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Evaluation of benefits and barriers of hydrogen in residential districts

Final Report

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Acknowledgement/Preface

This study is performed as a part of task 13 “*Evaluation and Optimisation of Integrated Hydrogen Energy Systems*” of the *Hydrogen Implementing Agreement* of the International Energy Agency (IEA). The ECN project number is 7.2888. Funding for this study came from the NOVEM (under contract 249.402-0030) and from ECN's ENGINE programme.

Abstract

In this report, the simulation results for the energy system of a district containing 1300 houses is presented. The starting points for these calculations are the electricity and heating demand patterns based on the ‘city of the sun’, a planned residential area in Heerhugowaard, the Netherlands. The main focus is concentrated on the possibility of using hydrogen as an alternative energy carrier in future districts. The results are compared to a number of other reference concepts. These concepts use natural gas or electricity as the main energy carrier.

The influence of the primary or secondary energy carrier (natural gas, electricity and hydrogen) on the CO_2-emissions, the cost and the primary energy consumption is considered. Components in the corresponding design of the energy system include buffers, fuel cells, burners and heat pumps.

Keywords

Fuel cells, energy system, system analysis, hydrogen, residential district, heat pump, steam reforming

CONTENTS

SUMMARY

As a part of the IEA-hydrogen implementing agreement Annex 13, *Design and optimisation of integrated systems*, a study has been carried out to evaluate the use of hydrogen as a future energy carrier in residential districts.
Using hydrogen offers several advantages:

- Hydrogen can be a clean and renewable energy carrier;
- Using hydrogen as an energy carrier can strongly reduce local emissions (NO_x, particulates) ;
- It is a potential storage medium for excess electricity from renewable sources
- Hydrogen is thé fuel for fuel cells (in particular Polymer Electrolyte Membrane Fuel Cells or PEMFC's)

This study has investigated potential benefits of using hydrogen as an energy carrier for a 1300-house residential area (City of the Sun in Heerhugowaard, the Netherlands). Because the Netherlands have an energy system which is dominated by natural gas, much attention is devoted to the development of combined heat and power systems (CHP) for residential areas. In this study the CHP systems use hydrogen. The required hydrogen for the district is produced in a decentralised plant inside the district. Consequently, the gas is transported via a hydrogen grid to the houses for the production of electricity and heat. In the houses hydrogen is primarily fed to a PEMFC. Depending on the size of the fuel cell, additional heating and electricity is required. For the production of heat either a hydrogen burner or an electric heat pump can be used. The electricity grid can be used to buffer excess or supply extra electricity.

Table 1 *Reference systems*

System	Energy carrier	Configuration
A	Natural gas	NG heater/ electricity grid
B	Natural gas	SOFC/ NG heater/ electricity grid
C	Electricity	Electric heat pump/ electrical heater

The hydrogen based system is not the only conceivable system with the potential to reduce energy consumption and emissions. As such, the hydrogen based system has to compete with several other systems, using other energy carrier, for example on natural gas or electricity (see table 1).

- System A is the conventional system, which is present in most of the Dutch houses.
- In system B, a solid oxide fuel cell (SOFC) is used to supply a part of the heat and electricity in the district using natural gas as an energy carrier. Similar to the hydrogen case, extra heat is supplied by a heater and extra electricity from the grid.
- System C is all-electric and an electric heat pump converts electricity to the required amount of heat for the district.

In general the methodology developed in the IEA annex identifies three 'measures of performance' which are useful in comparing different energy systems:

1. Consumption of the primary energy or efficiency;
2. Environmental impact;
3. System cost.

Environmental impact in this case is based only on the CO_2 emissions. A more detailed analysis of the environmental impact (CO_2, NO_x, SO_2, etc.) of the reference system using a natural gas heater and the environmental impact of one of the hydrogen based systems is discussed in [22]. As all systems studied use natural gas as the primary energy carrier, the efficiency and CO_2 emissions are not independent numbers in this case.

In the study various configurations for the hydrogen based systems have been considered. For example the influences of the fuel cell size, control strategy and the buffer sizes on the system behaviour have been evaluated.

In the hydrogen system, the hydrogen production in a steam methane reformer has a large influence on the total system efficiency. Here, natural gas is reformed to hydrogen with an assumed efficiency of 75% (LHV). This means that a large part of the input energy (25%) is lost in this step. The efficiency of the PEMFC should therefore be high enough to make up for the losses. In theory the efficiency of the fuel cell operating on hydrogen (55-60%) is sufficiently high to compensate for losses in the hydrogen production step. However, in the actual system, where fluctuating electricity and heat demand must be satisfied at all times, achieving the high efficiency is more difficult. Fuel cells supply both heat and power in a ratio which depends on the efficiency of the fuel cell. However, this heat to power ratio is not equal to the required heat to power ratio of the district. The households in the district on average demand more heat than electricity. The fuel cell produces more electricity than heat. Sizing the fuel cell for the heat demand results in a large excess production of electricity. Sizing the fuel cell for the electricity demand means that a substantial part of the heat must come from another source. The imbalance between heat and electricity demand is already apparent in the average heat and electricity demand and production, but becomes even more relevant if the heat and demand patterns are taken into account.

The comparison with other energy carriers is also made on cost, emissions and primary energy consumption. For each system the results for a representative configuration are shown in table 2.

Table 2 *CO_2-emissions and annual costs per house for four main systems*

System	CO_2-emissions kg/a per house	Total annual cost $/a per house
NG/Heater	2422	893
NG/SOFC	2185	824
Electrical heat pump (EHP)	2201	1712
Hydrogen/PEMFC	2280	2174

Table 2 shows that the calculated CO_2 emissions and annual cost for the hydrogen system, the conventional natural gas (NG) system with heater, the natural gas fuelled SOFC system and the electrical heat pump (EHP). The data indicate that the reduction in emissions (and primary energy) in the SOFC and EHP system amount to 10%, while the hydrogen based system reduces primary energy consumption by 6%. The major cost components are the investments for the reformer, the fuel cell and, if present, the heat pump. Because of the complexity (a large number of conversion steps), the hydrogen systems are more expensive. However, the study identifies a number of possibilities to improve the general performance of the system: reducing CO_2 emission by 10…15% is feasible.

One of the main issues identified as critical is the efficiency of the steam reformer for the hydrogen production. Evidently, the hydrogen route requires an additional conversion step, from natural gas to hydrogen, which introduces substantial losses. Because of the higher efficiency with which hydrogen can be converted into electricity compared to natural gas, these losses can be compensated. However, the system is very sensitive to the efficiency of the reformer. The calculations show, that a five-percent (point) higher efficiency (from 75% to 80% LHV) already leads to higher CO_2-reduction than the all-electric EHP system. A high reforming efficiency is therefore a critical factor for the hydrogen based system.

Matching heat and electricity demand and production simultaneously turns out to be the main challenge for the hydrogen systems taken into account in this study. On one hand, a large fuel cell, although it is able to cover a large part of the heat demand, leads to a large excess production of

electricity. The electricity can be sold to the central grid, but returns are relatively small (in our study, the price paid for electricity sold to the grid is assumed to be half the purchasing price).
On the other hand, minimising excess electricity production with the fuel cell means that additional heating units are required to supply the remaining part using the available energy carriers. For the hydrogen districts a hydrogen burner and an electric heat pump are considered. Combusting hydrogen is not attractive because of the relative low chain conversion (due to the reforming step). The electric heat pump on the other hand has a high efficiency and can cause a high reduction in the CO_2-production. At this moment however, the costs for such units are high. In both cases, supplying additional heat with a burner and with a heat pump, the efficiency is determined by the design of the system: size of the fuel cell, control strategy, etc.. The design of the system, in particular with respect to the heat production, is identified as a second critical factor.

An option to improve the efficiency of the system is to utilise the heat which is produced in the reformer. Two configurations have been considered which use the heat of the reformer to heat a part of the district. Two different types of houses exist in these configurations. Part of the houses is equipped with a fuel cell and part is connected to a local heat grid which utilises (in part) the heat from the reformer. Electricity produced in excess by the fuel cell in one part is exported to the other part where it covers the electricity demand. These split-districts have lower CO_2-emissions than the all-electric system indicated above, even taking into account the substantial losses in the heat grid.. A configuration combining a hydrogen grid for part of the district and a central heat pump, achieves reductions which are substantially higher than those indicated for the SOFC system.

The costs calculated for the hydrogen systems in this study are prohibitive. It should be noted however, that these cost calculations are based on non-dedicated equipment. For example the cost for the small heat pumps, as required for the hydrogen FC/heat pump systems are based on the cost of much larger systems. Similarly for the reformer, the cost are based on down-scaled industrial type reformers. In general development of dedicated equipment, including stationary fuel cell systems for hydrogen may change the economic perspective.

Based on this analysis, the focus of research with respect to hydrogen systems for residential applications should be on:

- the improvement of the reformer efficiency;
- improved balancing heat production and heat consumption (both total as in time);
- more detailed assessment of cost and potential cost reduction by development of dedicated equipment.

The relevance of the concept of hydrogen for residential applications for a more sustainable energy system, for example in combination with CO_2 capture and sequestration or renewable concepts for residential systems, should be further developed.

1 INTRODUCTION

Dutch government policy aims at a 10% share of renewables in the Dutch energy consumption in 2020. Even with this ambitious targets, it is evident that fossil fuels, in particular natural gas, will continue to play an important role as a primary energy source for the Dutch energy supply in the first half of the 21st century. The Dutch policy is therefore aimed both at increasing the share of renewable energy and in reducing the harmful effects of fossil fuel use (emissions, depletion of resources, etc.).

Much work is being done to develop means to use natural gas more efficiently. For residential areas a possible option for efficient use of fossil fuels is the use of combined heat and power (CHP) units and heat pumps. In particular much attention is being devoted world wide to developing CHP units based on fuel cells. Although fuel cells convert hydrogen into electricity, the systems which are developed are generally natural gas fuelled. The two process steps, from natural gas to hydrogen (reforming) and from hydrogen to electricity in the fuel cell are integrated in one system. In this study a different approach is evaluated. The hydrogen for these fuel cells is assumed to be generated at a central reformer in the residential district. The main advantage of this set-up is that instead of a hydrogen production 'plant' to be installed in every home, only one central reformer is required. Because of the economy-of-scale, hydrogen production at a central location can be considerable cheaper. Furthermore the system which is inside each home becomes much simpler because the micro-scale hydrogen plant is eliminated.

