air (town gas quality) were also tested on the fuel cell system without problems. All tests with liquid and gaseous fuels clearly demonstrated the wide fuel flexibility of the ComfortPower unit.

The multifuel opportunity, however, comes with one drawback: it is necessary to include a complete fuel processing system designed for the worst fuel. This study indicates that it were possible to reach heating efficiencies as high as 300% if SOFC-stacks are used with internal reforming of methane. Internal reforming is only possible with pure methane since all other fuels would cause coke formation.

A long-term test (200 hours) was performed with upgraded biogas. The test showed a 15% decrease of the power output during the course of the test; more than 15 times higher than expected. The reason for this phenomenon is not complete clear even if phosphoric acid leaching and gas leakage from the stack due to imperfect pre tension of the stack are probable candidate explanations. Other possible reasons are connected to overheating of some membranes since the stack was operated at 160°C, which is close to the upper temperature limit (170°C). Development of transient temperature profiles might give rise to local overheating (which is not easily spotted by the thermocouples). It is, however, not likely that the stack has suffered from hydrogen starvation since the Optiformer has been operated to guarantee enough hydrogen supply.

Commercialization of the ComfortPower technology will depend on proven reliability, robustness, competitive technical performances and low cost. Indeed, the technical performance with respect to heating efficiency can be met but the major hurdles are associated with reliability and cost. It is essential to use technologies, which are inherently robust and not too sophisticated and complicated. Appliances like the ComfortPower will face various environments and operations conditions. In campus applications we see harsh temperature conditions, snow, dust, dirt. In addition, the unit must be ruggedized to tolerate transportation and be mechanically proof in general.
In domestic applications, maintenance free operation and longevity are taken for granted even if the environmental conditions are milder.

Even if reliability, robustness and longevity can be proven, it is equally important to converge to a realistic price level. The fuel cell system will replace a combustion engine (internal or external combustion) and the price level needs to match the corresponding price level of such units. Today, it is possible to buy a µCHP-system based on a combustion engine (output 1 kW_e) for about 8,000 Eur [7]. Larger units are sold at a relatively lower price per kW_e. A fuel cell µCHP, will probably always be more expensive but this is probably acceptable since the electric efficiency is higher. The current price level of the Japanese ENE-FARM system is about 25,000 Eur [8]. Increased sales volumes (>100,000/a) will reduce this figure and the expectation for 2015 is set to about 7,000 Eur per unit. Indeed, this value is close to the current price level for µCHP-systems based on combustion engines, which however also are sold in small numbers at the moment. This price will also come down and the competition will continue.

The µCHP-system must then be complemented with a heat pump, which however is a commodity on the market.

The combination of µCHP-systems and heat pumps is an effective approach to reduce the primary energy consumption and the carbon dioxide emissions in the domestic sector. The units will offer wide flexibility in operation and can supply not only heat but also surplus power and cooling. The wide range of fuel flexibility opens up for premium niches like Campus applications. The µCHP-powered heat pump (e.g. ComfortPower) will probably reach the market but the question mark is related to the choice of power generation system, i.e. fuel cell systems or combustion engines.

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