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Combined Cold Heat and Power Generation

Techno-economic assessment of integrated fuel cell and sorption heat pump systems

ECN Clean Fossil Fuels
ECN Energy Efficiency in the Industry
Shell Global Solutions

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Acknowledgement/Preface
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Abstract
This report contains the results of a feasibility study into the possibility of combining a fuel processor/fuel cell (FP/FC) system with an adsorption-cooling device to convert the waste heat of the former into cold. Such a combination is in general referred to as *trigeneration*, denoting the simultaneous production of power, heat and cold.

As starting point for this study a trigeneration system was proposed consisting of a PEMFC based CHP unit, equipped with a CPO based fuel processor of Shell (Hydrogen Source), and combined with the SWEAT solid sorption heat pump which is being developed at ECN. In addition, various alternative technologies have been considered as part of a trigeneration unit, both at the heat and power production side (SOFC, gas engine, gas turbine) as well as at the cold production side (silica/H_2O and $LiBr_2$-H_2O sorption chillers).

The trigeneration systems have been evaluated for surplus value in terms of energy saving compared to a reference situation consisting of cogeneration and production of cooling with an electric compression heat pump. The evaluation holds for a grid-connected situation, and own exploitation/ private ownership of facilities. It appears that in this situation, there is only potential for energy saving if the ratio of cooling efficiency of the trigeneration unit and the COP value of the reference cooling technology is larger than the difference between the average electrical efficiency of central power production and the electrical efficiency of the trigeneration unit. Most systems considered do not fulfil this criterion. Only trigeneration systems based on a Solid Oxide Fuel Cell with steam pre-reforming of fuel show potential. This appears to be not so much the result of a high cooling efficiency, but rather the result of a relatively high electrical efficiency. The application of trigeneration is illustrated by two case studies, the result of which indicate that combining cogeneration with a sorption cooler besides, or instead of electric compression cooling could lead to significant energy cost savings, and may thus be a way to enhance the viability of cogeneration.

Key words
Trigeneration, combined heat and power, cogeneration, fuel cells, fuel processing, cooling, sorption cooler, adsorption cooler, absorption cooler

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SUMMARY

This report contains the results of a feasibility study carried out by ECN and Shell into the possibility of combining a fuel processor/fuel cell (FP/FC) system with an adsorption-cooling device to convert the waste heat of the former into cold. Such a combination is conventionally referred to as *trigeneration*, denoting the simultaneous production of power, heat and cold.

The study has concentrated on identification of the potential of energy saving through trigeneration in a Dutch (or equivalently, a European) context. To this end the following activities were carried out:

- Market survey for trigeneration;
- Development of a system concept for a base case trigeneration system with assessment of performances via modelling and simulation;
- Exploration of alternative trigeneration systems by substituting the components used in the base case for other technologies
- Comparison of trigeneration with a reference situation (using specific Dutch data) to determine its significance upon application in terms of energy and other savings

Options for application of a trigeneration system that produces power, heat for space heating and hot tapwater (about 70°C), and cold (5-15 °C) for cooling purposes have been identified on the basis of an inventory of energy demands in Dutch market sectors. It is expected that trigeneration, as envisaged in this study, is a feasible option in industry sectors like meat production, dairy production and breweries. Furthermore, energy demands in utility buildings like offices, conference buildings, hospitals and the hotel and catering sector seem to offer good prospects. A system size of 150 kW_e was selected as appropriate for most applications. In the Netherlands, in residential buildings there is no significant demand for cooling. Consequently, residential buildings are not a market for tri-generation systems.

As starting point for this study a natural gas fuelled trigeneration system was proposed consisting of a PEMFC based CHP unit, equipped with a CPO based fuel processor of Shell (Hydrogen Source), and combined with the SWEAT solid sorption heat pump which is being developed at ECN[1]. Looking back it is concluded that this choice has been an unfortunate one:

- Compared with other sorption coolers, the SWEAT system offers a high power density and high storage density. However, as a consequence of its working principles/fundamentals, the applicability for trigeneration appears very limited. The temperature range that can be used for charging of the system is limited to about 90-95 °C. At higher temperatures the salt in the system will melt. At lower temperatures the system requires condenser temperatures (i.e. outside temperatures) well below 15-20°C. This will be a problem on hot summer days, just when the need for cooling is highest.
- A large part of the heat generated by the CPO-PEMFC is available at temperatures below the temperature range that can be used by the SWEAT sorption cooler. About 75% of the heat is available at temperatures below 70-80 °C, i.e. only 20-25% of the heat generated can be used effectively. This finding in combination with a CPO-PEMFC thermal efficiency of 64%, and a COP of the SWEAT cooler of about 0.5, leads to an overall cooling efficiency of less than 8%, which is rather disappointing.

[1] Under development at ECN Energy Efficiency in the Industry on the authority of SWEAT BV.

Various alternative technologies have been considered as part of a trigeneration unit, both at the heat and power production side (SOFC, gas engine, gas turbine) as well as at the cold production side (silica/H_2O and $LiBr_2$-H_2O sorption chillers). Most combinations offer perspective for a better cooling efficiency than in the base case combination. By combining thermal efficiencies, estimates for fractions of the heat that can be used for cold production, and COP values of different sorption coolers, overall cooling efficiencies ranging from 5% to 40% were found. A system consisting of a SOFC with CPO based fuel processor and a $LiBr_2$-H_2O absorption chiller showed the highest cooling efficiency.

General criteria have been derived to be able to assess the value of trigeneration compared to a reference situation consisting of cogeneration and production of cooling with an electrical compression heat pump. The criteria hold for a grid-connected situation, and own exploitation of facilities. It was found that trigeneration only offers potential for energy saving when the CHP part of the unit is formed by a Solid Oxide Fuel Cell with steam pre-reforming of fuel. This appears not so much the result of a high cooling efficiency, but more the result of a relatively high electrical efficiency. The criterion shows that there is only potential for energy saving when the ratio of cooling efficiency of the trigeneration unit and the COP value of the reference cooling technology is larger than the difference between the average electrical efficiency of central power production and the electrical efficiency of the trigeneration unit. The higher the COP of the reference cooling technology and the higher the efficiency of central power production, the tougher it will be for a trigeneration system as considered in this study to offer surplus value in terms of energy saving.

Contrary to primary energy saving, results for CO_2 emission reduction show that trigeneration does lead to CO_2 emission reduction. This is, however, not the result of energy saving, but the result of fuel substitution; An additional part of the electricity produced by a fuel mix, which partly consists of coal, is replaced by electricity (and heat) produced by natural gas.

Finally, it was found that the criterion results with respect to energy cost savings depend very much on the level of gas and electricity consumption. At low consumption levels natural gas appears to be relatively expensive compared to electricity, and as a result there seems to be little potential for energy cost savings. At increasing consumption levels, however, the ratio of the natural gas and electricity price eventually becomes such that the savings on avoided purchase of electricity outweigh the cost for additional purchase of gas. In other words, combining cogeneration with a heat driven sorption cooler for the production of cold instead of an electrical compression cooler, may result in energy cost savings. Since the cost of a sorption cooler as part of a trigeneration unit, are not expected to be higher than that of a conventional compression cooler, this means that extension of cogeneration to trigeneration by adding a sorption cooler to the system can create additional room for investment for cogeneration, and may help to enhance the economic viability of cogeneration.

1. INTRODUCTION

It is a recognised fact that application of combined heat and power (CHP) offers good prospects for energy saving. However, in many parts of the world and in a variety of circumstances when there is little need for heat, or there is a cooling need, which is at least as important as the heating need, CHP is a less suitable option. The present study was initiated based on the realisation that extension of cogeneration with heat driven cooling, thus creating trigeneration, may offer a good possibility for application of CHP in those circumstances and may lead to a better usability of small scale CHP.

The study initiated builds on an earlier study carried out by Shell, ECN and GasUnie into the prospects for small-scale Combined Heat & Power systems, based on fuel processor and fuel cell technology, which had a positive outcome. In terms of technical components, the present study considers a Shell-design fuel processor (as presently under development by Hydrogen Source, a joint partnership of UTC Fuel Cells and Shell), in combination with a low-temperature PEM fuel cell and SWEAT solid sorption cooling technology (as presently under development by SWEAT B.V., a joint venture of ECN, NUON and De Beijer RTB).

The study has concentrated on identification of the potential of energy saving through trigeneration in a Dutch (or equivalently, a European) context. The most important consequence of this context is that potential users (be it industrial, commercial or residential) are grid-connected: they will power their trigeneration unit with Natural Gas (NG) and possible excess electricity production is fed back to the grid. Furthermore, a situation of own control of facilities has been assumed, as opposed to a situation in which an energy service company controls facilities.

The report is built up as follows. Chapter 2 contains a (Dutch) Market Survey for trigeneration. The main markets that were identified are in the commercial sector, in particular offices and hospitals. In chapter 3 a system concept of an integrated trigeneration unit, based on the above technologies, is discussed. Results are presented of a modelling and simulation study, which is carried out to allow for a quantitative assessment of the performance of the system. In addition, a technical comparison of the base case system with alternative system configurations is presented. In Chapter 4, the findings of chapters 2 and 3 are used to assess the environmental and economic potential of trigeneration. The 5th and final chapter contains the conclusions.

2. MARKET FOR TRIGENERATION APPLICATIONS IN THE NETHERLANDS

2.1 Introduction

A tri-generation system will be evaluated which is based on a CPO-PEMFC cogeneration subsystem for the production of heat and power (CHP), and a SWEAT subsystem for the production of cold. The system will be designed to produce 220V AC electricity, heat for space heating and hot tapwater (about 70^{o}C) and cold at about 10^{o}C for air conditioning. The CPO-PEMFC-SWEAT system is taken as a base case tri-generation system. Other choices for the CHP part and the sorption cooler may yield heat and cold at different temperatures, e.g. > 100^{o}C and < 0^{o}C. The heat to power ratio is also variable.

The goal of this part of the project is to make an inventory of the energy use in the following sectors:
- Industry
- Buildings
- Residential buildings

In addition to magnitude of energy use for heating, cooling and use of electricity, a quick scan of available data into the load characteristics of the energy demands is performed. Based on the results of the inventory a choice can be made with respect to the most appropriate market segments for application of tri-generation. The criterion for tri-generation to be applicable in a given situation is *the simultaneous demand for heat, cold and power*.

2.2 Energy use in industry

The most important industrial sector for tri-generation systems is the food and beverages sector. Details on this sector can be found in Appendix A. Figure 1 shows the ratio of end demand for heating, cooling (>0^{o}C), freezing (<0^{o}C) and electricity (power) per subsector in the food and beverages sector in The Netherlands. To illustrate the significance of each subsector, in Figure 2 the contribution of each subsector to the total amount of primary energy used in the sector is given.

It is clear from Figure 1 that the base case tri-generation system is a feasible option in the subsectors meat, dairy and breweries. Due to a lack of one of the three required energy demands tri-generation is not an option in the subsectors warehousing and edible oils and fats. In the remaining subsectors, tri-generation seems possible, but other options for the SWEAT system must be considered due to the demand for freezing temperatures.

In principle all processes in the mentioned industrial sectors are continuous and a typical utility size for cooling would range from a few 100 kW in e.g. meat production to several MW e.g. in breweries. Process temperatures are in between 50 and 150^{o}C. The number off full-load operation hours of the cooling utilities is about 4333 per year. Growth of the cooling demand is not expected.

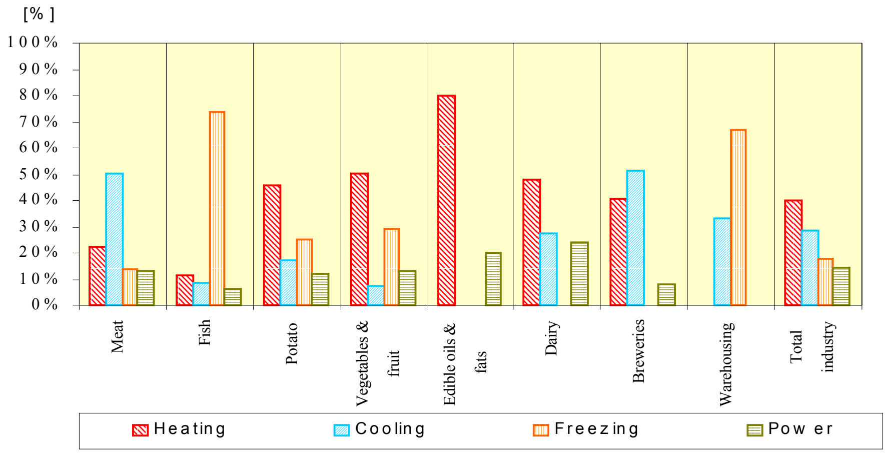

Figure 1 Energy demand breakdown for heating, cooling, freezing and power in several industries

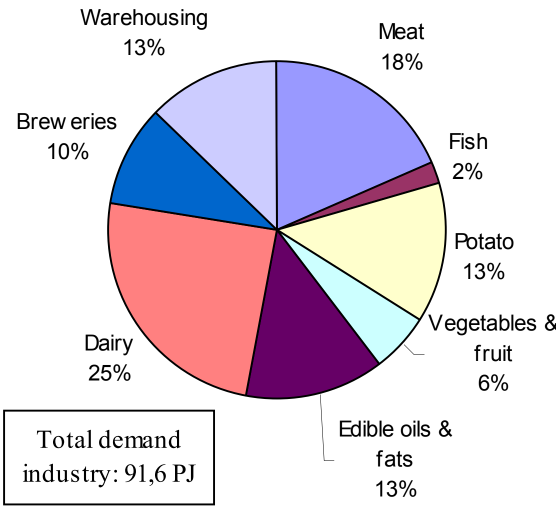

Figure 2 Fraction of the total energy demand per sector

2.3 Energy use in buildings

Another important sector for tri-generation may be the utilities sector. Details of gas and electricity consumption in various building types are given in Appendix A. In Figure 3 the end demand ratios for heating, cooling and electricity in the building types considered are given. The contribution of each building type to the total amount of energy demand in utility buildings is given in Figure 4.

It is clear from Figure 3 that the most obvious areas for application of tri-generation systems are offices, hospitals and the hotel and catering sector. Typical values for energy use average Dutch offices and hospitals are given in Table 1. The overall growth in this market is estimated to be about 0,5 % a year. Temperatures for heating are below 100^{o}C. Cooling temperatures are in between 5 and 15^{o}C. Full-load operation of the cooling utilities amounts to 1250 hours a year. More than 95% of the cooling utilities have a system size smaller than 100 kW.