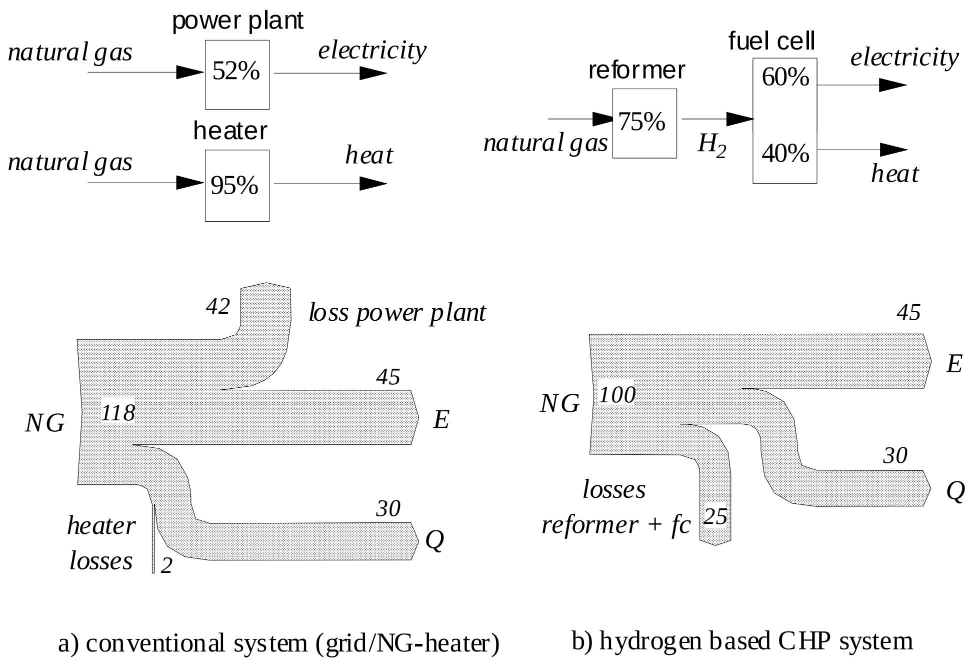


Figure 1.1: Comparison of the natural gas (NG) use for the conventional system for supply of heat (Q) and electricity (E) to a household and a hydrogen/fuel cell systems

The advantage of using CHP in an energy system is the high efficiency in simultaneous generation of heat and electricity. In figure 1.1 a CHP fuel cell system using hydrogen as an energy carrier is compared with the current system for supplying heat and electricity to homes using a natural gas heater and the electricity grid. This simplified example illustrates the potential reduction of the primary energy consumption using the hydrogen fuel cell system. The example is based on a reformer efficiency of 75 % (LHV) and a PEM Fuel Cell with an electrical efficiency of 60% (LHV). The CHP option is compared to an all electric system, assuming a state-of-the-art natural gas combined cycle power plant (η_e = 55% LHV, grid losses 5.5%) and a natural gas heater (η = 95% LHV) as used currently to heat buildings in the Netherlands. In this example the efficiency of the hydrogen system is approximately 15% higher than the conventional system. This figure depends strongly on the simplified assumptions used here. Only more detailed analysis of the system can give a more accurate view of the potential benefits of the hydrogen based system.

Other potential advantages of using hydrogen as the energy carrier in the district is that the hydrogen/electricity based district fits well in more advanced scenarios. For example, if much more stringent measures with respect to CO_2 emission reductions will be adapted, the use of hydrogen fuel cell opens the possibilities for centralised CO_2 capture and sequestration. Similarly, hydrogen is expected to play an important role as an energy carrier in energy systems with a substantial share in renewable energy. Using hydrogen is therefore also very interesting from the point of view of transition to a more sustainable energy system. However, in this study, using hydrogen as an energy carrier is only considered for the 2010 timeframe

1.1 Purpose of the study

In this report different hydrogen based energy system options on CO_2-emissions, costs, etc. have been simulated. The purpose of the study is to obtain a better insight in the characteristics of hydrogen energy systems to supply heat and electricity for a residential district. The objectives are to identify the technological and economical barriers for using hydrogen as an energy carrier in a residential district. Once these barriers are identified, efforts can be made to reduce or eliminate them through:

1. Identification of the research needs (technical and economical)
2. Improvement of the concept of design of a H_2-based residential energy system
3. Identification of possible demonstration projects

The hydrogen based system is not the only conceivable system with the potential to reduce energy consumption and emissions. As such, the hydrogen based system has to compete with several other systems, using other energy carrier, for example on natural gas or electricity. In figure 1.3 the three basic options for the energy carriers taken into account for this study. Depending on the energy carrier, different units or equipment required to generate heat and/or electricity can be considered.

In the first system, a hydrogen grid is present in the district. Here, hydrogen is produced at one location within the district from natural gas and then fed to the district grid.

The second option is the conventional system, using a natural gas grid. The third system is all-electric and electricity is, like in the other two systems, considered to be produced centrally in a gas-fired power plant and transported to the district. An electric heat pump is used to convert electricity to heat.

1.2 General approach of the study

For this study, the approach is to use a given energy demand for the district as the starting point for the simulations (see figure 1.1). The simulations are based on the momentary energy demand (i.e. a demand pattern) and not the total annual demand. The reason for using demand patterns rather than an annual demand is that this approach enables sizing the units in the district taking into account the peak load requirements and the 'phase shift' between heat and electricity demand over time. The total amount of natural gas and electricity depends on the demand patterns and on the 'design' of the energy system: the configuration of the units in the energy system. Varying the configuration enables a comparison on basis of costs, CO_2-emissions and distribution of the energy carrier (natural gas & electricity) for different designs.

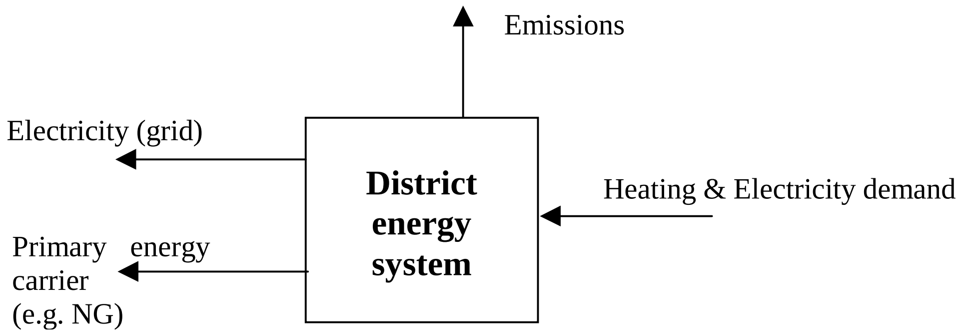


Figure 1.2 *Schematic representation of the model for the energy system for a district*

In some configuration, the energy system produces more heat and/or electricity than the district demands. If, for example, a base-load operating fuel cell is used, a constant amount of heat is produced independently of the heat demand. Excess heat is produced in times of low demand and depending on the configuration can either be stored or disseminated. Similar to the heat production, electricity can be produced in excess as well, which in the modelled systems is subsequently exported to the grid. The results of the simulation provide insight on the influence of these factors on costs etc.

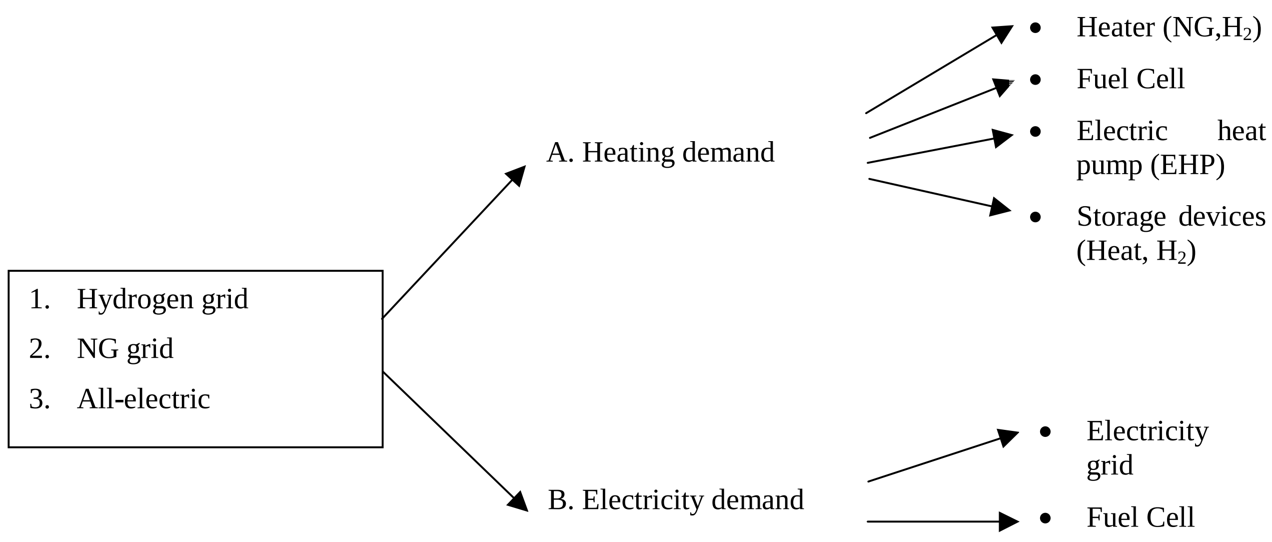


Figure 1.3 *Overview of the various options to satisfy the momentary heat and electricity demand (all districts do have an electricity grid as well).*

1.3 Definition of the demand patterns of the district

Because the starting points for the evaluation of the energy system are the electricity and heat demands, the background for the demand patterns will be outlined first. The simulated district comprises in total 1300 houses requiring energy in the form of electricity and heat for tap water and space heating. The calculations are based on the "The city of the sun [1]", which is a plan for a new residential area in Heerhugowaard. This area has an annual average heating and electricity demand of respectively 5292 kWh and 3371 kWh per household. The total energy demand pattern [2] per house is a function of the

- type of household (number of persons) and the
- characteristics of the house (in terms of the EPC value[1] and type of house).

It is assumed that the district consists of both terraced and semi-detached houses. The distribution of the household is represented in table 1.1.

Table 1.1 *Structure of the district (1300 houses): number of houses per household and type of house*

Type of house	Terraced house		Semi-detached house	
EPC	0.3	1.2	0.3	1.2
1 person	40	151	20	76
2 persons	56	212	28	106
3 persons	37	137	18	69
4 persons	31	117	15	58
> 5 persons	18	69	9	34

The calculation of the space heating demand is based on the EPC (Energy Performance Coefficient) of the considered houses. In table 1.2, the annual demand and the EPC value are given for each type of house. For the simulation of the district two EPC values have been considered, namely 0.3 and 1.2. The latter value (EPC=1.2) was the Dutch standard for 2000. An EPC of 0.3 is a future goal and represents a house with very low energy consumption. In order to obtain the reference heating demand for the residential area [1], the number of terraced and semi-detached houses have been chosen in such a way that this is achieved.

Table 1.2 *Calculated energy consumption for space heating per house and type of house*

EPC	House type	Energy consumption [GJ]	Frequency [%]
0.3	Terraced house	2.77	14.00
	Semi-detached house	4.71	7.00
1.2	Terraced house	11.54	52.70
	Semi-detached house	16.20	26.30

In table 1.3 the annual consumption of tap water and electricity for each type of household is given, divided in the demand per house. The last column shows the frequency of the household in the simulated district. The calculated average values of both tap water and electricity are represented in the last row.

[1] The EPC or Energy Performance Coefficient is used in the Netherlands to characterise houses with respect to insulation quality etc. The coefficient is building related.

Table 1.3 *Energy consumption for tap water and electricity per house*

Persons/ household	Annual consumption tap water [GJ]	Annual consumption electricity [GJ]	Frequency [%]
1 person	4.50	7.28	22.00
2 persons	6.80	10.87	31.00
3 persons	9.00	13.81	20.00
4 persons	10.80	15.55	17.00
> 5 persons	12.50	17.59	10.00
Average	7.98	12.13	

Having specified the complete characteristics of the district, the total demand pattern for both electricity and heating (space and tap water) for this area can be generated. The demand patterns are based on a reference year, which represents the average climatological conditions for the Dutch situation. In figure 1.4 the averaged patterns for a house in the district are shown for the whole year. From the graphs the influence per season can clearly be discerned in terms of higher energy demand during wintertime and lower demand in summertime.

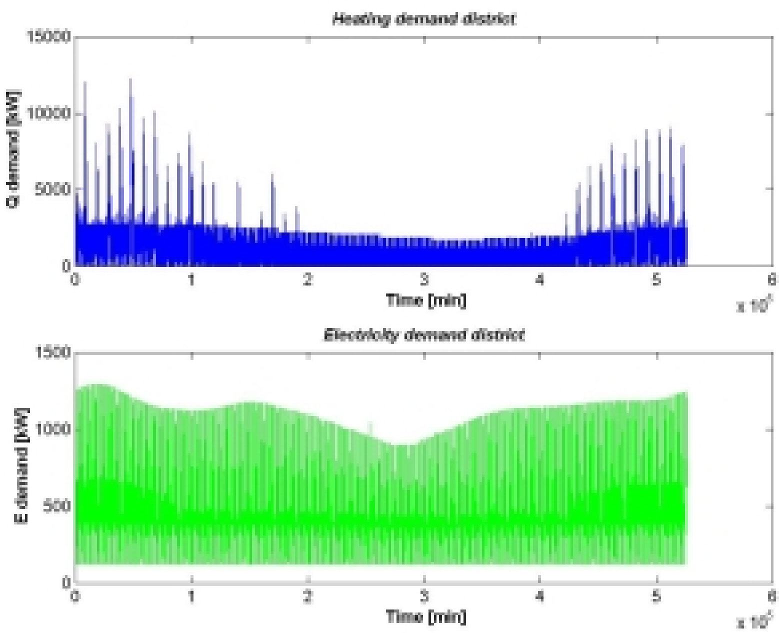


Figure 1.4: Heating and electricity demand patterns for the specified district

These demand patterns serve as input for the TOPICS (Tool for OPtimisation of Integrated Conversion Systems (see section 1.4)), which are defined in chapter 2, in order to calculate the measurements of performance.

1. total CO_2-emissions,
2. total system energy flows

Apart from the time specific demand curves, it is interesting to know the distribution of the load in time, given by a load curve. In figure 1.5, the load curves for respectively heating and electricity are shown. They are useful in determining the size of for example the fuel cell or a heating device. In this study the curves are used to determine the minimum size of the fuel cells.

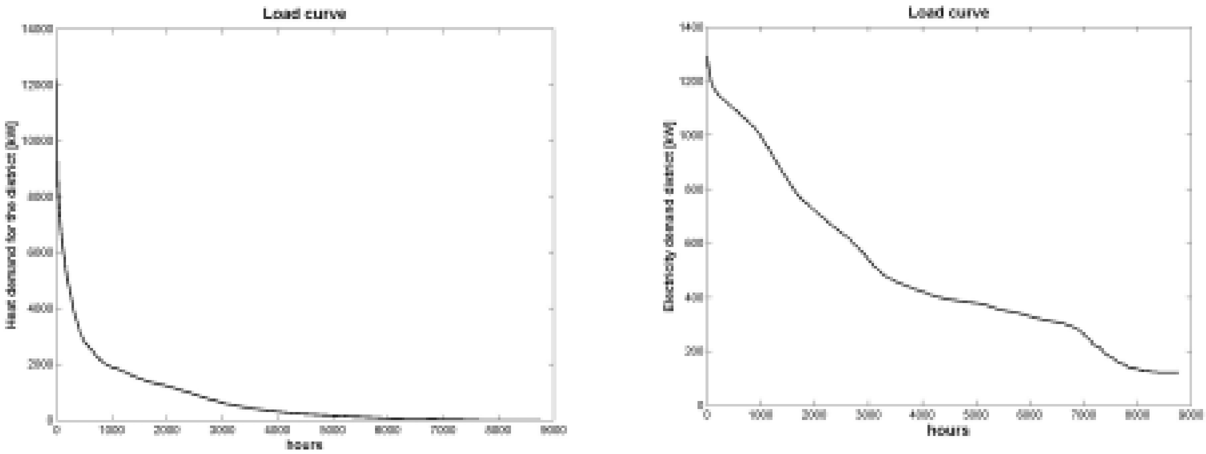


Figure 1.5 *Heating and electricity demand patterns for the specified district*

1.4 TOPICS

For the evaluation of integrated energy systems ECN has developed the software tool TOPICS (Tool for OPtimisation of Integrated Conversion Systems). The starting point for the evaluation is the energy demand or the energy function that has to be fulfilled. In fossil fuel based energy systems a varying demand can generally be met by operating the producing technology demand following. Increasing process integration (for example CHP) and use of renewables make it necessary to design the energy system specifically to be able to meet the demand at any moment. TOPICS therefore uses time dependant demand patterns (for example annual demand of electricity in 15 minute periods) and availability patterns (solar, wind). Using models for energy conversion and energy storage design an energy system, which matches the demand and supply.

1.5 Structure of the report

This report describes the background and the results for different options for the energy system for a residential district. The simulation of the systems has been carried out in TOPICS. The starting points and results of the simulations are described in separate chapters. The report is built up as follows:

- The general background of the models is described in chapter 2. Here, the background and input parameters of the various models are discussed.
- In the third chapter the cost calculations are discussed. The total annual costs per household are calculated using the unit operation costs and the cost of delivered energy.
- In chapter 4 and 5 the simulation results for all cases are presented together with the costs.
- The last chapter summarises the calculation results and looks at the barriers for the application of hydrogen in the residential system.

2 DEFINITION OF THE SIMULATED SYSTEMS

The electricity and heat demand for a standard household in the Netherlands is at present supplied from the electricity grid and by a central heating system, respectively. Because the energy use of households makes up 20% of the Dutch total energy use, it is interesting to research alternatives with more efficient ways to meet the present day heating and electricity demand.
In this chapter the starting points and input data of the systems based on the three energy carriers (as presented in chapter 1) and the corresponding models will be discussed. For a better insight, a number of systems are simulated for each energy carrier both for hydrogen as for the references natural gas and electricity. Before the hydrogen systems will be outlined in more detail, the reference systems will be discussed.

- The first energy carrier is natural gas and is supplied via a grid. The configurations to be discussed are the conventional system (system A) and a fuel cell system (system B). The latter is similar to system A, though a part of the demanded heat and electricity is produced by an internal reforming solid oxide fuel cell (SOFC).
- The all-electric district (system C) describes a system with a heat pump that uses electricity for the production of heat.
- With hydrogen as the secondary energy carrier, the SOFC is replaced by a proton exchange membrane fuel cell (PEMFC). The PEMFC converts hydrogen rather than natural gas to heat and electricity. The hydrogen is produced from natural gas. These are the D systems.

2.1 General model assumptions

Different configurations for each of the three types of systems have been simulated. The general assumptions used for each of the main systems are described in this section. Specific assumptions are presented in the next sections. Important for the simulation of a residential district is the availability of an energy carrier. In the Netherlands natural gas is widely available by pipeline. It was assumed that the natural gas grid is available for the district. For the calculation of the CO_2-emissions it is assumed that electricity is generated in a central power plant outside the district and subsequently transported to the area/houses by the electricity grid. The power plant itself is not modelled, though the CO_2-emissions corresponding to the electricity consumption of the district is taken into account.
The simulations are carried out for a complete residential district, though it is assumed that the fuel cells, heaters and heat pumps are located in each house.
All efficiency data presented in this report are based on LHV values.

2.2 Definition of the reference systems

2.2.1 District with a natural gas and electricity grid as energy source

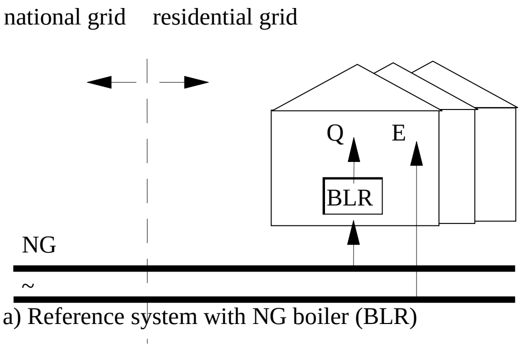
Searching for alternative energy systems based on natural gas has a number of advantages. Because all the heat and electricity is produced from natural gas, a lot of experience has been acquired for handling and distributing natural gas over the past decades. When building a new residential district, the residential grid can be connected to the main grid.
Two cases are considered:

A. The conventional system: Natural gas is converted to heat with a natural gas burner (central heating system). Electricity is supplied from the electricity grid.
B. SOFC system: Here natural gas is converted in a SOFC to both heat and electricity. Depending on the size of the SOFC, a co-heater is required to supply extra heat when the fuel cell heat production is not sufficient to cover the demand. Excess heat production by the fuel cell, on the

other hand, is either stored in a heat buffer or lost. A similar reasoning is valid for the electricity production of the fuel cell. The electricity grid functions here as the ‘buffer’ for temporarily electricity storage.

2.2.1.1 Conventional system (A)

For a comparative simulation study a reference situation is required. In the first reference case it is assumed that the natural gas and electricity grid supply the total heat and electricity demand of the defined district. In this system, heat for both tap water and space heating is supplied by a central heating system located in each house, which is the current situation in most of the present day houses in the Netherlands. In table 2.1, the unit specifications of the central heating system (a heater) are given.



a) Reference system with NG boiler (BLR)

Table 2.1 *Specifications of the heater*

Variable	Value (district)	Value (house)	Unit
Efficiency	95	95	%
Nominal power	13000	10	kW_{th}
Electricity consumption	0.005	0.005	$kW_e/kW_{th,installed}$

The value for the nominal power is derived from the heat demand pattern and equals the value of the peak demand for the district in the reference year. The presented data will be used for all heaters in the other simulations in this study.

The TOPICS model is used to calculate the total CO_2-emissions, the annual heating and electricity demand, the amount of electricity exported to the grid and the primary energy consumption.
For the conventional system (and all other systems), electricity is generated by a gas-fired power plant, with an efficiency of 55% (LHV). This efficiency is the present day value for a new to build power plant.