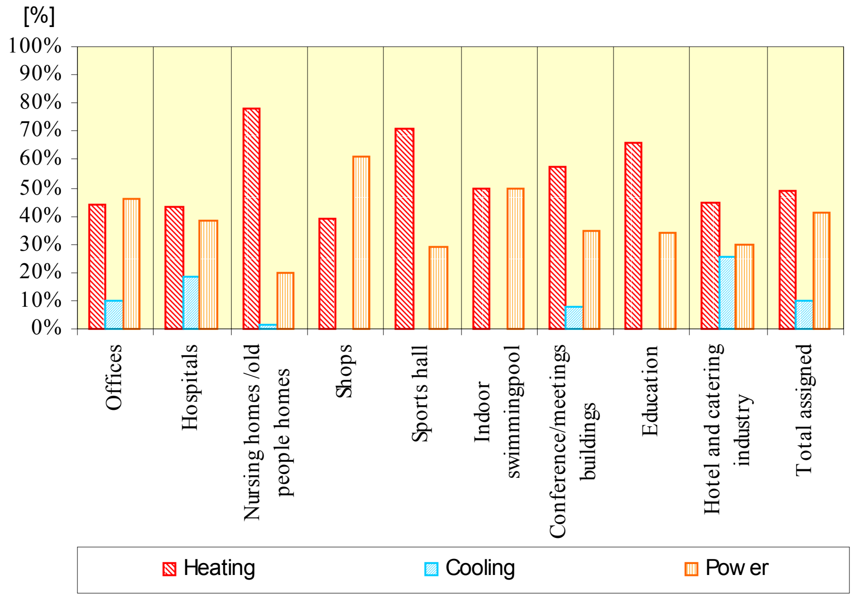

Figure 3 Energy demand breakdown for heating, cooling, freezing and power in buildings

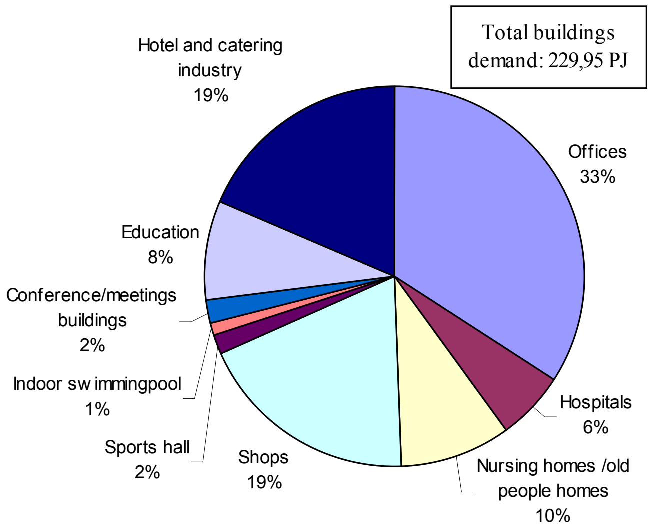

Figure 4 Fraction of the total energy demand per building type

It is a widespread misunderstanding that the ICT sector (data hotels and telecom switches) is the ideal place for the implementation of tri-generation systems. There is indeed a huge primary energy demand of about 5 PJ in 2000. This number may increase by a factor 10 in the most 'optimistic' scenario by the year 2005. This sector has however no heat demand and, following the latest insights, in principle no cooling demand other than by means of natural ventilation. The installation of a CHP installation is already questionable and appears to be feasible only if there is a large enough heat demand in the direct industrial or urban surroundings (Huiberts, 2001; Kester, 2001).

Table 1 Typical energy use and cooling demand in an average hospital (CBS statistics, 1999) and three types of average bank offices (CBS statistics, 1996)

	Heating (NG) /TJ	Electricity /TJ_e	Cooling [1)] /TJ
Average hospital (about 400 beds)	46	13	6.3
Total hospitals (60000 beds)	8706	2794	945
Average office building (bank 6 employees, 210 m^2)	0.07	0.09	0.04
Average office building (bank 30 employees 1050 m^2)	0.35	0.44	0.2
Average office building (bank 3500 employees 122500 m^2)	40.43	50.45	24.3
Total offices ($3.5 \cdot 10^7$ m^2)	$1.2 \cdot 10^7$	$1.4 \cdot 10^7$	$0.7 \cdot 10^7$

[1)] Cooling demand: hospital 3,5 kW/bed; office 44 W/m^2.

2.4 Energy use in residential buildings

In The Netherlands the demand for cooling in residential buildings can be neglected and therefore tri-generation is not an option. Details of the energy demand are given in Appendix A. This situation may be very different from the situation in e.g. Japan, the USA or the Mediterranean countries. Additional study will be required to determine the potential of tri-generation in these situations.

2.5 Evaluation

Industry

Tri-generation in general is a feasible option in most of the mentioned industrial activities except warehousing and the production of edible oils and fats. Whether tri-generation with the base case CPO-PEMFC-SWEAT system is suitable will depend on the extent to which similarity between the temperature levels on demand and supply side can be obtained. Most heat applications are based on open steam systems (atmospheric) having a temperature higher than 100°C. Alternative CHP systems will then probably be more appropriate. For tri-generation in combination with freezing a different heat driven absorption heat pump, e.g. based on NH_3-H_2O, should be used. Taking into account these considerations, tri-generation with the base case system is expected to be a feasible option in the following food and beverages subsectors:

- Meat production
- Dairy production
- Breweries

Buildings

Tri-generation with the CPO-PEMFC-SWEAT system is an option in

- Offices
- Hospitals
- The hotel and catering sector

Residential buildings

In The Netherlands, in residential buildings there is no significant demand for cooling. Consequently residential buildings are not a market for tri-generation systems.

3. TRIGENERATION SYSTEM LAY OUT AND PERFORMANCES

3.1 Introduction

In this chapter a trigeneration system concept is described and evaluated for electrical and thermal performance characteristics. Starting point for this study is a trigeneration system consisting of a Proton Exchange Membrane Fuel Cell (PEMFC) cogeneration subsystem and a Salt-Water Energy Accumulation & Transformation (SWEAT) heat pump for the production of cold. The SWEAT heat pump, or adsorption chiller, is a heat driven system. For proper functioning it requires heat of a certain quality (=temperature). The cooling efficiency of the trigeneration system, therefore, not only depends on the Coefficient of Performance (COP) of the heat pump, but also on the extent in which heat generated by the cogeneration subsystem can be used by the SWEAT heat pump. An indication of the amount and quality of the available heat was obtained through simulation using a steady state thermodynamical model[2] of the CHP subsystem. The results are used as input for a detailed model of the SWEAT subsystem[3] to obtain an estimate of attainable cooling capacity and system dimensions. The combined results are used to determine the overall system performance.

3.2 Starting points

A system concept was developed based on the following starting points:

- Use of conventional PEMFC technology
- Use of Shell proprietary CPO-based Fuel Processor technology. The Fuel processor forms an integrated subsystem linked to the rest of the system only via the fuel processor product stream. Excess heat of the fuel processor (if any) will be used to vaporise water, and, as a result will be transferred to the heat recovery section via the fuel cell
- Use of SWEAT BV proprietary sorption cooler technology based on the working pair $Na_2S.xH_2O/H_2O$
- System capacity 150 kW_e
- Natural gas of Slochteren quality as fuel
- Ambient air as oxidant stream
- Atmospheric (non-pressurised) operation
- Closed water balance operation (sets requirements on flue gas temperature level)
- Conversion efficiency electrical of CHP subsystem ≥ 30 %, LHV
- Conversion efficiency total of CHP subsystem ≥ 90 %, LHV

3.3 System description

A process scheme of the trigeneration system is presented in Figure 5. Overall natural gas is converted with air into three products, namely electricity at 220 V and 50 Hz, hot water of around 40 to 70°C for heating purposes (e.g. space heating and hot tap water), and cold water of around 10°C for cooling purposes. In the system five main functional units can be distinguished. These are:

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[2] AspenPlus, version 10.1, is used as tool for modelling and simulation of the CPO-SPFC cogeneration system
[3] An existing dynamic Matlab/Simulink based SWEAT-model was used.

- Fuel and oxidant cleaning and conversion unit (S, CPO, WGS, PrOx)
- Power production unit (PEMFC)
- Power conditioning unit (AC/DC)
- Heat and water recovery unit (burner and hex)
- Unit for production of cold (SWEAT).

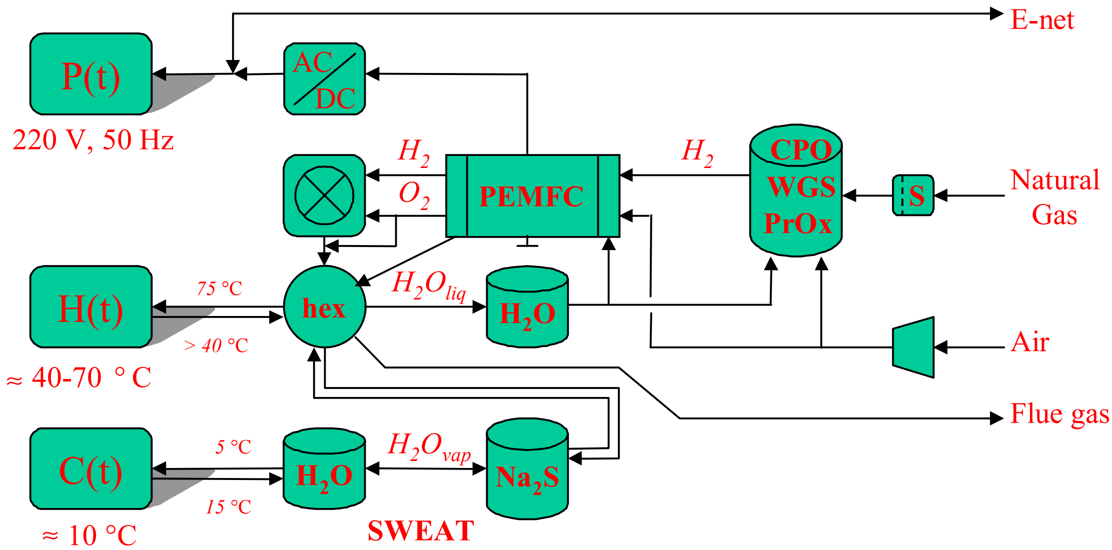

Figure 5 Process scheme for a trigeneration system consisting of a PEMFC based cogeneration unit and a SWEAT solid sorption heat pump for the production of cold

3.3.1 Fuel and oxidant cleaning and conversion

In practice, natural gas entering the system will first pass through a desulphurisation unit. In this unit the sulphur compounds are removed that are present in natural gas (e.g. thiophenes and mercaptanes). A part of these compounds is of natural origin. Another part is added to the gas as odorant after exploration. Removal of sulphur compounds is required they act as poison for the catalysts present in the fuel processing section and the fuel cell. For the purpose of this system the desulphurisation stage is not further considered, i.e. it is assumed that the fuel does not contain sulphur components.

After desulphurisation, the fuel is fed to the processing section where it is converted into a hydrogen rich gas stream that can be fed into the solid polymer fuel cell. In this study the catalytic partial oxidation based fuel processor technology of Shell is taken as starting point. A detailed model of the fuel processor is used to evaluate the system performances. However, for reasons of confidentiality only black box data are included in this report. In practice, the fuel processor comprises the following components:

- *Syngas production unit*; In this unit preheated natural gas and (a substoichiometric amount of) air, in the presence of steam, are converted into a mixture of hydrogen and carbon monoxide through catalytic partial oxidation (CPO). Main reactions taking place in this section are:

$$2\,CH_4 + O_2 \leftrightarrow 2\,CO + 4\,H_2$$
$$CH_4 + H_2O \leftrightarrow CO + 3\,H_2$$
$$CO + H_2O \leftrightarrow CO_2 + H_2$$

- *Carbon monoxide conversion unit*; Carbon monoxide acts as a poison for the noble catalyst in the solid polymer fuel cell. The CO content of the gas, therefore, needs to be reduced to a level of around 10-20 ppm. In the CO conversion unit the major part of the CO is converted with H_2O into CO_2 and H_2 by means of the water-gas-shift (WGS) reaction. To this end the fuel processor comprises a high temperature and a low temperature shift reactor. The shift reaction is represented by the following reaction equation:

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

- *Reformate purification unit*; After the major part of the CO is removed in the shift section the remaining part of the CO is removed from the reformate gas stream through catalytic preferential oxidation (PrOx) of CO with air. Again this is performed in two steps. Excess air is used to enhance CO conversion. At the same time, however, an amount of H_2 is converted into H_2O. The reaction taking place in this section are as follows:

$$2\,CO + O_2 \rightarrow 2\,CO_2$$
$$2\,H_2 + O_2 \rightarrow 2\,H_2O$$

In the oxidant processing section the air required in the syngas production unit (CPO), the reformate purification unit (PrOx) and the Fuel Cell (Cathode gas) is cleaned is cleaned by means of air filters installed at the air intake. The air is slightly pressurised by separate blowers to compensate the pressure drop as a result of the flow resistances throughout the system.

3.3.2 Power production unit

Electric power is produced by electrochemical combustion of hydrogen with air, using a Proton Exchange Membrane Fuel Cell (PEMFC). At the anode, a hydrogen molecule is split into two protons:

$$H_2 \rightarrow 2\,H^+ + 2\,e^-$$

The proton is conducted by the electrolyte membrane to the cathode, where it reacts with oxygen from air to produce water:

$$2\,H^+ + O_2 + 2\,e^- \rightarrow 2\,H_2O$$

The electrons are transferred through the external electric circuit, where they produce work. For proper operation of the PEMFC the electrolyte membrane always needs to be sufficiently hydrated. This is achieved by humidifying the anode and cathode inlet flow. The PEMFC operating temperature lies in the range of 70 to 80°C.

3.3.3 Power conditioning unit

The fuel cell produces direct current power. In the power conditioning unit (inverter) this power is converted to an alternating current of 50 Hz and transformed to 2 phase, 220 V, to facilitate connection to the distribution grid.

3.3.4 Heat and water recovery unit

The heat and water recovery unit comprises a catalytic afterburner, an exhaust cooling unit and a water recovery and recirculation facility.