2.2.1.2 Solid Oxide Fuel Cell systems (B)

Using CHP units can increase the overall efficiency of the system and have the potential to lower the districts CO_2-emissions. The advantage of an internal reforming solid oxide fuel cell (SOFC) is that no changes to the infrastructure of the district are necessary. In fact the fuel cell is an extension of the conventional system, reforming natural gas to produce heat and power. Because of the use of the conventional energy carrier, the fuel cell and its reformer can be placed in both existing and planned districts. Another advantage is that, apart from the costs of the fuel cell, no extra investment costs are required.

In this section two configurations are described using a SOFC. The SOFC operates at high temperatures (around 900°C). Because of the high operating temperature, system control is rather difficult (it takes time and energy to warm up to 900°C) and it is therefore assumed that the fuel cell operates at base load, i.e. producing a constant amount of both electricity and heat. Since the demand is not constant, the fuel cell cannot cover the total demand at all times. The additional electricity required is imported from the electricity grid and excess electricity is exported to the grid. If

additional heating is required, a peak burner is used. Excess heat can either be stored if a buffer is used, or disseminated.
Each configuration is simulated with and without a heat buffer in order to obtain more insight in the effect of such a buffer. A summary of the systems is given in table 2.2.

Table 2.2 *Simulated SOFC systems*

System	SOFC (BL)	Heater	Heat buffer
1	x	x	-
2	x	x	x

BL = base load

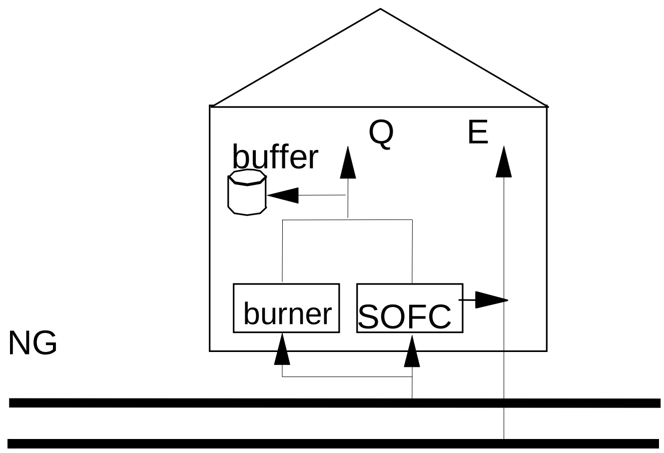


Figure 2.1 *Schematic representation of the natural gas fuelled SOFC CHP system (Case B) with additional burner and heat buffer*

The internal reformer for the SOFC can either be a catalytic partial oxidation (CPO) or a steam reforming unit (SMR). The fuel cell efficiency depends on the type of reforming. Based on [8] and [9] the electrical and total efficiencies for both CPO and SMR are given in table 2.3. As is seen in the table, the electrical efficiency is higher for SOFC-SMR, but the total efficiency was lower. Since electricity is the more valuable product of the fuel cell, the steam reformer is chosen as the hydrogen generator.

The specifications for the heater remain unchanged and are given in table 2.3.

Table 2.3 *Efficiency data SOFC [8], [9]*

Reformer type	Variable	Current status	Expected status in 10 years	Unit
Catalytic partial oxidation	Electric efficiency	28	32	%
	Total efficiency	98	98	%
	DC/AC conversion loss		6	%
Steam reforming	Electric efficiency	39	45	%
	Total efficiency	95	95	%
	DC/AC conversion loss		6	%

SOFC systems without heat buffer
In the case where no heat buffer is placed in the house, the generated excess heat cannot be stored and will therefore be disseminated. An alternative is to switch off the fuel cell. However, taking into

account the high operating temperature and the relative long start-up time this is considered not realistic. The heater in this system is heat demand following, or load-following.

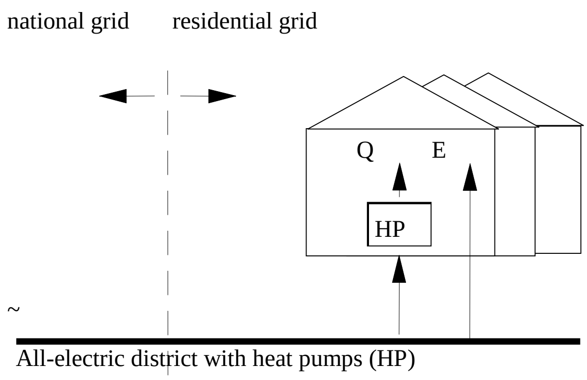
SOFC systems with heat buffer

The second system assumes that a boiler is present in the house that is able to store 7.8 MJ (corresponding to a vessel volume of approximately 100 litres). Here, the excess produced heat can be stored. In the model, heat is primarily supplied by the fuel cell and secondly the heat buffer is addressed for additional heat supply. The heater is only used in times that the heat buffer is below a certain level (here 15% of the total capacity). At this point the heater is switched on and fills the buffer to 70% of its capacity. When, on the other hand, the buffer is full (90%) a control switch turns off a valve, ensuring that the heat produced by the fuel cell is disseminated.

The heat buffer itself is not considered to be adiabatic. In practise the vessel leaks heat to the environment. In this study energy loss is estimated to be 0.01%/h of the total vessel capacity, which in the case of the 100 litres vessel is about 78 kJ/h.

2.2.2 District with an electricity grid as energy source

A possible alternative for the conventional system is the use of an electric compression heat pump instead of a heater. Because the heat pump converts electricity to heat, no gas grid is required in this system, only an electricity grid. This simpler infrastructure involves lower investment costs. With an all-electric energy system, the CO_2-emissions shifts from the central heating system to a centralised power plant. This shift is especially beneficial when, as a result of more stringent environmental regulations in the future, CO_2 has to be stored.



The advantage of a heat pump is the high CO_2-emissions reducing potential. In this study ground heat is used as the heat source. An alternative is ground water, but this source depends on the availability and quality of the groundwater and is therefore unreliable. Because of the available surface area in residential districts, vertical inserted heat source is mostly used.

Table 2.4 *Specifications of (per house)*

The electric heat pump		
Variable	Value	Unit
Carnot efficiency (C_f)	0.38	-
High temperature	65	°C
Low temperature	15	°C

The electrical heater		
Variable	Value	Unit
Efficiency	100	% (Q_{out}/E_{in})
	55	% (Q_{out}/NG_{in})

The electric heat pump is load following and the maximum capacity is based on the peak demand. In table 2.5, the unit specifications of the heat pump are given.

The efficiency of the heat pump is expressed by the coefficient of performance (COP) of the heat pump. This coefficient represents the heat to power ratio of the heat pump and is calculated with

$COP = C_f * \frac{T + 273.15}{T - T_0}$. For the data given in table 2.4, the calculated COP = 2.57. This means that the heat pump uses 1 unit of electricity to produce 2.57 units of heat.
A disadvantage of the heat pump system is the relative high cost of both the heat pump and the heat source (see chapter 3). A means to reduce the total system cost is to use a co-heater to supply heat in peak times. Since a natural gas grid is not available in the district, an electrical heater is used. An electrical heater is a very inefficient but very cheap heat source. As a consequence the total CO_2-emissions will increase with respect to the systems with only a heat pump.

2.3 Definition of the hydrogen systems

In this study, the hydrogen for the residential district is generated from natural gas using a decentralised steam reformer. Similar to the all-electric situation, no CO_2 is emitted inside the district but centrally near the power and hydrogen plant. This is certainly attractive in case CO_2 has to be stored in the future.
In each house a PEMFC is used to generate heat and electricity via the conversion of hydrogen. This in contrast to the SOFC, that uses natural gas as the fuel source in the home. As a result of this difference, the performance of the fuel cells is different as well. Compared to the SOFC the PEMFC has:

- a higher electrical and total efficiency on pure hydrogen
- a lower operating temperature (± 80°C)
- lower investment costs[2]

For the selected district, hydrogen will be produced from natural gas in a steam reforming production unit located centrally in the district and will subsequently be supplied to the houses. To cover variations in the hydrogen demand a high-pressure hydrogen storage park is located next to the reformer. A schematic representation of the hydrogen-based district is shown in figure 2.2.

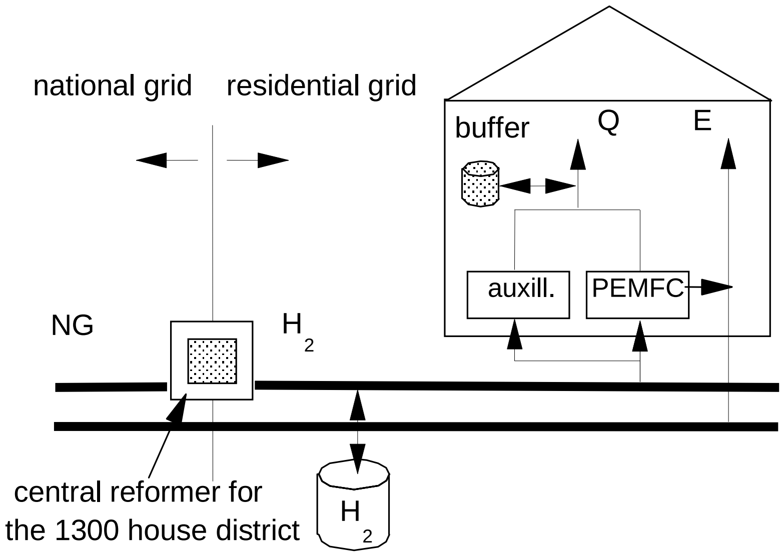


Figure 2.2: *Schematic representation of the hydrogen-fuelled PEMFC CHP system with additional heating unit and heat buffer*

[2] Because of the high interest of using fuel cells (PEM) in the automotive industry, it is expected that the costs will decrease: in our cost estimate the price for the PEMFC system is higher

Since the heat production of the PEM fuel cell is not sufficient to cover the demand, an additional heating unit is required. Possible units for this are heat pumps and hydrogen burners. From an environmental point of view, the heat pump is the most attractive co-heater but is expensive. Similar to the all-electric case, the cost for these systems is reduced by using an electrical heater as peak-heater. A hydrogen burner on the other hand is much cheaper but the conversion step from hydrogen to heat is highly inefficient.
For this energy carrier four systems are simulated, as represented in table 2.5.

Table 2.5 *Simulated PEMFC systems*

System	PEMFC (base load)	PEMFC (load following)	Electric heat pump	Electrical heater	H_2 burner	Heat buffer	H_2 buffer
1	x	-	x	x	-	x	x
2	x	-	-		x	x	x
3	-	x	x	x	-	x	x
4	-	x	-		x	x	x

The PEMFC is compared to the SOFC easier to control. Due to the lower operating temperature and consequently faster start-up and response times, the fuel cell can also be used in load-following operation. The influence of both operation modes is considered. Specifications for the PEMFC are given in table 2.6.