Fuel and oxidant utilisations in the Fuel Cell typically are in the order of 80% and 50%, respectively. This means that the anode outlet stream still contains 20% of the original amount of H_2 introduced into the Fuel Cell, and the cathode outlet stream still contains 50% of the original amount of oxygen. The hydrogen level is too low to be used as fuel for power production. As an alternative the anode outlet is mixed with the cathode outlet and subsequently fed to a catalytic burner where H_2 reacts with O_2 to produce H_2O and heat.

In the exhaust cooler excess heat from the system is recovered. There will be a contribution of both the afterburner unit as well as the fuel cell and the fuel processing section as all reactions in the systems are exothermic. The excess heat can be applied for heating or cooling purposes. Part of the excess heat will be present as latent heat in the water vapour. To be able to use this heat the exhaust gas has to be cooled to temperatures below 54°C. By recovering the water and recirculating the water into the process (water-gas-shift reaction, humidification of the Fuel Cell), a closed loop operation with respect to water can be established. Otherwise water should be fed to the system which would require a water purification unit (demineralised water).

3.3.5 Unit for cold production

A Salt Water Energy Accumulation and Transformation (SWEAT) system is taken as unit for the production of cold. This system is applicable for air-conditioning and process cooling. It is based on the pair $Na_2S.xH_2O/H_2O$. The SWEAT process is a batch process. To obtain a continuous process several SWEAT modules are required. Each module consists of two vessels, the accumulator, which contains the salt, and the condenser/evaporator. The vessels can be separated from each other through a valve. Two modes of operation can be distinguished for a module: charging and discharging. Figure 6 shows a simplified phase diagram of water and $Na_2S.xH_2O$, illustrating the two modes of operation.

During *charging* a heat flow (Q_h), preferably waste heat, of adequate temperature (T_h) is absorbed and (partially) dehydrates the $Na_2S{\cdot}xH_2O$ crystals in the so-called accumulator. The water vapour is transferred to the condenser/evaporator, where it condenses and releases latent heat that is emitted to the environment (T_{m1}).

Once fully charged, the SWEAT module can be *discharged* at any suitable moment (intrinsic cold storage capability) and produces cold. Heat is extracted from an external source (the surroundings) at low temperature (T_c) in order to vaporise the water inside the low-pressure water vessel. This produces an external cold water flow (Q_c). The water vapour is transferred back from the condenser/evaporator to the accumulator, where it is adsorbed. The sensible heat released during this process (heat of adsorption) is emitted to the environment (Q_{m2}).

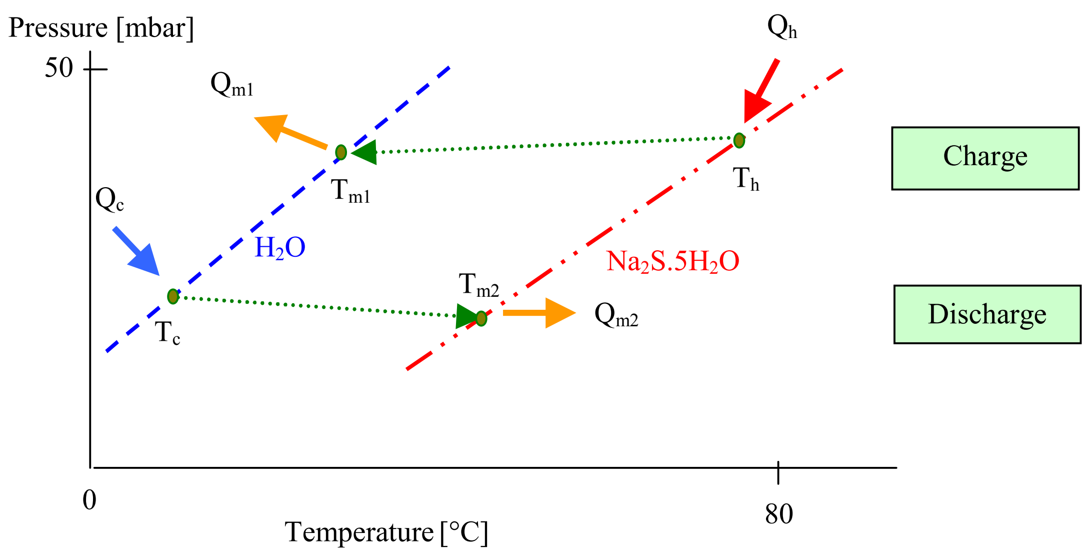

Figure 6 A simplified phase diagram of water and $Na_2S.xH_2O$ to illustrate the charging and discharging of a SWEAT module

In Figure 7 a more detailed pressure-temperature equilibrium diagram of the SWEAT working pair is presented. The attainable power during charging of a SWEAT module is given by the equation P = U·A·dT, where U is the overall heat transfer coefficient, A the area of the heat exchanging surface, and dT the temperature difference between the heat transfer fluid and the accumulator or condenser. U is a constant for a given configuration. A is determined by the allowable cost of the system. The temperature difference, dT, is in fact the only tuneable parameter. At the accumulator the temperature is determined by the melting point of the salt, which is 83 ^{o}C. At the condenser the lowest attainable temperature of the rooftop cooler (dry or wet) is the determining factor. This temperature is determined by the actual outside temperature. The SWEAT working principle/fundamentals requires a cooling temperature of 15-20°C at most for charging of the system. In the summer during the daytime, when demand for cooling is highest, the temperature usually is higher. Considering these facts, it is clear from Figure 7 where indicative dT's are incorporated that the operating window for daytime operation (charging mode), as is required in tri-generation application, is extremely narrow if melting of the salt is to be prevented. This will severely limit the use of the SWEAT technology for the trigeneration application as proposed.

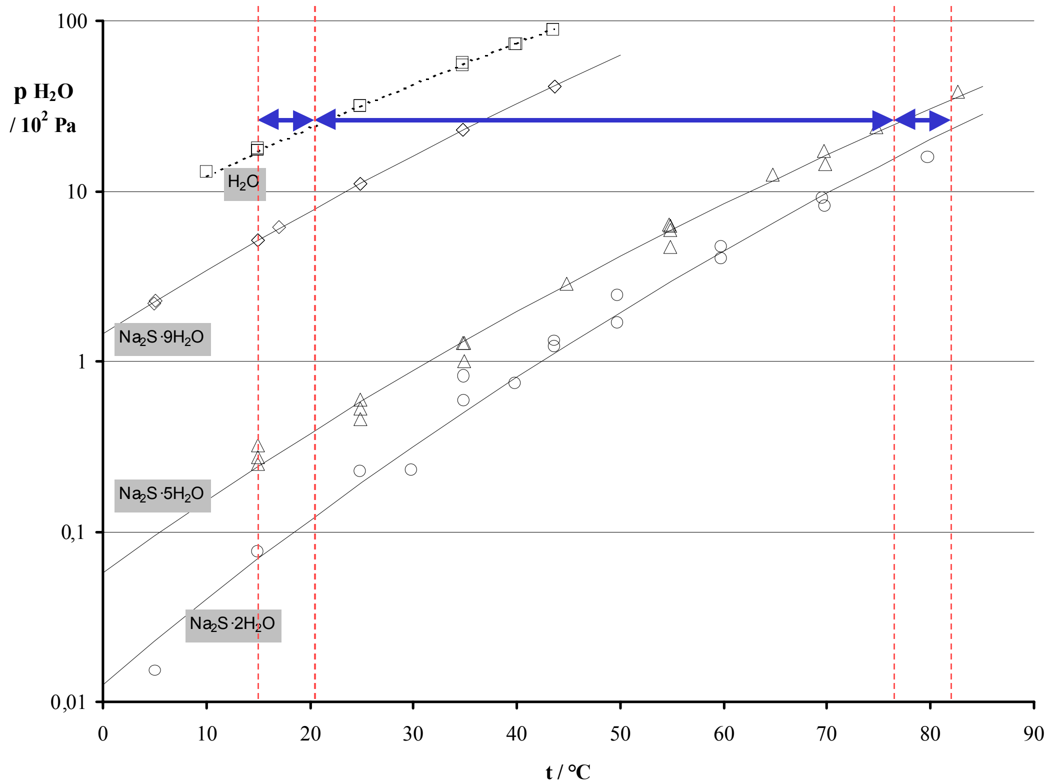

Figure 7 The p.T equilibrium diagram of water and the different phases of $Na_2S.xH_2O$ [source: R. de Boer; et. al. ECN-RX, 2002]

3.4 System performance

The main assumptions used in simulation of the CHP subsystem to obtain an indication of the amount and quality of heat generated by the CHP subsystem is summarised below. A more extensive list of process design parameters and assumptions is given in Appendix B:

- Fuel cell operation at 70°C and 700 mV cell voltage
- Fuel utilisation is 80%
- Oxidant utilisation is 50%
- Thermodynamic equilibrium is assumed in all process stages
- Adiabatic operation

The results of the modelling and simulation study are summarised in Table 2 and Figure 8 and Figure 9. Figure 8 is a graphical representation of the amount of heat produced by the cogeneration system and the temperature level at which it is available (upper curve in the diagram). It appears that the major part of the heat available is low temperature heat from condensation of water vapour in the fuel cell/-afterburner exhaust stream at dew point (70°C), and low temperature heat from the fuel cell cooling stream. To charge the SWEAT system, heat of 90-95°C is required (curve below in the lower right hand corner). Clearly, only a limited amount of the available heat is suitable for use in the SWEAT. The limited amount of useable heat, together with the relatively low COP of the SWEAT sorption heat pump leads to an overall cooling efficiency for the trigeneration system of about 7.7%.

The results shown in Figure 8 were used as input for a detailed SWEAT module to calculate the consequences for the SWEAT system performance and dimension. The results are given in Appendix C. The results are not further discussed here.

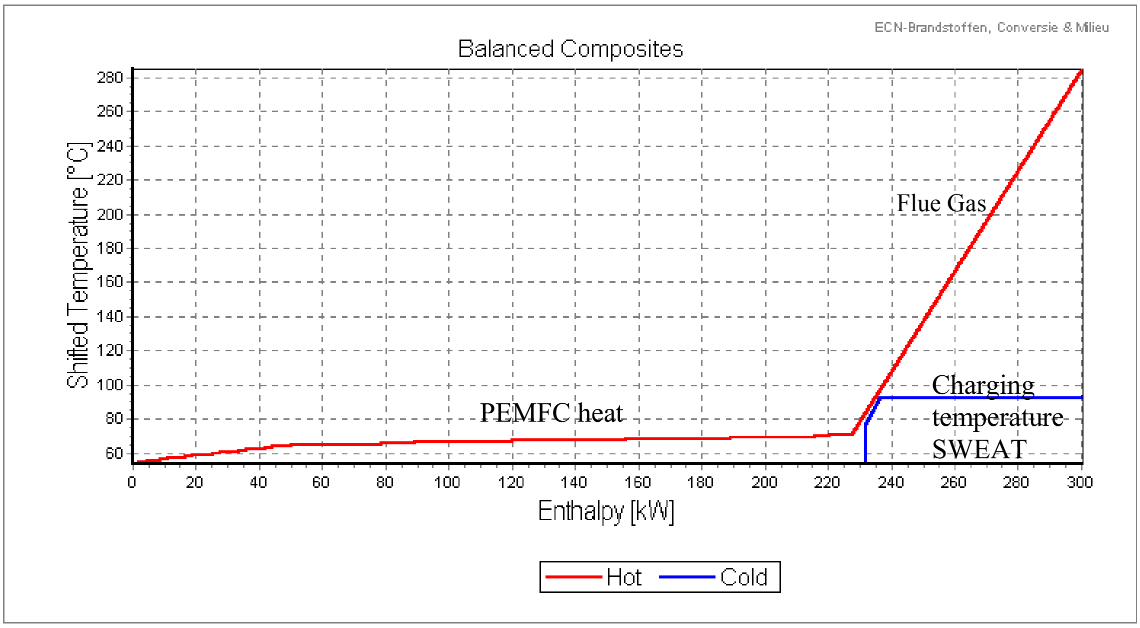

Figure 8 Quantity and temperature level of the available heat of a 150 kW_e CPO-PEMFC cogeneration system, compared to the heat and temperature demand of the SWEAT system.

Table 2 shows that in the combined heat and power mode the calculated electrical, thermal and total efficiencies are 31.6%, 64.4% and 96.0%, respectively. In trigeneration mode the total efficiency drops to 88.9%. The 148 kW_e system then yields 232 kW of heat and only 36 kW of cold. If there is no demand for heat, and the system operates in the combined cold and power mode the overall efficiency will only be 39.3%.

Table 2 Summary of calculated performance characteristics for the CPO-PEMFC-SWEAT trigeneration system concept

	Cogeneration Heat & Power	Trigeneration Cold, Heat & Power	Cogeneration Cold & Power
Natural gas (kW)	468	468	468
Net power (kW_e)	148	148	148
Net heat (kW_{th})	301	232	
Net cooling duty (kW_{cold})		36	36
Net electrical efficiency	31.6%	31.6%	31.6%
Net thermal efficiency	64.4%	49.6%	
Net cooling efficiency		7.7%	7.7%
Net total efficiency	96.0%	88.9%	39.3%

The efficiency results presented in Table 2 are presented in graphical form in Figure 9. The left side of the graph indicates the energy content of the fuel entering the system. In CHP mode heat and power are produced with efficiencies of 64% and 32%. About 23% of the heat produced, or about 15% of the total fuel energy input can be used for the production of cooling by the SWEAT, resulting in a system cooling efficiency of about 8%. Compared with CHP operation, in trigeneration mode the overall efficiency decreases from 96% to about 89%. If the heat can not be used directly or stored for use later on, the efficiency further decreases to about 39%.