Table 2.6 *Specifications of the PEMFC [8]*

	BL	PL	
Variable	Value	Value	Unit
Electrical efficiency	0.60	0.66	%
Thermal efficiency	0.40	0.34	%
Cell voltage	750	825	mV
Minimum partial load	0.25 - 0.15	0.25 - 0.15	%
DC/AC conversion efficiency	0.94	0.94	%

BL = Base load; PL=Part load

Base load PEMFC systems
Operating the fuel cell in base-load can be beneficial to the overall efficiency and system costs. Because the fuel cells are relatively expensive, it is desired to maximise the use of the units. Especially for smaller sized fuel cells a part of the heat and electricity demand in the district can be covered with a base load fuel cell. If a heat pump is used as co-heater, the steam reformer only has to produce hydrogen for the fuel cell. Since both units operate in base load, no hydrogen buffer is required to cover fluctuations in the hydrogen demand.
The energy system with a PEMFC operating in base-load is considered with a heat buffer. The characteristics of the heat buffer are similar to the SOFC systems in the energy system with a natural gas grid.

Load following PEMFC systems
The disadvantage of operating the PEMFC in base load is the excess production of both heat and electricity when the demand is low. Although electricity can be sold to the grid, excess heat is disseminated. The lower operating temperature of the PEM fuel cell enables load following operation. The difference with base-load operation is the higher electrical efficiency in part-load operation. Dependent on the nominal power of the fuel cell, a heat pump or burner is required to supply heat at peak times. Because of the relatively small fuel cells used, a load following co-heater is placed in the houses. A control unit is used to switch the device on and off. The device is switched on when the heat demand is higher than the fuel cell heat production and off in the opposite situation. In the models the efficiency at a certain cell voltage is an interpolated value between the 60 and 66%.

Steam reformer
In literature the overall plant efficiency varies between 62% and 89% (see table 2.7), mainly differing in the way the steam energy (required and/ or exported) is accounted for and the size of the plant. In table 2.7, the maximum efficiencies of some steam reforming processes are given.

Table 2.7 *Maximum plant efficiencies and corresponding plant sizes*

	Max. efficiency [%]	Annual hydrogen output [10^6 m^3 H_2/yr]	Source
Linde Process	81.4	800	[20]
Caloric	85.1	-	[4]
-	75.2	500	[3]
Howe Baker	72.8	3.5	[19]
Howmar Industries	67.6	9 – 47	[5]

The lowest efficiency is reached when the excess steam cannot be exported and the internally produced steam is not included in the underneath equation. The highest efficiency is reached in the opposite situation. In this study an average efficiency of 75% is assumed, mainly because the SMR plant in this study is smaller than the discussed plants in literature.

The overall plant efficiency can be calculated with *[3]:*

$$\eta_{plant} = \frac{energy\ in\ product\ H_2 + steam\ energy\ exported}{natural\ gas\ energy + electricity + steam\ energy\ required / imported}$$

Because smaller reformer plants do not always have an adequate heat recovery and the steam credits that large plants have are not available. This is the reason that these plants have a lower overall efficiency. In table 2.8 the specifications for the SMR are given.

Table 2.8 *Specifications of the SMR*

Variable	Value	Unit
Hydrogen plant efficiency	75	%
Boiling feed water	0.671	(kg/h)/kW H_2
Cooling water	0.013	(m^3/h)/kW H_2
Electricity	0.014	kW/kW H_2
Export steam	0.328	(kg/h)/kW H_2

Hydrogen buffer
Hydrogen has to be stored in order to cover the fluctuations in the demand pattern. Baring the more exotic methods, there are four options for the storage of the component in stationary systems, which are

- High-pressure storage;
- Storage of liquid hydrogen
- Metal hydrides
- Underground storage

For this study only the high-pressure storage is taken into account and is described below. Underground storage requires an overview of the geology of the area. Since this information is not available, the option is not considered. Metal hydrides on the other hand typically store 2%- 6% by weight, which means that a very large volume of hydrides is required for large amounts of hydrogen. Because of the high volume and corresponding high cost, this option is left out as well. For similar reasons, liquefaction of the gas is considered to be a very expensive option and not worthwhile option as well.

The SMR unit is operating in base-load and excess production of the gas is compressed and stored in a high-pressure buffer. When the buffer is 90% full, the SMR is turned off. The unit is switched on again at a hydrogen storage level of 15%.
When, on the other hand, the buffer is almost empty (15%) a control switch turns off the fuel cell and H_2-burner to allow the buffer to be filled. To minimise the 'down time' of the units, they will be switched on again at a buffer level of 30%.

Characteristics of gaseous hydrogen storage
High-pressure storage is the simplest form of storing hydrogen; the unit operations that are required are a high-pressure vessel and a compressor. The amount of H_2 that can be stored depends on the storage pressure. Optimum pressure is a trade-off. The higher the pressure, the higher the capital and operating costs but the smaller the storage volume.
Based on [6], a pressure of 200 bars has been used for the storage vessels. One of the problems or concerns with high-pressure storage is the cushion gas, which remains in the vessel at the end of the discharge cycle[3]. On basis of the study of S. Schoenung [7] it is estimated that 40% of the storage volume remains in the vessel.
For small quantities, normally cylinders are used. Since in that case a large amount of cylinders are required for the quantities in this study (200 000 Nm^3), larger storage units are preferred. According to Amos [6] the maximum amount of hydrogen that can be stored is 1240 kg in a spherical tank. This is assumed for this study as well.

2.4 Summary of systems

In the previous sections the systems for each of the three types of district have been described. In table 2.11 all the mentioned systems are summarised.

Table 2.11*: Overview of the simulated systems*

No.	Systems	Base-load (BL) Load following (LF)	H_2 heater	CH_4 heater	Heat pump	Electrical heater	Heat buffer	Hydrogen buffer
	Natural gas based							
1	A			x				
2	B.2	BL		x				
3	B.3	BL		x			x	
	Electricity based							
4	C.1				x			
5	C.2				x		x	
6	C.3				x	x		
	Hydrogen based							
7	D.1	BL			x		x	x
8	D.2	BL	x				x	x
9	D.3	LF			x		x	x
10	D.4	LF	x				x	x
	Hydrogen based	**(split district: see chapter 5)**						
11	E.1	LF	x	x			x	x
12	E.2	LF	x		x		x	x

[3] A possible way to retrieve this gas from the storage vessels is to inject a liquid such as brine. This is not considered to be an option for the short time storage used in this study.

3 BACKGROUND OF COST CALCULATIONS

In this section, the calculation of the costs is discussed. This calculated costs are the total annual average costs per household for the given heat and electricity demand and include:

1. Energy consumption
   - Natural Gas (NG)
   - Electricity from grid
2. Operation and maintenance (O&M)
3. Capital costs and depreciation
4. Profit from exported electricity

3.1 Energy consumption

The tariff structure for the costs for both natural gas (NG) and electricity from the grid in the Netherlands is rather complicated. The price for electricity and natural gas depends on three factors: the production costs, the VAT and the energy tax. In the Netherlands a specific energy tax (REB = regulating energy tax) is paid on the amount of energy used.
The 2001 tariff structure for natural gas and electricity is shown in table 3.1 and 3.2 and in figure 3.1

Table 3.1 *Natural gas price structure*

Nm^3	USD/ Nm^3	Tax	Total USD/Nm^3
0 - 800	0.20	0.18	0.38
801-5000	0.20	0.18	0.38
5001 – 170 000	0.20	0.10	0.30
170 001 – 1 000 00 0	0.20	0.05	0.25
1 000 001 – 3 000 000	0.20	0.04	0.24

Table 3.2 *Electricity price structure*

kWh	USD/kWh	Energy tax	Total USD/kWh
0 - 800	0.07	0.08	0.15
801-10000	0.07	0.08	0.15
10001 – 50 000	0.07	0.04	0.11
50 001 – 10 000 000	0.07	0.02	0.10

In the cost calculation for the simulated system, the difference between peak and base electricity demand has not been taken into account. This is because in most current Dutch households the electricity meter only measures the total electricity demand for the household. In the calculations it is assumed that the meter differentiates between electricity consumption and electricity exported to the grid. It is assumed that the electricity that is exported to the grid can be sold for 50% of the purchasing price. Dutch energy markets are undergoing liberalisation. Future tariffs for selling and purchasing electricity are therefore highly uncertain. However sell-back prices well below purchasing prices are expected.

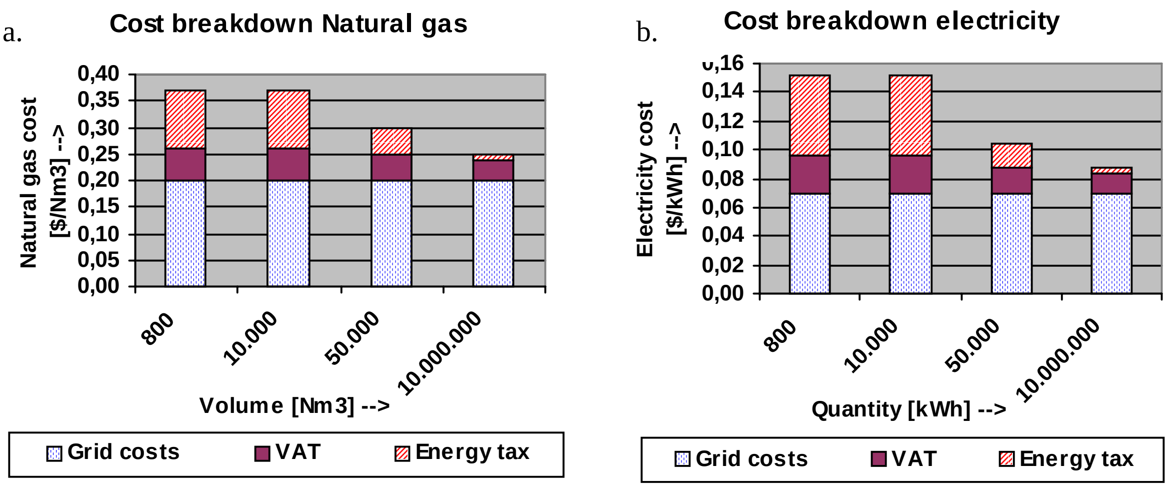


Figure 3.1 *Cost breakdown for natural gas ($/Nm^3) (a) and electricity ($/kWh) (b)*

3.2 Operation and maintenance

Each component has its operating and maintenance (O&M) costs. These costs are a certain percentage of the capital costs and are dependent on both the scale as the type of equipment.

Table 3.3 *Operation and Maintenance cost per unit*

Unit	O&M
SMR	2.5%
Hydrogen distribution	2.0%
Heat distribution	2.0%
Fuel Cell	2.5%
Heater	2.0%
Electric heat pump	2.0%
Electrical heater	0.5%
Heat buffer	2.0%
Hydrogen buffer	0.5%
Hydrogen compressor	2.0%

3.3 Capital costs and depreciation

3.3.1 Capital costs of the components

The capital costs of the units considered in the simulated systems have been calculated based on either the scaling rule or engineering data. For most of the units it is difficult to find its cost, especially when it concerns future prices as well. Therefore, the scaling rule is applied for most of the cases using data found in literature. The engineering rule has been used for the heat pump and the steam reformer

3.3.1.1 Scaling rule

The scaling factor is used to determine the price of the component used and is given by:

$$\frac{I_0}{I} = \left(\frac{P_0}{P}\right)^n$$

Where:

I_0	=	investment of reference component with capacity P_0
I	=	investment of component with capacity P
P	=	capacity of component
P_0	=	capacity of reference component
n	=	scale factor

Table 3.4 gives the cost data for the components used for the calculations:

Table 3.4 *Data used for the various units*

Component	Size	USD/unit	n	Reference
Heater	12 kW_{th}	75/ kW_{th}	0.7	[11]
Electrical heater		41.6/ kW	1	
PEMFC	5 kW_e	1400/ kW_e	0.7/0.85[4]	[14]
SOFC	5 kW_e	1080/ kW_e	0.7/0.85[4]	[15]
Heat buffer	10 MJ	45 /MJ	0.7	[16]
Hydrogen buffer	1000 Nm^3	35.7 /Nm^3	0.7	[17]

Hydrogen Grid

In reference [17] the costs of a hydrogen grid are estimated to be twice the cost of a natural gas grid. The costs for the natural gas grid for a district of 1300 houses is estimated using a method developed specifically for the Dutch residential area’s {OEI-model} [13]. Because only the PEMFC system with a centralised reformer requires a hydrogen grid, additional costs for the hydrogen grid will be used in the calculations. All other calculations do not include the costs for a natural gas grid: the costs of local distribution are part of the consumer price.

Polymer Electrolyte Membrane Fuel Cell

The costs of a PEMFC consists of the cost for the fuel processor, the stack and the Balance of plant (BOP). Roughly each of the components contributes for one third of the total cell capital costs. In our case the fuel processor is not required and it is assumed that the stack and the BOP contribute half of the total investment costs. Because stacks are modular units, a scale factor of 1 is assumed for the

[4] Different scaling factors are used for the stack and the balance of plant respectively

PEMFC-stack. For the BOP the value of 0.85, an average between the stack value (=1) and the "standard" value (= 0.7), has been taken for the scale factor.

SOFC
The capital costs of the SOFC consist of the SOFC stack and the BOP. Both contribute one half to the costs at reference scale. Costs for the stack are estimated on bases of the scarce data available in literature. Where for the BOP a scaling factor of 0.85 is estimated, for the stack 1.00 is more likely because of the modular character of a stack.

Heater
The costs for the heater are for the type of heater commonly used in Dutch houses. The heater is load-following, where the power can vary from 6-21 kW_{th}

Heat Buffer/ Hydrogen buffer
For the estimation of the costs, a heat buffer is assumed to be similar to an electrical boiler without an electrical heating device. Therefore the price of a heat buffer, which is not commonly used in Dutch households, is based on that of an electrical boiler, for which data are available.

The hydrogen buffer is a vessel wherein pressurised hydrogen is stored. For the simulation a storage pressure of 200 bar is assumed.

3.3.1.2 Engineering rule

The engineering rule has been applied for the heat pump and the steam reformer. Based on data from suppliers, the data points were fit.

Electric Heat Pump
In case of the heat pump this is discussed in detail in [21]. The cost of the heat pump is determined by the heat pump itself and the heat source. According to [21] the cost can be calculated with the linear relationship $C = 4180 + 457.6 \cdot x$, in which x represents the size of the heat pump per house and C the cost per house.
The costs include the heat exchangers and the piping system for the supply of low temperature heat to the cold side of the heat pump and the heat source.

SMR (Steam Methane Reformer)
SMR units are usually large-scale production units that operate at high pressure and high temperature. For purification a PSA (Pressure Swing Absorption) unit is used. The cost estimates for the calculations have been based on various engineering quotes. Fitting a line through these data results in a straight line with the equation:

Cost = 991*Capacity+1428732. In which the capacity is given in Nm^3/h and the cost in $.

3.3.2 Capital depreciation

The capital depreciation depends on the interest rate and the lifetime of the unit. For the calculations in this project, an interest rate of 7.5% is used. The lifetime of the units differs for each unit and is given in table 3.4.

Table 3.4: Lifetime for the various units

Component	Size	Lifetime [years]
Heater	12 kW_{th}	15
Hydrogen distribution		25
Heat distribution		25
PEMFC	5 kW_e	10
I/C PEMFC	5 kW_e	10
SOFC	5 kW_e	10
I/C SOFC	5 kW_e	10
Electric heat pump	6.5 kW_{th}	15
Electrical heater		15
Heat buffer	10 MJ	15
Steam reformer	1MW	20
Hydrogen buffer	1000 Nm^3	25
Hydrogen compressor		10

An example calculation for the conventional system can be found in appendix C.

4 RESULTS SIMULATION

The system calculation results will be presented and analysed in this chapter. In order to obtain a better insight in the influence of the configuration of the energy systems, the calculated data for CO_2-emissions, primary energy use and costs will be presented in graphs. All detailed system information can be found in appendix D.
The system results are described in the following sections:

Results of the reference systems (4.1)
- Results for the conventional NG based reference system (system A) (4.1.1)
- Results for the advanced NG based reference system (SOFC (4.1.2)
- Results for the all-electric reference systems (4.1.3)

Hydrogen systems versus reference systems (4.2)
- Base-load systems (4.2.1)
- Load-following systems (4.2.2)
- Performance of the PEMFC systems versus the all-electric system (4.2.3)

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4.1 Results of the reference systems A, B and C

4.1.1 Results for the conventional NG based reference system (system A)

The output results for the conventional system are given in table 4.1.
The total CO_2-emissions is the summation of the CO_2 production by the electricity and heat generation. The value for electricity is calculated with a power plant efficiency of 55% and transport losses in the grid of 5.5%. For heating an efficiency of 95% is used.

Table 4.1 *Output results of the conventional system (per house; The bold numbers are the totals)*

Variable	Value	Unit
Total heat requirement	**5292**	kWh
	633	m^3
Total electricity requirement	**3369**	kWh
Total CO_2-emissions	**2422**	kg
CO_2 from electricity	1301	kg
CO_2 from heating	1121	kg

It must be stressed that the low energy consumption values represent values which correspond to the values which will be required by the EPN regulations for new Dutch houses on short term.

In figure 4.1, the energy flow diagram is shown.

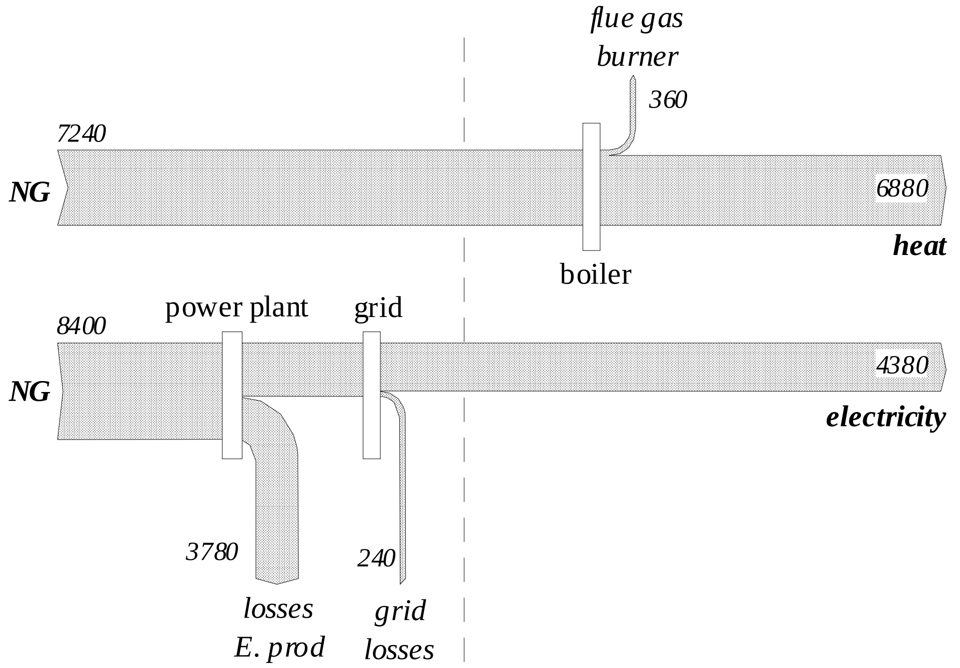

Figure 4.1 *Sankey diagram for the conventional system (numbers are shown in MWh/year for the district)*

In figure 4.2 the results of the conventional system are shown. Note that in the third bar electricity causes the major part of the total costs (62%) in contrast to natural gas. If this is compared with the first bar, showing the distribution of the total energy demand per type (heat and electricity), almost 60% of the total natural gas consumption is used for the production of heat. The difference in the relatively high natural gas consumption and electricity cost is a direct result of the higher cost for electricity than for natural gas.

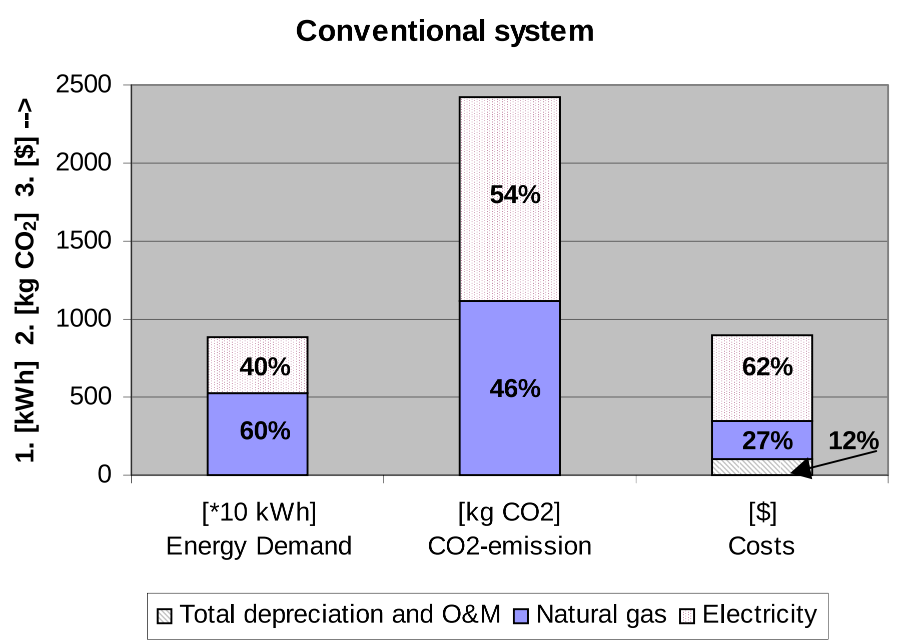

Figure 4.2 *Results of the conventional system*

The second bar in the figure represents the total CO_2-emissions for the heater and the gas-fired power plant. Due to the difference in efficiency of both units (95% and 55% respectively), the total CO_2-emissions for both units is almost similar (48%/52%), in contrast to the consumption of heat and electricity.