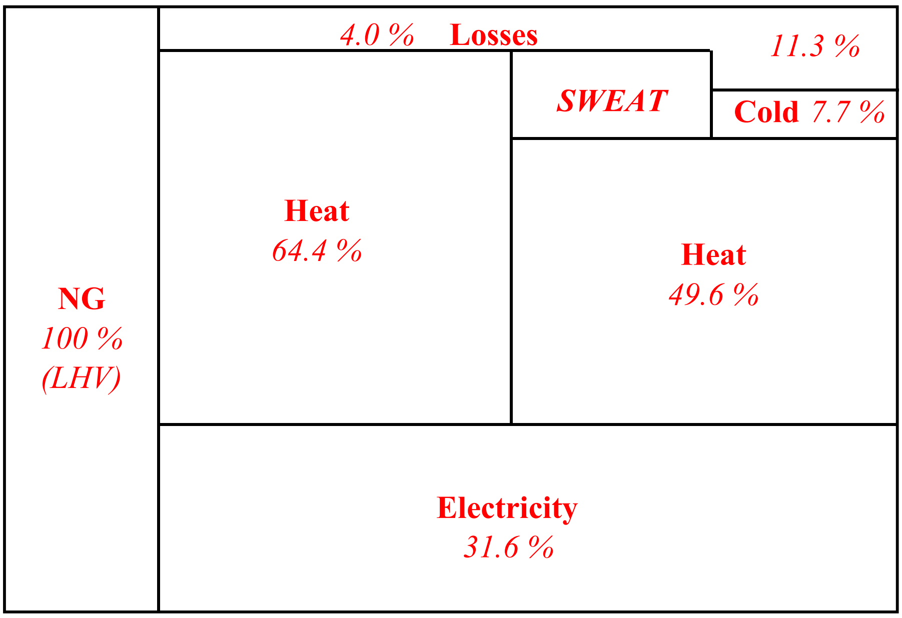

Figure 9 Breakdown of energy flow, “winter/CHP” versus “summer/CCHP”

3.5 System alternatives

Improvement of the cooling performance of the system requires that a larger part of the available can be used for the production of cold. There are two options that will further be considered in the next paragraph:

- Use of an alternative sorption cooling technology that can use heat at temperatures well below 90°C for charging.
- Use of an alternative CHP subsystem that produces heat at higher temperature.

3.5.1 Alternatives heat driven cooling technologies

The salt $Na_2S{\cdot}xH_2O$ used in the SWEAT system is favoured over other sorption pairs due to its high reaction enthalpy and therefore high power density and high storage density. Compactness and storage/buffering capability may be important advantages, especially in relatively small scale systems in the built environment. However, the low temperatures required for releasing heat of the condenser to the environment during charging of the cooler, typically 15-20°C at most, severely limits the applicability for trigeneration because the need for cooling is highest when outside temperatures are well above this range.

Adsorption systems based on silica gels, like the Mycom system, offer a more practical choice (Figure 10). There is no danger of melting (operation virtually independent of outside weather conditions) and due to the fact that there is not one but a whole set of p,T equilibrium lines (isosteres) a much larger fraction of the waste heat from the CPO-PEMFC unit can be used, just by using a different window of maximum and minimum water content of the silica (wt% in Figure 10). The coefficient of performance (COP) of this system is about 0.6, which is comparable, or slightly better than the present COP of the SWEAT system.

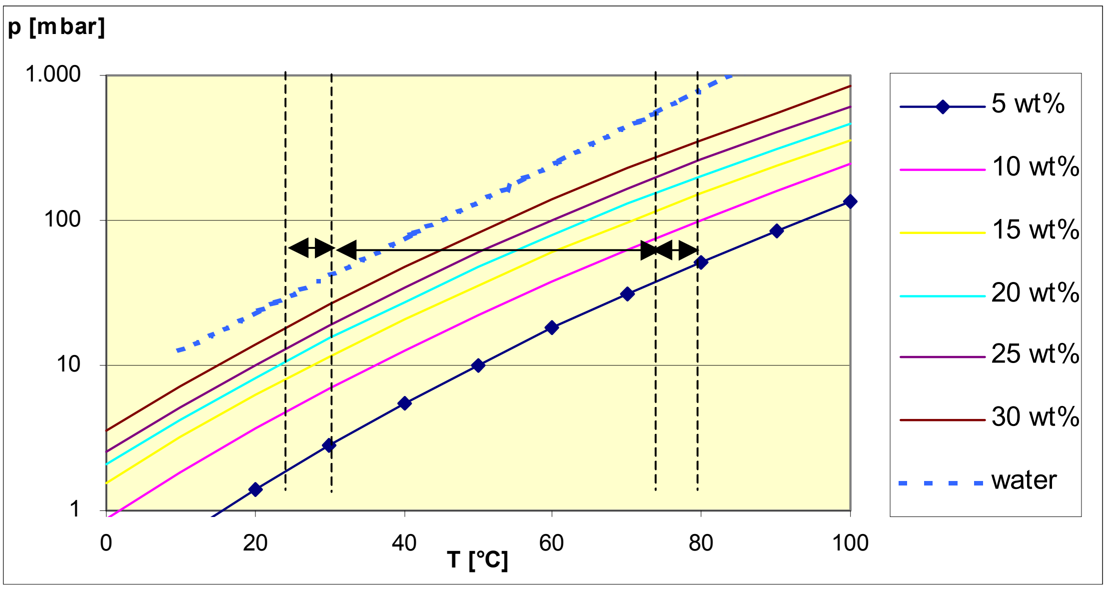

Figure 10 A pressure-temperature diagram of silica gel [source: Restuccia et. al ISHPC München page 219]

Another alternative is an absorption chiller based on the pair $LiBr_2$-H_2O. However, the capacity range in which this system is available is typically somewhat larger than that of the Mycom system, and also as envisaged for the SWEAT system. At this moment heat of 80°C is the lower limit to charge the system, but developments are aimed at reaching 70°C. The COP of absorption chillers lie in the range of 0.6 to 0.7. A summary of the main characteristics of the various technologies is presented in Table 3.

Table 3 Main technical characteristics of sorption cooler technologies

	T-cold °C	T-supply °C	COP_{th}	Capacity range	Thermal storage capacity
SWEAT (Na_2S/H_2O)	5-15	90-95	0.5-0.55	2-500 kW_{th}	yes
Mycom (Silica/H_2O)	5-15	70-80	0.6	50-350 kW_{th}	no
LiBr-H_2O	5-15	80-90	0.6-0.75	0.2-10 MW_{th}	no

3.5.2 Alternative CHP systems

In case of the CPO-PEMFC system it appears that the major part of the available heat is low temperature heat from cooling of the fuel cell (fuel cell operates at 70°C), and from condensation of water vapour in the fuel cell/afterburner exhaust gas stream. It is feasible to operate the “common” type PEMFC at temperatures up to 80°C. However, little benefits of this increased operating temperature are to be expected considering the results shown in Figure 8. Indeed, the effect was found to be negligible. The cooling efficiency was calculated to increase from 7.7% to only 8.5%.

An alternative type of PEMFC based on a phosphoric acid doped membrane material (PBI) allows operating temperatures of about 180°C. In this case, probably, much higher fractions of the heat produced by a CHP system based on this technology could be used for production of cold in a sorption chiller. However, the heat characteristics of such a CHP system have not further been evaluated.

Another fuel cell alternative is to use a high temperature solid oxide fuel cell (SOFC) instead of a PEMFC. Two versions were considered based on use of ECN proprietary planar SOFC technology with operating temperatures in the range of 700-800°C. In one case, a SOFC was used instead of a PEMFC, thus in combination with a CPO-based fuel processor. In the other case the SOFC was combined with Steam (Pre)-Reforming. Because of the high temperatures in the SOFC, internal reforming is possible (reforming inside the SOFC). However, to prevent carbon formation, addition of steam is required. In Steam (Pre)-Reforming usually only the higher hydrocarbons in the gas are converted. For calculations, reforming is carried out at 700°C and a steam-carbon ration of 2.5. Thermodynamical equilibrium is assumed. The results[4] are shown in Figure 11, Figure 12 and Table 4.

Figure 11 shows that in case of the CPO-SOFC system about 80% of the heat generated, could be used by the SWEAT sorption cooler. This percentage can even be higher if the CPO-SOFC system is combined with a silica/H_2O or $LiBr_2$-H_2O sorption cooler, as the temperature required for charging these coolers can be lower. Opposite to the large fraction of usable heat for the production of cooling, the electrical efficiency of the CPO-SOFC is rather low. Due to the use of CPO part of the heating value of the fuel is lost in fuel processing. Furthermore, a large part of the gross electric power of this system is used for ventilator energy as the system requires a large quantity of air for cooling of the fuel cell stack. Due to the high air factor the

[4] Main assumptions in case of CPO- and SR-SOFC: cell voltage 700 mV and fuel utilisation 80%. Resulting oxidant utilisation for CPO-SOFC and SR-SOFC 6,7% and 7,1%, respectively.

concentration of water vapour is low, so that there is no contribution of condensation heat to the thermal efficiency. As a result also the overall efficiency is lower than in the case of CPO-PEMFC.

In case of the SR-SOFC (Figure 12) a considerable part of the heat is present in the form of latent heat, which can only be recovered by condensation of the water vapour, which occurs only at relatively low temperatures. As a result also in this system the SWEAT sorption cooler can use only a small fraction of the heat. Considering the temperature profile, the use of one of the other sorption coolers offers better perspectives. By using $LiBr_2$-H_2O or silca/H_2O instead of SWEAT the amount of heat that can be used for cooling will increase from about 20% to about 50% to 70%.

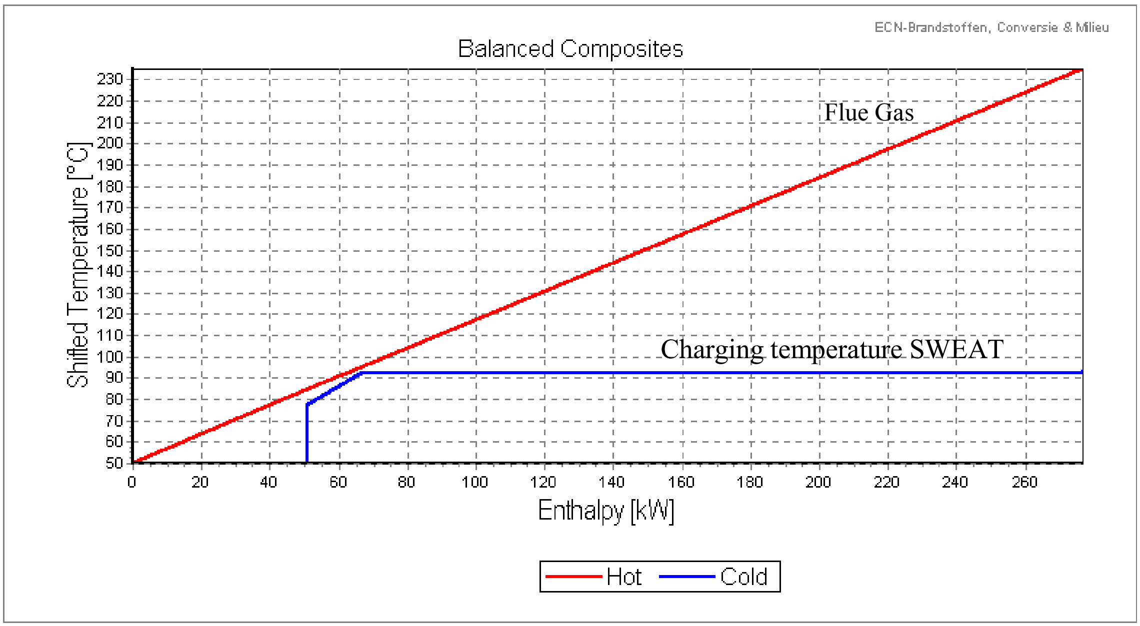

Figure 11 Indication of quantity and temperature level of the available heat of a 150 kW_e CPO-SOFC cogeneration system.

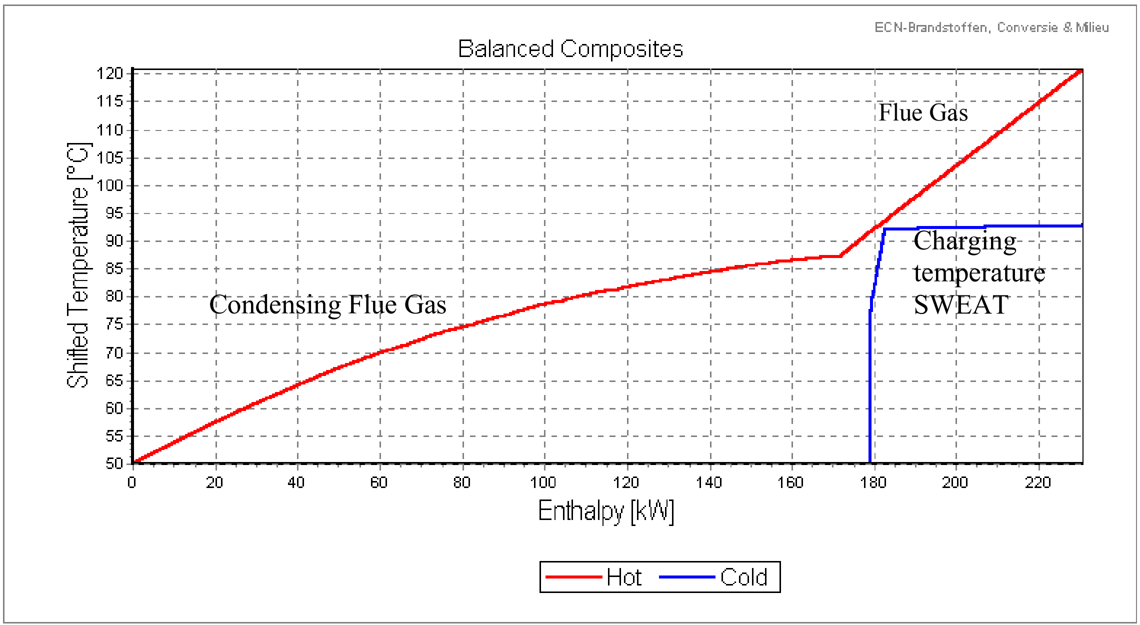

Figure 12 Indication of quantity and temperature level of the available heat of a 150 kW_e SR-SOFC cogeneration system.

Besides fuel cell systems it is also possible to use a gas engines or a small gas-turbine as CHP generator. The temperature profile of the heat available from the gas-turbine is expected to show great resemblance with that of the CPO-SOFC. The temperature profile of the gas engine will probably resemble more that of the CPO-PEMFC. However, both the upper temperature limit, which is determined by the engine exhaust gas temperature (about 400°C), as well as the temperature of the plateau in the profile, which is determined by the engine cooling temperature (about 100°C), are expected to be higher. Thus the fraction of heat that can be used for charging of one of the sorption coolers will be much larger. Based on the CPO-SOFC results, a fraction of 0.8 is assumed in case of SWEAT. A somewhat larger fraction may then be expected for the other alternatives.

In Table 4 some of the characteristics of the CHP alternatives are summarised. By combining the thermal efficiency with the fraction of heat that can be used for the sorption cooler and the COP of the sorption cooler, the cooling efficiencies of the various systems are obtained. By combining the lowest figures and the highest it appears that the overall cooling efficiency ranges from about 5% for the SR-SOFC-SWEAT combination to about 40% for the combination CPO-SOFC-$LiBr_2/H_2O$.

Table 4 Efficiency and temperature characteristics of alternative technologies for a CPO-PEMFC CHP system

	CPO-SOFC	SR-SOFC	Gas engine	Gas turbine
Electrical efficiency	29%	43%	32%	30%
Thermal efficiency	63%	49%	58%	55%
Total CHP efficiency	91%	93%	90%	85%
Indication quality of heat available (°C)	280 → 50	120 → 85 85 → 50	exhaust/cooling 400/100 → 50	275 → 50
Fraction heat use SWEAT	77%	22%	80%	80%
Fraction heat use other	85%	50%-70%	85%	85%

4. ENVIRONMENTAL AND ECONOMIC EVALUATION OF TRIGENERATION CONFIGURATIONS

4.1 Introduction

In this chapter the application of trigeneration is considered in order to determine what the benefits are in terms of primary energy saving. Also the benefits in terms of CO_2 emission reduction and savings on energy costs are considered. To this end, the use of trigeneration is compared with a reference situation in which heat and power are primarily produced by a CHP unit and cooling is produced by an electrical driven compression heat pump (EHP). Starting points for the evaluation are that the facilities are grid connected, and they are in own control (unlike control by an energy service company). Both situations are represented schematically in Figure 13.

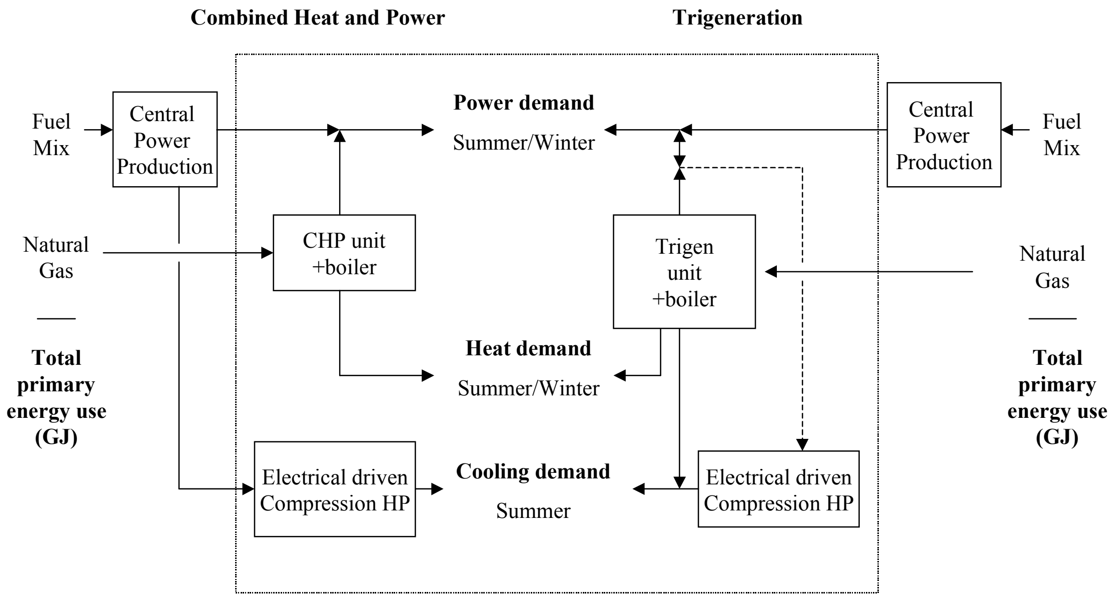

Figure 13 Energy flow diagram for trigeneration and its reference situation in an arbitrary application

Central in the scheme are the energy demands of the application considered. The scheme shows a large resemblance between the two situations. Gas is purchased to produce heat and power. Both are produced at the same time, in a ratio determined by the technology applied. In general, the ratio in which heat and power are produced does not match the heat and power ratio of the demand. If not enough heat is generated, additional heat will be produced by a conventional boiler, which is an integral part of the CHP or trigeneration unit. If not enough electricity is produced, the remaining part will be obtained from the grid. In case, excess electricity is produced it can be delivered to the grid.

The only difference exists in the way the cooling demand is fulfilled. In the reference situation, the cooling demand is provided entirely by an EHP. The power required to operate the EHP comes from the grid, but may also be supplied by the CHP (line not drawn), for instance when the costs for producing electricity in CHP mode are lower than for buying electricity from the grid. In the situation with trigeneration the cooling demand is filled in by the heat driven sorption cooler, which is part of the trigeneration unit. If the sorption cooler can not generate enough cooling the remaining part will be provided by an EHP. The power required for the EHP will, in principle, be supplied by the trigeneration unit, but can also be provided by the grid (line not drawn).

It is clear that in both situations the demand for natural gas will be larger than in a conventional situation without CHP or trigeneration. Thus the energy costs resulting from natural gas are higher. These additional costs will have to be compensated by savings, for CHP or trigeneration to be an economic option. Savings will result mainly from the avoidance of purchase of relatively expensive electricity. Another item is the revenues from the electricity that is delivered to the grid. However, this item will be small compared to the savings on purchase of electricity as the fee for delivery of electricity to the grid is relatively small, and under many circumstances probably not much higher or even lower than the fuel costs for production of the electricity (marginal costs). Therefore, in operating the CHP or trigeneration unit as considered here (grid connected, own control), the objective will be to avoid as much purchase of electricity as possible, and to deliver as little electricity as possible to the grid. This means that trigeneration can only have additional value compared to CHP if there is a remaining electricity demand that can be avoided, and if the efficiencies of the trigeneration unit are such that the additional gas costs are compensated by avoided costs of purchasing electricity from the grid.

4.2 Criteria for profitability

As discussed above the CHP and trigeneration situation are the same as far as combined heat and power production is considered. Furthermore, it was argued that trigeneration can only have additional value compared to CHP if there is a remaining electricity demand that can be avoided. Both findings can be used to derive general criteria for profitability of trigeneration. To this end, for the right hand side of the scheme shown in Figure 13, one has to determine the energy required to produce one unit of electricity by means of the trigeneration facility, and the cooling demand that can be filled in simultaneously with the heat produced. This should be compared with the energy required to produce the same amount of electricity and cooling at the left-hand side of the scheme. A similar exercise can be executed for CO_2 emissions and energy costs. As a result the following criteria arise.

Criterion for primary energy saving:

$$\frac{\eta_{CPP}}{\eta_{elCHP} + \eta_{thCHP} * \left(\frac{F_{\mathrm{supp}} * COP_{sc}}{COP_{cc}} \right)} < 1$$

Criterion for CO_2 emission reductions:

$$\frac{EF_{CHP}}{EF_{CPP}} * \frac{\eta_{CPP}}{\eta_{elCHP} + \eta_{thCHP} * \left(\frac{F_{\mathrm{supp}} * COP_{sc}}{COP_{cc}} \right)} < 1$$

Criterion for energy cost saving:

$$\frac{F_{price}}{E_{price}} * \frac{1}{\eta_{elCHP} + \eta_{thCHP} * \left(\frac{F_{\mathrm{supp}} * COP_{sc}}{COP_{cc}} \right)} < 1$$

Where:

η_{CPP}	= average efficiency of the central power production
η_{elCHP}	= electrical efficiency of the CHP unit
η_{thCHP}	= thermal efficiency of the CHP unit
F_{supp}	= CHP thermal output fraction used by the sorption cooler
$COPsc$	= Coefficient of performance of the sorption cooler
$COPcc$	= Coefficient of performance of the compression cooler (EHP)
EF_{CPP}	= Central power production CO_2 emission factor [kg CO_2/GJ]
EF_{CHP}	= CHP fuel CO_2 emission factor [kg CO_2/GJ]
F_{price}	= Average CHP fuel price [€/GJ]
E_{price}	= Average electricity price [€/GJ]

Trigeneration leads to savings if the outcome of the equation is smaller than one. Electrical and thermal efficiencies of CHP units, as well as fractions of heat produced by the CHP unit that can be used by various sorption coolers, and typical COP values of these sorption coolers were presented in the previous paragraph. The COP of the EHP is determined by the state-of-the-art of this technology. At present, a typical value is 4 to 5. The value varies slightly as a function of unit size, but given a size the value is universal. This does not hold for the remaining parameters. These are site specific, or better country specific. The average efficiency and the fuel mix of the Dutch central power production are not the same as those for the United States, Germany, France or whatever country considered. As a result also the CO_2 emission factor and electricity price will vary. Also the fuel used for CHP and the price of the fuel may vary per country.

Furthermore it is important to notice that the criteria act as boundary conditions for profitability. They are not a guarantee or a measure of profitability. In principle, the profits can be larger the smaller the outcome of the equations. Whether or not the profits can be realised in practice will largely depend on the extent in which the power demand and cooling demand occur simultaneously, or can be made simultaneous through the use of temporary storage of one of the energy forms.

4.3 Criteria results

The criteria have been worked out for the Dutch situation. In addition to the parameter values of the technologies as presented in Table 2, 3 and 4, the following parameter values have been used:

- COP_{CC}, Coefficient op Performance of a typical EHP: 4,0
- η_{CPP}, Average central power production: 42%
- EF_{CPP}, CO_2 emission factor for CPP fuel mix: 77 kg/GJ
- EF_{CHP}, CO_2 emission factor for natural gas: 56 kg/GJ
- F_{price}, Average price of natural gas[5]: 8.7/5.3 [€/GJ]
- E_{price}, Average electricity price: 23 [€/GJ]

[5] The prices of gas and electricity are based on 2002 tariffs of NUON for large consumers [www.nuon.nl and www.continuon.nl]; prices are including ecotax but excluding VAT. Two prices of natural gas are given. The higher price is an average price for consumptions up to 170,000 m^3/yr. The lower price is an average price for larger consumptions, i.e. >170,000 m^3/yr.

The criteria results for primary energy saving are shown in Table 5. It appears that there is only potential for primary energy saving in case of a trigeneration unit consisting of a SR-SOFC CHP subsystem and a sorption cooler. In case a silica/H_2O or $LiBr_2$-H_2O sorption cooler is used the potential is somewhat larger than for a SWEAT sorption cooler. The reason the SR-SOFC shows the best results is because of its high electrical efficiency. The efficiency is even higher than that of the average central power production, so that even without the use of heat for the production of cold the criterion is smaller than 1, viz. 0.97. In the other cases the second factor in the denominator of the criterion does not offer enough compensation for the lower electrical efficiency of the CHP subsystem compared to the average central power production. The main reason for this appears to be the low COP value of the sorption coolers compared to the EHP.

Table 5 Primary Energy saving criteria results for the various combinations of CHP and sorption cooling technologies

	SWEAT	Mycom (silica/H_2O)	$LiBr_2$-H_2O
CPO-PEMFC	1.24	1.23	1.21
CPO-SOFC	1.20	1.13	1.09
SR-SOFC	0.95	0.87	0.89
Gas Engine	1.11	1.07	1.03
Gas Turbine	1.18	1.13	1.10

If the results of Table 5 are multiplied by the ratio of the CO_2 emission factors of the fuel used for the trigeneration unit and the fuel mix of the average central power production, the criteria results for CO_2 emission reduction are obtained. The ratio is 0.73. This means that if the values in Table 5 are smaller than 1.38 there is potential for CO_2 emission reduction. However, this potential is not so much the result of energy saving, but mainly the result of substitution of the fuel mix, which partly consists of coal, by natural gas.

In Table 6 the criteria results for savings on energy costs are shown for situations with natural gas consumption up to 170,000 m^3/yr. Although only trigeneration units based on a SR-SOFC CHP subsystem offer potential for primary energy savings, there are more combinations that may lead to energy cost savings. Clearly, these potentials are not the result of energy savings. They are the result of the current energy tariff structure.

Table 6 Energy Costs savings criteria results for the various combinations of CHP and sorption cooling technologies for relatively small trigeneration units with electrical capacities of about 100-150 kW_e (170,000 m^3/yr at 4380 hours/yr full load operation)

	SWEAT	Mycom (silica/H_2O)	$LiBr_2$-H_2O
CPO-PEMFC	1.12	1.11	1.09
CPO-SOFC	1.08	1.02	0.99
SR-SOFC	0.85	0.79	0.80
Gas Engine	1.00	0.96	0.93
Gas Turbine	1.07	1.02	0.99

A closer look into the criterion and specific parameter values shows that there is already potential for savings on energy costs for CHP subsystems with an electrical efficiency of 38%, even without using heat for cooling purposes. This value drops if the consumption of natural gas is increasing because it appears that the average price per m^3 decreases with increasing consumption, whereas the corresponding average electricity tariff remains the same. At a tenfold natural gas consumption the average price has gone down to about 5.3 €/GJ. At this tariff the criterion indicates that there is already potential for savings on energy costs if the electrical efficiency of the CHP subsystem is 23%.

Although it may seem that large profits can be obtained by applying trigeneration, it should be noticed, as stated before that the criteria act as boundary conditions for profitability. They are not a guarantee or a measure of profitability. Whether or not the profits can be realised in practice will largely depend on the extent in which the power demand and cooling demand occur simultaneously, or can be made simultaneous through the use of temporary storage of one of the energy forms. Furthermore it should be noticed that the potential holds for trigeneration in comparison with cogeneration. It says nothing about the cost-effectiveness of cogeneration for the application that is considered.

As the potential for primary energy saving through application of trigeneration is limited within the scenario considered, the application of trigeneration in specific cases to determine savings in terms of PJ, ton CO_2 and €/yr is not further considered in this chapter. However, two examples are worked out in Appendix D, considering the application of a steam-prereforming SOFC/ $LiBr_2$-H_2O based system in an average Dutch hospital and an average large office building in the Netherlands. The results confirm that combining cogeneration with a sorption cooler offers no large potential for additional primary energy saving compared to cogeneration/compression cooler scheme. At the same time, however, the results indicate that the former option can lead to considerable energy cost savings, especially in the case of the large office building. At present, for small consumers, natural gas prices are relatively high compared to electricity prices, but apparently, at increasing consumption levels, the ratio of the natural gas and electricity price eventually becomes such that the savings on avoided purchase of electricity outweigh the cost for additional purchase of gas. This means that, if a cooling demand exists, extension of cogeneration to trigeneration by adding a sorption cooler to the system, could create additional room for investment, and may help to enhance the economic viability of cogeneration[6].