4.1.2 Results for the advanced NG based reference system (SOFC / systems B)

In this section the influence of a solid oxide fuel cell (SOFC) in a house is discussed. In table 4.2, the six discussed systems are shown. The starting points of the simulation are given in table 4.3.

Table 4.2 *Discussed systems*

System	Configuration (excl. heater)
B-1	0.32 kW_e SOFC
B-2	0.32 kW_e SOFC + small heat buffer
B-3	0.32 kW_e SOFC + large heat buffer
B-4	1 kW_e SOFC
B-5	1 kW_e SOFC + small heat buffer
B-6	1 kW_e SOFC + large heat buffer

Table 4.3 *Starting points of SOFC systems B-1 to B-6*

		B-1	B-2	B-3	B-4	B-5	B-6
Fuel cell	kW_e/house	0.32	0.32	0.32	1.00	1.00	1.00
Heater	kW_e/house	10	8.8	8.8	7.7	7.7	7.7
Heat buffer	MJ/house		3.8	7.7		3.8	7.7

Because the high operating temperature of the SOFC limits the operation characteristics of the fuel cell, only base load operation is considered. The choice for a rather small fuel cell is the result of several trade-offs. Increasing the size of the fuel cell causes a higher production of electricity. When the production is higher than the demand, the excess is exported to the grid that functions as a temporarily storage. The economics depend on the price paid for electricity in relation to the purchasing price. Because it is assumed that the price paid for export electricity is 50% of the purchasing price, it is generally more cost effective to utilise the produced electricity than to export it. Therefore, a small fuel cell is preferred. A larger fuel cell also increases the heat production. If the production of excess heat is to be avoided, the unused heat should be stored. The investment cost for the storage unit therefore rises with the heat production (larger storage vessels).
Secondly, the investment costs per kW of the fuel cell are higher compared to conventional units. Using a large fuel cell result in substantially higher investment cost.
Because the fuel cell is operating in base load, a larger part of the produced heat will be lost when using larger fuel cells. On the other hand, the contribution of the burner to the total heat production decreases.
The size of the fuel cell is based on the median value of the electricity load curve, which is 0.31 kW/house. Taking into account the losses due to the DC/AC conversion of 6%, the power of the fuel cell is set on 0.32 kW/house. The thermal output is 0.36 kW_{th} per house. The power of the larger fuel cell is set at the maximum demand of 1 kW_e/house.

In figure 4.3, the Sankey diagram of system B-3 is shown. The houses in system B-3 have a small fuel cell and a 100-liter heat buffer. Because the SOFC is operating in base load a large amount of the produced heat cannot be used directly and is stored or disseminated. It is clear from the diagram that in this case almost 43% of the heat produced by the fuel cell is lost because of this. Approximately 55% of the heat demand is still covered by the heater and no profit is obtained from

the heat of the fuel cell there. Still the overall system efficiency is almost 10 percent points higher than the conventional system: 81% (versus 71% of the conventional system) resulting in a lower use of the primary energy carrier.
Similar to the heat use, electricity cannot be used at all times and 16% of the produced amount with the fuel cell is exported to the grid and purchased back at a later time.

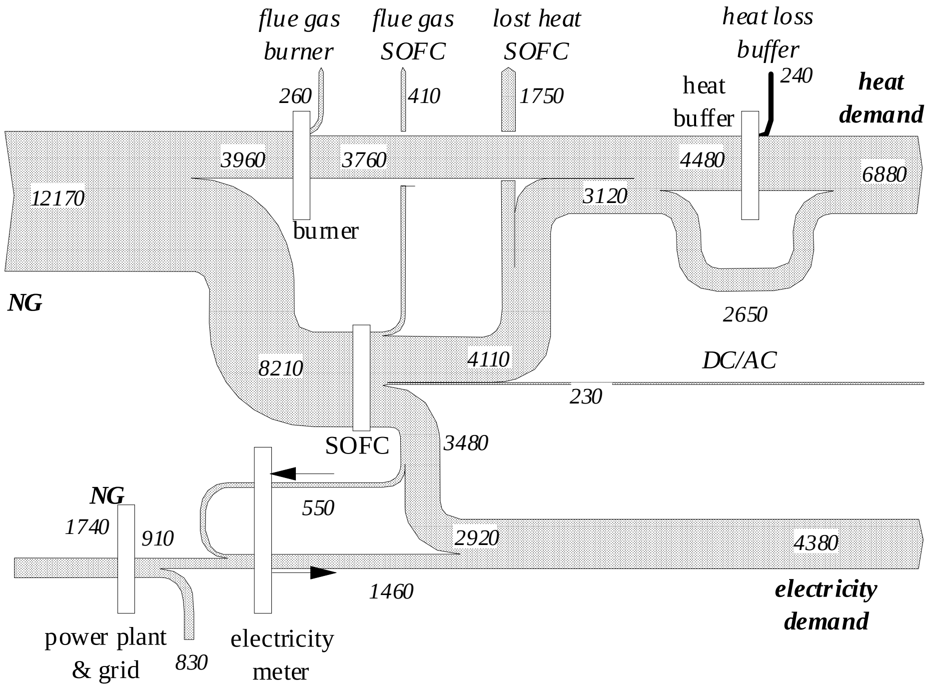

Figure 4.3 *Sankey diagram of system B-3 (numbers are shown in MWh/year for the district)*

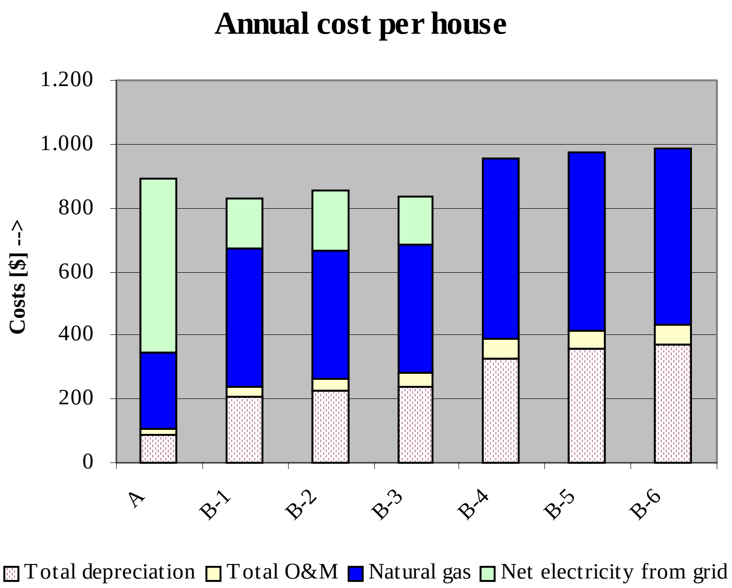

Figure 4.4 *Comparison SOFC containing systems with the conventional system (average total system costs/house)*

Figure 4.4 shows that the investment costs (O&M + depreciation) for the conventional system are lower than the SOFC systems (B-1 and B-2). This is because the conventional system only consists of a heater in comparison to the SOFC systems, which also have a fuel cell and a heat buffer. The influence of the fuel cell to the annual costs is evident by comparing the depreciation costs for the small (0.32 kW_e) fuel cell systems (B-1 – B-3) with the large (1kW_e) fuel cell systems (B-4 – B-6).
Although the system investment costs are higher, the total costs are lower. Because of the co-generation of heat and electricity in the fuel cell, the system is more efficient (see section 1.2) and the primary energy consumption and costs (variable costs) are lower.

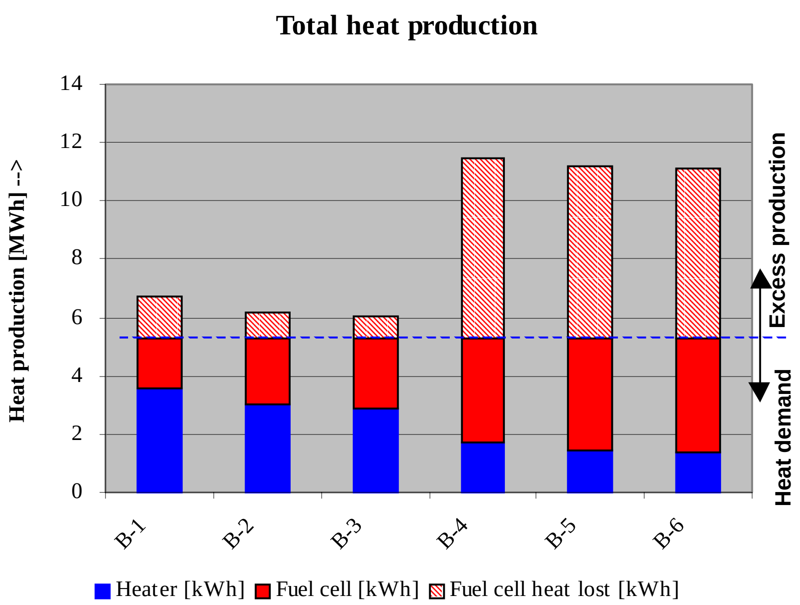

Figure 4.5 *Distribution of the total heat production. Hatched area's represent the total heat emissions.*

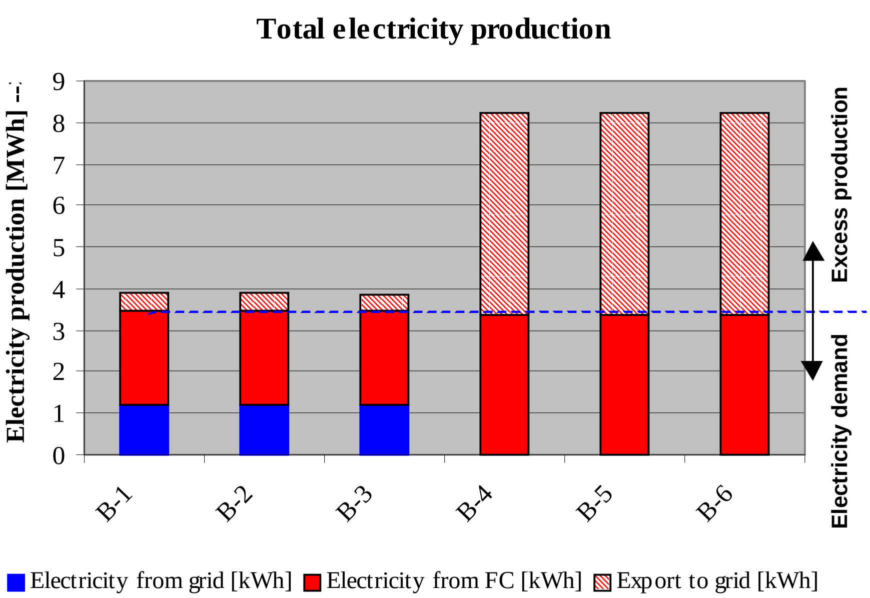

Figure 4.6 *Distribution of the total electricity production. Hatched area's represent the total electricity exported to the grid*

Since the SOFC operates in base-load, excess production of both heat and electricity on an annual basis result. The consequence is that a certain fraction of the thermal energy is not used. Excess electricity is exported to the grid. In figure 4.5 and 4.6, respectively the total heat and electricity production are shown. System B1 to B-3 contain a small fuel cell (0.32 kW_e/house), the other systems have a 1 kW_e/house fuel cell. From these figures, the influence of the heat buffer can clearly be seen in the reduction of the emitted heat. For the small fuel cell systems, the heat loss reduces by 39% for the 50-liter buffer (B-2) and 47% for the 100-liter buffer (B-3). By using a heat buffer the amount of heat which the heater has to produce becomes lower. For the large fuel cell (B-4, B-5 and B-6) this effect is only 5 to 6%. This large difference is not so surprising since the excess produced heat is far larger than the capacity of the heat buffers. Therefore, less is to be disseminated by using a heat buffer. Furthermore, in the 1 kW_e system the contribution of the heater is already smaller because the fuel cell covers a larger part of the heat demand.
The electricity distribution (see figure 4.6) is not influenced, since the heat buffer does not effect the electricity consumption/ production of the system.