4.4 Alternative scenario's

As opposed to own exploitation, the combined heat and power unit may be exploited by an energy service company. The cost structure and objectives for operation of the CHP unit may then be different. There may be circumstances at which it is profitable to produce power although there is little demand for heat. If this situation occurs frequently, and if at the same time there is demand for cooling, the use of waste heat for cooling production through a sorption cooler does offer potential for energy saving. The heat would otherwise be released to the environment.

Another situation is when there is no connection to the grid (stand-alone). In this situation the CHP unit will always run when there is a power demand, even when there is no heat demand. Electricity is the preferred product. If there is no need, the heat will be released to the environment. If at the same time there is a cooling demand, the use of waste heat to produce cooling will always lead to savings with respect to energy, emissions and energy costs.

[6] The costs (investment, O&M) of a sorption cooler as part of a trigeneration unit should then not be than the costs of a conventional compression cooler, which seems to be a reasonable assumption.

5. CONCLUSIONS

Options for application of a trigeneration system that produces power, heat for space heating and hot tapwater (about 70 ^oC), and cold (5-15 ^oC) for cooling purposes have been identified on the basis of an inventory of energy demands in Dutch market sectors. It is expected that trigeneration, as envisaged in this study, is a feasible option in industry sectors like meat production, dairy production and breweries. Furthermore, energy demands in utility buildings like offices, conference buildings, hospitals and the hotel and catering sector seem to offer good prospects. A system size of 150 kW_e was selected as appropriate for most applications. In the Netherlands, in residential buildings there is no significant demand for cooling. Consequently, residential buildings are not a market for tri-generation systems.

As starting point for this study a natural gas fuelled trigeneration system was proposed consisting of a PEMFC based CHP unit, equipped with a CPO based fuel processor of Shell (Hydrogen Source), and combined with the SWEAT solid sorption heat pump which is being developed at ECN[7]. Looking back it is concluded that this choice has been an unfortunate one:

- Compared with other sorption coolers, the SWEAT system offers a high power density and high storage density. However, as a consequence of its working principles/fundamentals, the applicability for trigeneration appears very limited. The temperature range that can be used for charging of the system is limited to about 90-95 ^oC. At higher temperatures the salt in the system will melt. At lower temperatures the system requires condenser temperatures (i.e. outside temperatures) well below 15-20 °C. This will be a problem on hot summer days just when the need for cooling is highest.
- A large part of the heat generated by the CPO-PEMFC is available at temperatures below the temperature range that can be used by the SWEAT sorption cooler. About 75% of the heat is available at temperatures below 70-80 ^oC, i.e. only 20-25% of the heat generated can be used effectively. This finding in combination with a CPO-PEMFC thermal efficiency of 64%, and a COP of the SWEAT cooler of about 0.5, leads to an overall cooling efficiency of less than 8%, which is rather disappointing.

Various alternative technologies have been considered as part of a trigeneration unit, both at the heat and power production side (SOFC, gas engine, gas turbine) as well as at the cold production side (silica/H_2O and $LiBr_2$-H_2O sorption chillers). Most combinations offer perspective for a better cooling efficiency than in the base case combination. By combining thermal efficiencies, estimates for fractions of the heat that can be used for cold production, and COP values of different sorption coolers, overall cooling efficiencies ranging from 5% to 40% were found. A system consisting of a SOFC with CPO based fuel processor and a $LiBr_2$-H_2O absorption chiller showed the highest cooling efficiency.

General criteria have been derived to be able to assess the value of trigeneration compared to a reference situation consisting of cogeneration and production of cooling with an electrical compression heat pump. The criteria hold for a grid connected situation, and own control of facilities. It was found that trigeneration only offers potential for energy saving when the CHP part of the unit is formed by a Solid Oxide Fuel Cell with steam pre-reforming of fuel. This appears not so much the result of a high cooling efficiency, but rather the result of a relatively high electrical efficiency. The criterion shows that there is only potential for energy saving when the ratio of cooling efficiency of the trigeneration unit and the COP value of the reference cooling technology (electrical compression heat pump) is larger than the difference between the

[7] Under development at ECN Energy Efficiency in the Industry on the authority of SWEAT BV.

average electrical efficiency of central power production and the electrical efficiency of the trigeneration unit. The higher the COP of the reference cooling technology and the higher the efficiency of central power production, the tougher it will be for a trigeneration system as considered in this study to offer surplus value in terms of energy saving.

Calculations on specific cases indicate that, although there is no large potential for additional energy saving, trigeneration, i.e. a combination of cogeneration and sorption cooling, could lead to considerable energy costs savings compared to a configuration consisting of cogeneration and electrical compression cooling. In other words, if a cooling demand exists, extension of cogeneration to trigeneration by adding a sorption cooler to the system, could create additional room for investment, and may help to enhance the economic viability of cogeneration. The potential for energy cost savings, however, seems to be present only at larger applications. Results indicate that only at increasing consumption levels, the ratio of the natural gas and electricity price eventually becomes such that the savings on avoided purchase of electricity outweigh the cost for additional purchase of gas. An exact size cannot be given. As it depends on many factors, the potential should be evaluated on a case by case basis.

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APPENDIX A MARKET ANALYSIS

A.1 : Energy use and demand in several industrial activities (Kiesewetter, 2001).

	Number of businesses -	electricity Pje	fossil fuel PJ	total energy use PJ (Pjfossil+Pje)	primary energy use PJ (45 % eff. Electricity)
Energy balance. Food, beverages and tobacco industry, CBS 1998	6758	22,83	81,73	104,56	132,46
< 20 employees	5921	1,6	7,3	8,9	10,86
>20 employees	837	21,23	74,3	95,53	121,48
Meat	188	2,4	3,82	6,22	9,15
Fish	38	0,24	0,21	0,45	0,74
Potato	21	1,34	5,65	6,99	8,63
Vegetables & Fruit	37	0,57	2,69	3,26	3,96
Edible oils & fats	17	1,07	9,59	10,66	11,97
Dairy	32	3,25	10,83	14,08	18,05
Breweries	11	0,92	3,67	4,59	5,71
Warehousing (cooling + freezing)	170				
Total	**514**	**9,79**	**36,46**	**46,25**	**58,22**

	Heat PJ	Theat C	Cooling Pje	freezing Pje	other Pje	operation time h	typical utility size MW	CHP?, ratio
Energy balance. Food, beverages and tobacco industry, CBS 1998								
< 20 employees								
>20 employees								
Meat	3,82	60-120	1,1	0,3	1	continuous	<0,2	no, steam
Fish	0,21	*100*	0,02	0,17	0,05	continuous	-	no
Potato	5,65	70-150	0,27	0,4	0,67	continuous	2,5	no, steam
Vegetables & Fruit	2,69	40-125	0,05	0,2	0,32	continuous	-	no, steam
Edible oils & fats	9,59	50-150			1,07	continuous	2,5	yes, 5
Dairy	10,83	60-130	0,8	0	2,45	continuous	2,5	no, steam
Breweries	3,67	50-100	0,6	0	0,32	continuous	3,1	yes, 2,5
Warehousing (cooling + freezing)			0,5	1		continuous	-	no
Total	**36,46**		**3,34**	**2,07**	**5,88**	**11,29**		

A.2 : Energy use and demand in the buildings sector(Arkel, 1999).

Use of natural gas (PJ primary)

Sector	Total	Heating	Hot tap water	Cooling	Humidification	Rest
Offices	33,9	31,7	1,8			0,4
Hospitals	7,7	4,7	1,0	0,3	0,7	1,0
Nursing homes /old people homes	18,1	14,7	1,9	0,0	0,5	1,0
Shops	18,3	14,5	2,1			1,7
Sports hall	3,2	2,7	0,2			0,3
Indoor swimmingpool	2,3	1,1	0,1			1,1
Conference/meetings buildings	2,4	2,3	0,1			0,0
Education	12,5	12,2	0,2			0,1
Hotel and catering industry	19,8	16,8	1,6			1,4
Total assigned	118,2	100,7	9,0	0,3	1,2	7,0
Not assigned	52,1					
Total	170,3					

Use of electricity (PJ primary)

Sector	Total	Lighting	Ventilation	Cooling	Humidification	Pumping	Hot tap water	Heating	Rest
Offices	39,2	12,7	2,8	2,3		2,3		0,8	18,3
Hospitals	5,5	1,8	0,0	0,4	0,0	0,4	0,0		2,9
Nursing homes /old people homes	5,1	1,9	0,0	0,1	0,2	0,5	0,0	0,6	1,8
Shops	26,8	9,8	2,0				0,0	0,4	14,6
Sports hall	1,2	0,7	0,1			0,1		0,0	0,3
Indoor swimmingpool	1,2	0,2	0,3	0,0		0,2		0,0	0,5
Conference/meetings buildings	1,7	0,7	0,2	0,1		0,1		0,1	0,5
Education	7,1	4,3	0,0	0,0		0,3	0,0	0,4	2,1
Hotel and catering industry	16,4	1,8	2,6	3,1				0,6	8,3
Total assigned	104,2	33,9	8,0	6,0	0,2	3,9	0,0	2,9	49,3
Not assigned	37,1								
Total	141,3								

Gas + Electricity (PJ primary)

Sector	Heat	Cold	Power	H + C + P
Offices	34,3	2,3	36,1	72,7
Hospitals	5,7	0,7	5,1	11,5
Nursing homes /old people homes	17,2	0,1	4,4	21,7
Shops	17,0	0,0	26,4	43,4
Sports hall	2,9	0,0	1,2	4,1
Indoor swimmingpool	1,2	0,0	1,2	2,4
Conference/meetings buildings	2,5	0,1	1,5	4,1
Education	12,8	0,0	6,7	19,5
Hotel and catering industry	19,0	3,1	12,7	34,8
Total assigned	112,6	6,3	95,3	214,2
Not assigned				
Total				

A.3 : Energy use and demand in residential buildings in The Netherlands (1995).

Commodity	Space heating	Hot tap water	Lighting	Total
Natural gas (PJ)	300,0	79,0		379,0
Electricity (PJe)	5,9	6,3	10,9	23,1
Heat (PJth)	6,7	1,5		8,2
Oilproducts (PJ)	3,5	1,6		5,1

Data on residential heating in The Netherlands*	Average over several housing types
Heat demand (GJ/y)	46
Heating period (hours)	3981
Peak-load (kW)	15
Natural gas consumption (m^3)	1640

**Numerical values of the power demand for heating per 15 minutes interval are available on CD-ROM: Warmtevraagpatronen DEGO 2000 (Bakker, 2000).*

APPENDIX B PROCES DESIGN PARAMETERS USED FOR SIMULATION OF THE CPO-PEMFC SYSTEM

Starting points used for development of CPO-PEMFC system concept were:

- Use of conventional PEMFC technology
- Use of Shell proprietary CPO-based Fuel Processor technology. The Fuel processor forms an integrated subsystem, linked to the rest of the system only via the fuel processor product stream. Excess heat of the fuel processor (if any) will be used to vaporise water, and, as a result will be transferred to the heat recovery section via the fuel cell
- Use of SWEAT BV proprietary sorption cooler technology based on the working pair $Na_2S.xH_2O/H_2O$
- CPO-PEMFC system capacity 150 kW_e
- Natural gas of Slochteren quality as fuel, 55 m^3/h
- Ambient air as oxidant stream
- Atmospheric (non-pressurised) operation
- Closed water balance operation (sets requirements on flue gas temperature level)
- Conversion efficiency electrical of CHP subsystem ≥ 30 %, LHV
- Conversion efficiency total of CHP subsystem ≥ 90 %, LHV

General assumptions

- Blower efficiency 65%
- Pump efficiency 60%
- General composition of Slochteren Natural Gas: 82% CH_4, 14% N_2, 3.5% higher hydrocarbons, rest CO_2. LHV = 31,67 MJ/m^3, HHV = 35,10 MJ/m^3. (N.V.Nederlandse Gasunie, 1988)
- Inverter efficiency 96%.
- Ambient temperature 15 oC, ambient pressure 1.013 bar, air humidity 65%
- Thermodynamic equilibrium is assumed in all process stages
- Adiabatic operation

Assumptions PEMFC

- Fuel cell operation at 70°C and 700 mV cell voltage
- Fuel utilisation is 80%
- Oxidant utilisation is 50%

Assumptions SOFC

- Cell voltage is 700 mV
- Fuel utilisation is 80%
- Partly internal reforming.
- In SR cases is the steam to carbon ratio 2.5
- Fuel cell operation between 700 °C (inlet) and 800 ^oC (outlet).
- Oxidant utilisation dependent on stack cooling demand

APPENDIX C RESULTS CALCULATIONS SWEAT SYSTEM

C.1 A SWEAT system as adsorption cooler

C.1.1 Introduction

The Salt Water Energy Accumulation & Transformation (SWEAT) unit uses the salt $Na_2S.xH_2O$, which has a very high heat storage capacity ($\Delta H \approx 300$ kJ/mol $Na_2S \approx 1$ kWh/kg Na_2S).

Process functions
A single SWEAT module has two modes of operation: *charging* and *discharging*.

During charging:
- Charging the salt by flowing hot water (70 – 90 °C) through the heat exchanger pipe with a thin layer of salt on the outside (accumulator). In this regeneration step the salt releases the absorbed water vapour.
- Condense the water vapour on a condenser through which cold water flows (15 to 25 °C). The condenser and the accumulator are connected through a vapour channel. It is possible to use also the area of the evaporator for condensing. The released heat of the condenser will be lost to the surroundings (wet- or dry cooler).

During discharging:
- Unloading the salt by flowing / pumping water (20 to 60 °C) through the accumulator. The released heat of the hydration reaction will be carried of to the surroundings (wet- or dry cooler).
- Evaporation of water under low partial vapour pressure (< 10 mbar). The wall temperature of the evaporator will be cooled down to < 10 °C.

The current SWEAT unit is a batch system. For a continuous cooling system it is necessary to use two or more SWEAT units. With valves it is possible to switch a unit from charge to discharge and vice versa.

C.1.2 Limitations

The melting point of $Na_2S.xH_2O$ is low: (T_m = 83 °C).
A condenser in combination with a dry cooler has a working temperature of 30 °C in summer. In combination with a wet cooler it will be somewhat lower (± 15 to 25 °C).

C.1.3 Modelling

In the dynamic simulation program Simulink (part of Matlab™) a program is developed for dynamic calculations. All calculations are carried out with one SWEAT module.

One module
Using process design parameters of a real module and the parameters of the heat transfer medium water (Table 7) the performance of one module has been simulated.

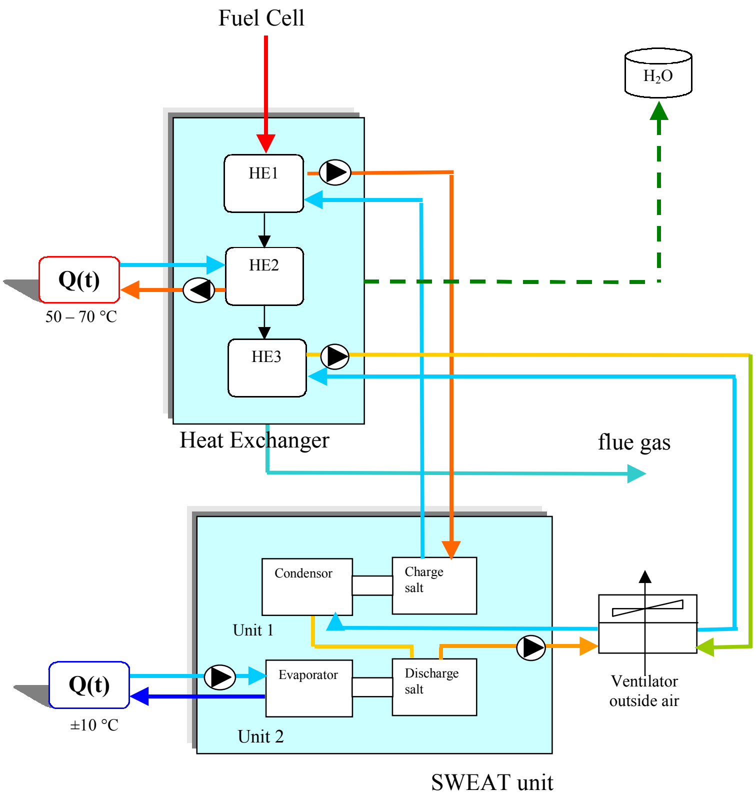


Figure 14 Process flow diagram of the Heat and Water Recovery (Heat Exchanger) unit and the a SWEAT unit

Table 7 Properties of heat transfer water flows supplied to the SWEAT module

Parameter	Unit	Load salt	Condenser	Unload salt	Evaporator
Medium	-	water	water	water	water
Temperature	°C	87			10
- Dry cooler[8]			22.5	27.5	
- Wet cooler			17.5	22.5	
Flow	l/min	3.0	1.5	3.0	1.5

Table 8 Properties of one SWEAT module (Base case)

Parameter	Unit	Load	Unload	Total
Time	min			
- Continue		90	40	130
- Storage (average power)		130	130	
Power	W			
- waste heat		585	-	405[9]
- surrounding				615
- cooler		-	683	210
COP[10] (gross)				0.52

[8] Not calculated
[9] Time average
[10] The performance of the SWEAT module is expressed by a conversion efficiency number (COP), which represents the ratio of the generated cold product and the total heat input

Results of the calculations were the heat absorbed during charging, condensation heat, heat rejected while discharging, low temperature heat absorbed by the evaporation, and the heat supplied and rejected for heating up and cooling down the module during the switch between the two modes, all for one cycle. Also charging, discharging and switching times were results of the simulations. The simulation results are used as input for the total system efficiency and size (number of modules).

Total system

Because a solid sorption process is a batch system one needs at least two modules (one charging and the other discharging). Nevertheless the demand of waste heat and the supply of cooling power will be unstable. By taking more than two SWEAT modules each switching out of phase, it is possible to get a more stable system. Table 9 gives a summary of a design of a SWEAT unit in combination with a 150 kWe Fuel Cell (basic calculation) in a CCHP system.

Table 9 Properties of a complete SWEAT system (Basis case)

Parameter	Unit	Load	Unload	Total
Groups of modules out of phase		12	5	
Nr of modules in one group		10	10	
Total number of modules		120	50	170
Average power	kW			
- waste heat		69	-	69
- surrounding				104
- cooler		-	35	35
Time	min			
- continue		90	40	130
- storage (average power)		130	130	
COP (gross)				0.52
Cost	€ / $kW_{cooling}$			275[11]

C.1.4 Results of calculations

The storage density the SWEAT system is high, but the power density is relative low (0,3 $kW_{cold\ continuous}$ / kg $Na_sS.½H_2O$). The power is a function of the temperature difference between the medium water and the salt / condenser ($P = UA\Delta T$). The low melting temperature of the salt in combination with a limited condenser temperature is the reason that the driving force is too small when loading the system (see the small arrows left and right in Figure 15).

C.1.5 Conclusions

The salt $Na_2S.xH_2O$ has a very good heat storage capacity.

- The charging time of the system is 130 minutes with a continuous waste heat stream of 69 kW
- The discharging time of the system is 130 minutes with an average cooling power of 35 kW or 40 minutes with an average cooling power of 114 kW

The storage capacity is hardly necessary for this application. Furthermore:

- The melting temperature of the salt (± 83 °C) is very low. When using a dry cooler in summer conditions the temperature difference between loading the salt and the condenser is too small.
- The consequence is a very low power / power-density which may be improved only slightly.

[11] Target retail price

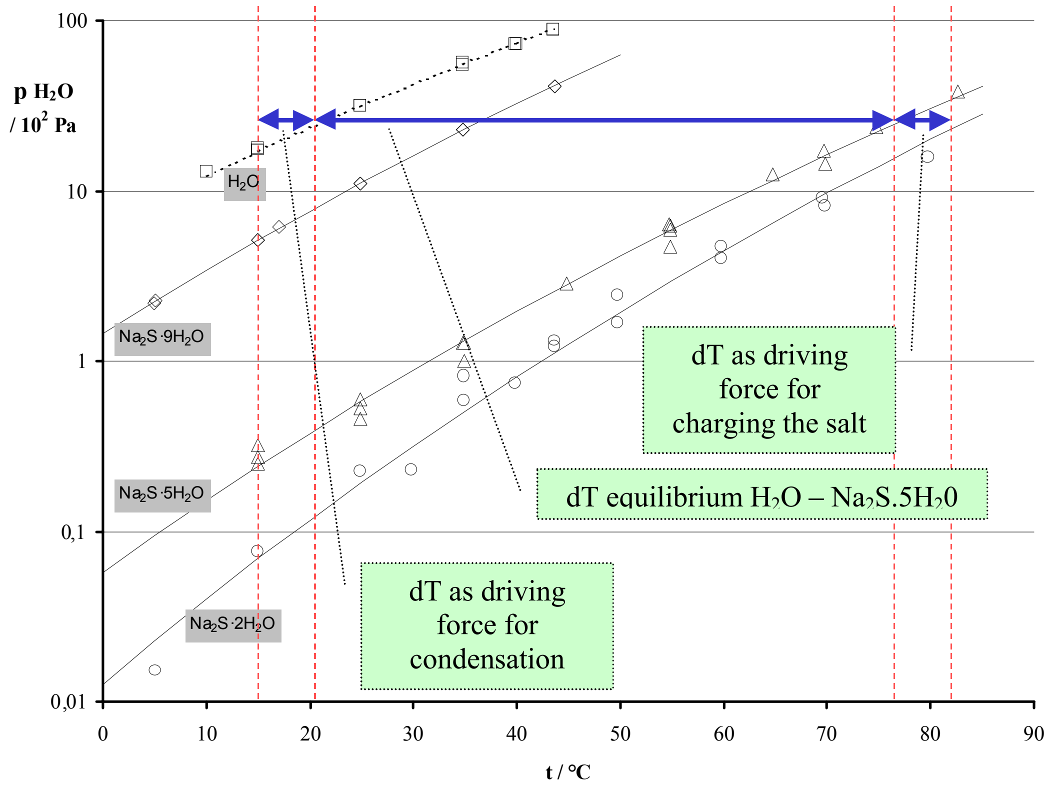


Figure 15 A phase diagram of water and $Na_2S.xH_2O$ [source: R. de Boer et. al. ECN, 2002]

C.2 Alternative adsorption systems

Another waste heat (< 100 °C) adsorption system is a silica gel/water system. A Japanese company produces the Mycom adsorption refrigerator. The system contains also two heat exchangers embedded in silica gel, an evaporator with vaporising nozzles and a condenser. The specifications of the system are given in Table 10.

Table 10 Specification Mycom ADR-20

Parameter	Unit	Used heat	Cooling load	Chilling	Other	Overall
Temperature	°C					
- in		75	29	14		
- out		70	33	9		
Flow	m^3/h	20	41	12		
Average power	kW	120	190	70		
Power consumption	kW					
- pump			3,7	0,3	0,3	
COP (gross)	-					0.6
Weight	kg					7500
Dimensions	m					2,4x2,1x2,8
Cost	€ / kW					± 500

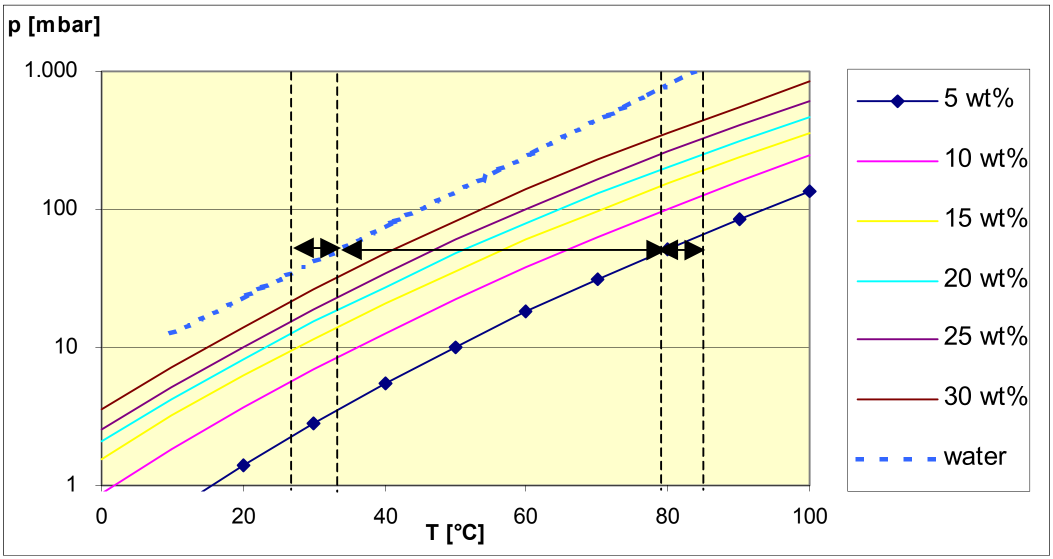
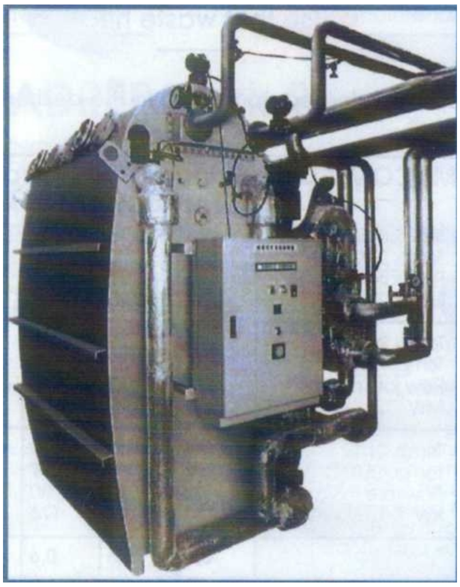


Figure 16 A pressure-temperature diagram of silica gel [source: Restuccia et. al ISHPC München page 219]



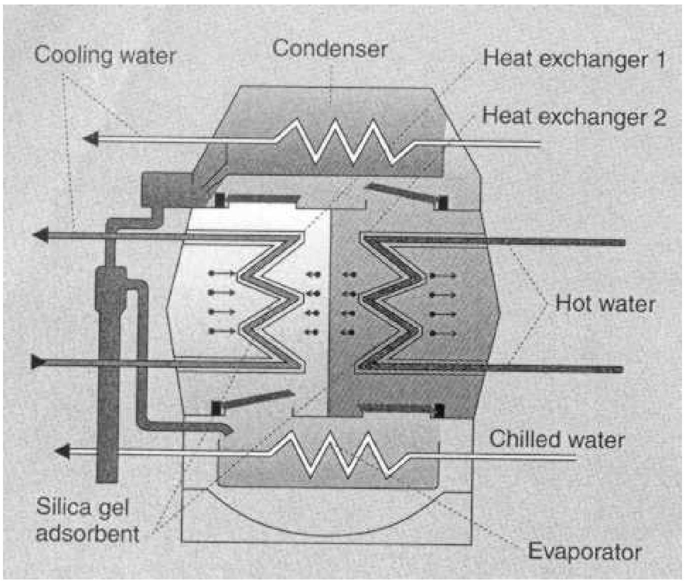


Figure 17 A photo (left) and a drawing of the cross-section (right) of a Mycom adsorption cooler

C.3 Conclusion

Choice of SWEAT for proposed trigeneration systems seems unfortunate:

- A large part of the heat from the fuel processor-PEMFC subsystem is available in a temperature range that can not be used for the SWEAT;
- Due to modest COP value (0.52) the overall cooling capacity is low;
- As a result of the time required for charging and discharging the system an unexpected large number of SWEAT modules is required to obtain a quasi-continuous cooling power output;
- The SWEAT system has a very good heat storage capacity. But the storage capacity plays no role in this application.

- Application is limited because the SWEAT working principle/fundamentals requires a cooling temperature of 15°C for charging of the system. In the summer during the daytime, when demand for cooling is highest, the temperature usually is higher.
- For a continuous system like this CCHP it is better to choose another adsorption cooler. An alternative is a system based of silica gel (Mycom). Silica gel has a low storage capacity, but performs well in the temperature regime of the CCHP. There is no danger of melting the sorbent.

APPENDIX D EVALUATION OF TWO APPLICATIONS OF TRIGENERATION SYSTEMS

In this appendix the application of trigeneration is evaluated for two cases. The characteristic energy demands of the cases considered are given in table 1 of this report:

- An average Dutch hospital (about 400 beds)
- An average large office building in the Netherlands (bank, 3500 employees, 122500 m^2)

Table 1 Typical energy use and cooling demand in an average hospital (CBS statistics, 1999) and three types of average bank offices (CBS statistics, 1996)

	Heating (NG) /TJ	Electricity /TJ_e	Cooling [1)] /TJ
Average hospital (about 400 beds)	46	13	6.3
Total hospitals (60000 beds)	8706	2794	945
Average office building (bank 6 employees, 210 m^2)	0.07	0.09	0.04
Average office building (bank 30 employees 1050 m^2)	0.35	0.44	0.2
Average office building (bank 3500 employees 122500 m^2)	40.43	50.45	24.3
Total offices ($3.5 \cdot 10^7$ m^2)	$1.2 \cdot 10^7$	$1.4 \cdot 10^7$	$0.7 \cdot 10^7$

[1)] Cooling demand: hospital 3,5 kW/bed; office 44 W/m^2.

The potential of trigeneration is evaluated for a SR-SOFC/LiBr-H_2O system, and compared to two alternative energy supply schemes, i.e. a scheme combining a SR-SOFC based cogeneration unit with an electrical compression cooler, and a scheme with separate production of power and heat in a central power plant and a local heater. In the latter case cold is again produced using an electrical compression cooler. The performance characteristics of the trigeneration unit are as follows:

- Electrical efficiency of CHP system 43%
- Thermal efficiency of CHP system 49%
- The COP of the sorption heat pump is 0.7
- The fraction of heat that can be used for the production of cooling is 0.85.

Assumptions made with respect to the energy demands of the average Dutch hospital and the average large office building in the Netherlands are as follow:

- Hospital
  - Power demand evenly distributed throughout the year
  - Power demand seven days a week, 16 hours a day
  - 75% of heat demand is space heating, the remaining for hot tapwater
  - Space heating demand only in the winter period (6 months)
  - Hot tapwater demand is evenly distributed throughout the year
  - Cooling demand only in the summer period
- Office building
  - Power demand evenly distributed throughout the year
  - Power demand not in the weekends and only in daytime, 10 hours a day
  - Heat demand is mainly for space heating
  - Space heating demand only in the winter period (6 months)
  - Cooling demand only in the summer period

In case of CHP and trigeneration the following considerations with respect to operation of the system are made:

- The control strategy is designed to maximise the electricity production for own demand, and minimise export to the grid. In determining the energy costs it is optimistically assumed that all electricity produced by the CHP unit can be used directly on the site. In case electricity can not be used directly it has to be supplied to the grid for which usually only a small fee is obtained. At a later moment, when the electricity is needed, it should be bought back for a higher price.
- There is enough storage/buffering capacity available to match heat supply and demand.
- The CHP unit will not produce electricity if the heat cannot be used.
- In case a heating and cooling demand exists at the same time, heat from the CHP unit is first used for heating purposes. The remaining heat is used for cooling purposes.
- In case the CHP unit does not produce enough electricity, the remaining part is obtained from the central grid. Overall electrical efficiency of the central power production is 42%.
- In case the CHP unit does not produce enough heat for heating purposes, the remainder part of the heat is generated by a local gas-fired boiler with an efficiency of 100%
- If not enough heat is available for production of cooling with the heat driven sorption unit, the remainder of the demand is supplied by a compression heat pump with a COP of 4.0.

The results of the evaluation of the potential of trigeneration for primary energy saving, emission reduction and cost benefits is summarised in table 11 and 12, for the hospital case and office case, respectively, and depicted in figures 18 and 19.

Hospital

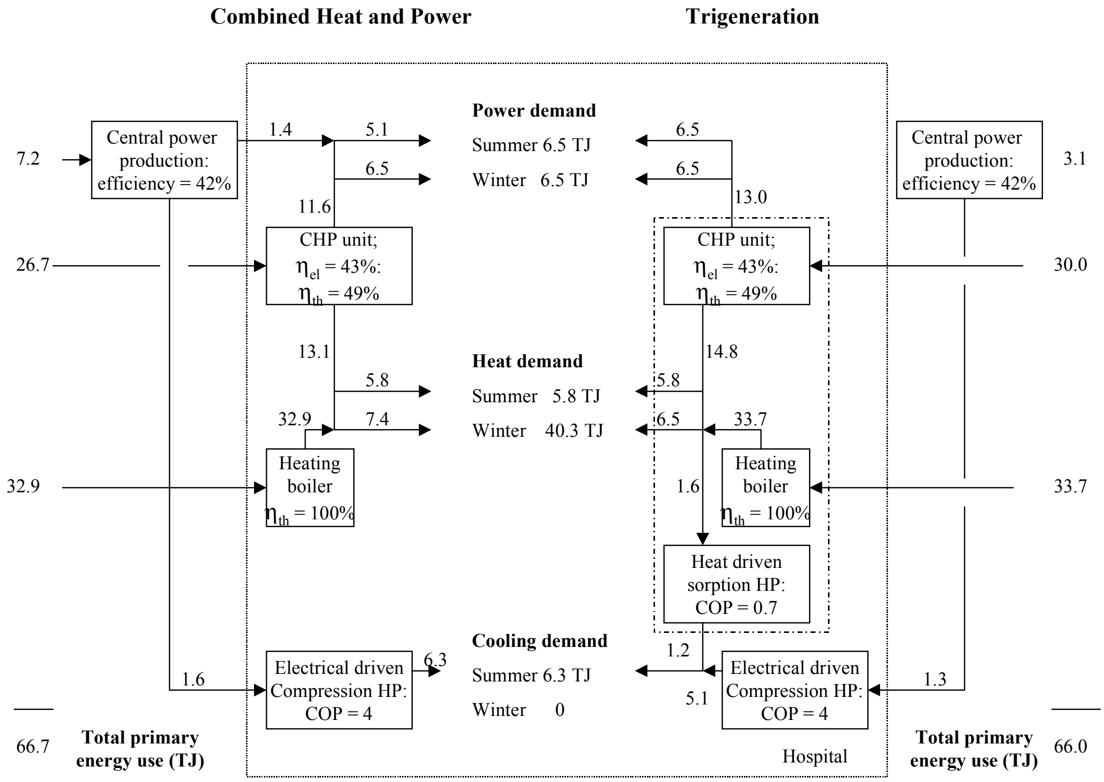


Figure 18 Comparison of the energy supply of an average Dutch hospital with a CHP system, to a trigeneration system equipped with a heat driven sorption heat pump.

Table 11 Primary energy use, CO_2-emission and energy cost for three different energy supply schemes of an average Dutch hospital

Hospital	Central scheme	CHP scheme	Trigeneration
Power demand (TJ)	13.0	13.0	13.0
Heat demand (TJ)	46.0	46.0	46.0
Cooling demand (TJ)	6.3	6.3	6.3
H/P ratio demand	3.5	3.5	3.5
H/C ratio demand	7	7	7
CHP running hours (hrs)	-	4380	4930
Electrical capacity (MW)	-	0.7	0.7
Thermal capacity (MW)	-	0.8	0.8
Cooling capacity (MW)	1.4	1.4	0.5+0.9*)
Primary energy fuel mix (TJ)	34.7	7.2	3.1
Primary energy natural gas (TJ)	46.0	59.5	62.9
Total primary energy (TJ)	80.7	66.7	66.0
CO_2 emission fuel mix (kton)	2.7	0.6	0.2
CO_2 emission natural gas (kton)	2.6	3.3	3.6
Total CO_2 emission (kton)	5.3	3.9	3.8
Electricity cost (k€/year)	390	80	40
Natural gas cost (k€/year)	310	390	410
Total energy cost (k€/year)	700	470	450

*) Sorption cooling and compression cooling capacity

Large office building

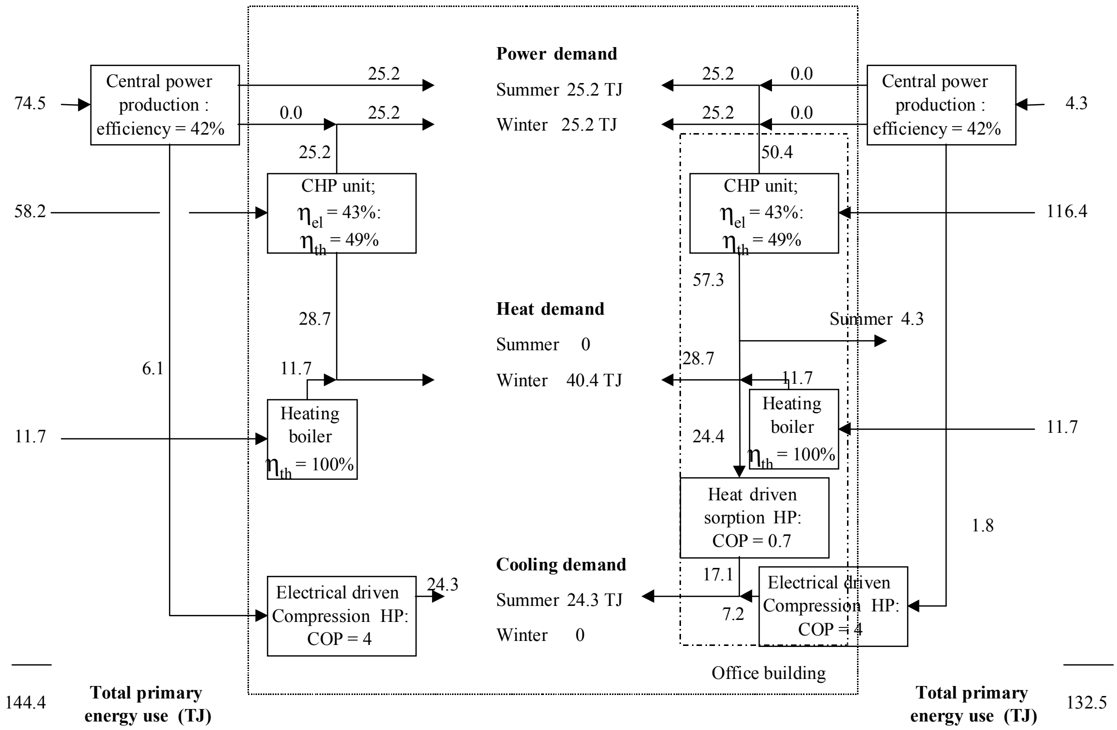


Figure 19 Comparison of the energy supply of an large office building with a CHP system, or a trigeneration system equipped with a heat driven sorption heat pump.

Table 12 Primary energy use, CO_2-emission and energy cost for three different energy supply schemes of an average Dutch large office building

Large office building	Central scheme	CHP scheme	Trigeneration
Power demand (TJ)	50.4	50.4	50.4
Heat demand (TJ)	40.4	40.4	40.4
Cooling demand (TJ)	24.3	24.3	24.3
H/P ratio demand	0.8	0.8	0.8
H/C ratio demand	1.7	1.7	1.7
CHP running hours (hrs)	-	1305	2610
Electrical capacity (MW)	-	5.4	5.4
Thermal capacity (MW)	-	6.1	6.1
Cooling capacity (MW)	5.4	5.4	3.6+1.8*)
Primary energy fuel mix (TJ)	134.5	74.5	4.3
Primary energy natural gas (TJ)	40.4	69.9	128.2
Total primary energy (TJ)	174.9	144.4	132.5
CO_2 emission fuel mix (kton)	10.4	5.8	0.3
CO_2 emission natural gas (kton)	2.3	3.9	7.2
Total CO_2 emission (kton)	12.7	9.7	7.5
Electricity cost (k€/year)	1490	850	50
Natural gas cost (k€/year)	270	450	800
Total energy cost (k€/year)	1760	1300	850

*) Sorption cooling and compression cooling capacity

The results presented in table 11 indicate that compared to separate production of power and heat, application of an SOFC-based cogeneration system may lead to considerable reductions of primary energy use, CO_2-emission and energy costs for an average Dutch hospital. Reductions of 17%, 26% and 33% are calculated, respectively. Adding a heat driven sorption cooler to the cogeneration system, thereby partly replacing the electrical compression cooler, leads to an extension of the cogenerator operation time of some 550 hours per year. Sorption cooling does not lead to significant additional primary energy reduction. Due to a further shift from partly coal-fired central production to gas fired local production, there is a small additional CO_2 emission reduction of about 3%. At the gas and electricity consumption level of the average Dutch hospital it appears that the additional savings on avoided purchase of electricity hardly compensate for the additional cost for gas. An energy cost reduction of about 5%, is calculated.

The results presented in table 12 indicate that also for the large office building, application of an SOFC-based cogeneration system may lead to considerable reductions of primary energy use, CO_2-emission and energy costs compared to separate production of heat and power. Reductions of 17%, 24% and 26% are calculated, respectively. In this case the addition of a sorption cooler leads to a much larger increase in the number of operating hours. A doubling is envisaged to some 2600 hours per year. Also does the use of a sorption cooler lead to a modest additional reduction of about 8% in primary energy use. The reduction in primary energy use together with a further shift from partly coal-fired central production to gas fired local production, results in a considerable CO_2 emission reduction of more than 20%. The results for the energy costs are even better. The calculations indicate that extension of cogeneration to trigeneration in this case could lead to an additional energy cost reduction of about 35%.

Conclusion

It can be concluded that adding a sorption cooler to a cogeneration unit, thus creating a trigeneration unit, only leads to minor or modest additional energy conservation compared to the savings that are obtained when changing from separate production of power and heat to cogeneration. Due to a further shift from a coal containing fuel mix to natural gas for electricity production, it may still lead to significant additional CO_2 emission reduction. Furthermore, if the energy demand characteristics of the application are such that addition of a sorption cooler leads to a considerable increase of own electricity production at a favourable price ratio of additional gas and avoided electricity purchase, trigeneration may lead to pleasant reductions in energy costs. Combining cogeneration with sorption cooling may therefore be a way to enhance the economic viability of cogeneration. In this way it might enhance the application of cogeneration and contribute in an indirect way to considerable primary energy saving and CO_2 emission reduction as cogeneration is without a doubt much more efficient than separate production of power and heat.