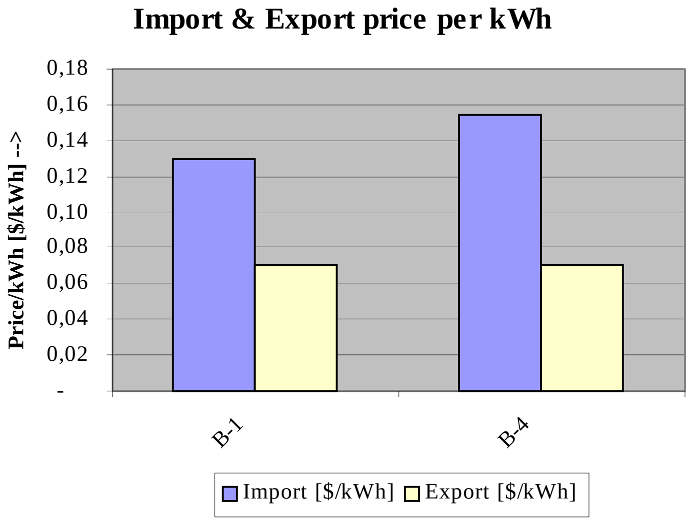

Figure 4.7 *Electricity import and export cost per kWh for the SOFC systems B-1 and B-4*

Figure 4.7 shows the electricity production and consumption of the systems B-1 and B-4. B-4, the larger variant of system B-1 exports a lot of electricity to the grid. As is seen in the graph, the amount of money that comes with it is 45% of the purchasing price. Because of this difference, exporting electricity to the grid is considered unattractive.

In table 4.4, the $\Delta\$/\Delta CO_2$ ratio for the discussed systems are shown. For the first three systems (B-1 to B-3) both the total costs and the CO_2 emissions are lower than the conventional system. The output of the $\Delta\$/\Delta CO_2$ ratio is in that case situated in the second quadrant (see appendix B). The most economical option is to use system B-1, though the CO_2 reduction is the lowest of the three. An extra 10$ in the annual costs for a large heat buffer reduces the CO_2 emissions by an extra 147 kg. In other words, the costs per kg CO_2 reduced are the lowest for option B-3.

All the fuel cell systems have been simulated with a large and a small heat buffer. The small heat buffer can store up to 3.85 MJ/house and the large buffer up to 7.70 MJ/house. These sizes correspond to a vessel volume per household of approximately 50 to 100 litres of water (assuming a 10°C temperature difference between the maximum and minimum value). The larger the heat storage vessel the larger the radiation losses (assumed to be 1% per hour of the maximum capacity). However, the larger buffer is effective for the base load systems. Because of the larger storage volume, less heat has to be disseminated. Table 4.4 shows that the CO_2 emission reduction for systems with a large heat buffer (100 liter) are considerable.

Table 4.4 *Costs per kg* CO_2 *reduced with respect to the conventional system*

System	Configuration (excl. heater)	Extra costs [$]	kg CO_2 reduced [kg CO_2]	Costs/kg CO_2 reduced [Δ$/Δkg CO_2]	Quadrant
B-1	0.32 kW_e SOFC	-65	116	-0.56	2
B-2	0.32 kW_e SOFC + small heat buffer	-69	237	-0.29	2
B-3	0.32 kW_e SOFC + large heat buffer	-55	263	-0.21	2
B-4	1 kW_e SOFC	62	9	7.12	1
B-5	1 kW_e SOFC + small heat buffer	79	71	1.11	1
B-6	1 kW_e SOFC + large heat buffer	95	88	1.08	1

Summarising this paragraph the following conclusions can be drawn.

1. A small SOFC-CHP system on natural gas potentially reduces both cost and CO_2-emissions
2. Lower energy costs beat the higher investment cost
3. The heat losses are higher for a larger solid oxide fuel cell (base load operation is assumed)
4. Increasing the fuel cell size has a substantial effect on the total annual costs.
5. The capital costs are determined by the fuel cell
6. Heat buffer has a positive effect on the carbon emissions reduction
7. Selling electricity to the grid is financially unattractive.

4.1.3 Results for the all-electric reference systems (systems C)

In this section four systems using only electricity as the energy carrier are discussed, see table 4.5 and 4.6.

Table 4.5 Discussed systems

System	Configuration
C-1	Electric heat pump (EHP)
C-2	EHP + heat buffer
C-3	EHP + small electrical heater
C-4	EHP + large electrical heater

Table 4.6 *Starting points of the all-electric systems*

		C-1	C-2	C-3	C-4
Heat pump	kW_e/house	10	6.5	3.07	1.92
Electrical heater	kW_e/house			6.15	8.07
Heat buffer	MJ/house		26.9		

The basic system, system C-1, only uses an electric heat pump to supply the required heat in the district. Because of the high capital cost of the heat pump and heat source, alternatives to bring down those costs have been considered.
One of the options is to use a very large heat buffer (C-2). With this system a smaller heat pump can be used, but the electricity consumption and the total CO_2-emissions of the system are higher. This is because the heat pump does not only have to produce the heat for the district but also compensate for the heat losses of the storage vessel.

Another option is to use an electrical heater, a cheap device that converts electricity to heat. Calculations were made for two different capacities (kW) C-3 and C-4.

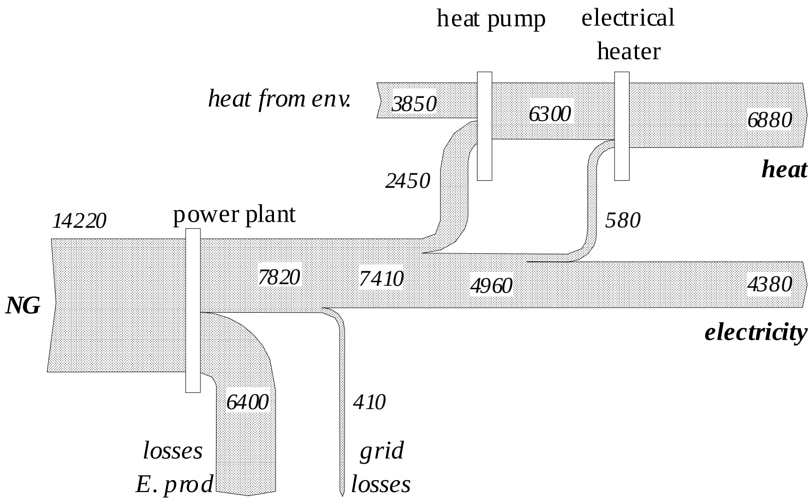

Figure 4.8 *Sankey diagram of system C-3 (numbers are shown in MWh/year for the district)*

For system C-3, the energy flow diagram is shown in figure 4.8. The district heat and electricity demand are respectively 6880 and 4380 MWh/year. Here the heat is generated for 92% with an electric heat pump, the remaining with the electrical heater. Decreasing the size of the electrical heater is beneficial for the CO_2-emissions but the total costs are much higher. For this system, the major losses occur in the production of electricity, but is compensated with the high efficiency of the heat pump. To be able to compare this system with the other systems that will be discussed in the next sessions the overall system efficiency can be calculated. This efficiency is defined as:

$$\eta_{overall} = \frac{[Q+E]_{out}}{NG_{in}}$$

and is for this system 79%. For all the system the heat to power ratio is constant (determined by the demand of the district) and all the input is related to the amount of natural gas required. This makes it possible to compare the CHP systems with the non-CHP systems.

In figure 4.9 and 4.10, the total system cost and the CO_2-emissions of each of the four options are shown respectively.

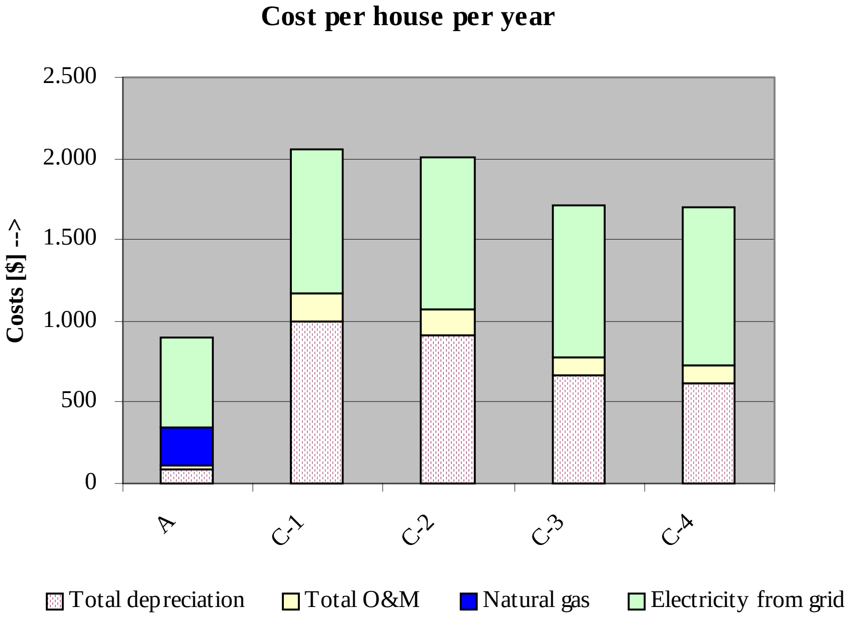

Figure 4.9 *Total system costs all-electric systems*

In comparison to system C-1, the systems C-3 and C-4 have a higher CO_2-emissions. Here, an electrical heater is used to cover the peaks in the heat demand instead of a single heat pump. Because the electrical heater is a very cheap but inefficient device, the total system costs are reduced by approximately 14% and the CO_2 emissions is higher. The contribution of the electrical heater to the total heat demand is 9% and 21% for the systems C-3 and C-4 respectively.
For system C-2, the system with an electrical heat pump and a large buffer, the lower investment costs cancel the higher energy cost out. The increase in energy costs is caused by the relative large losses of the heat buffer (11% of the total heat production)

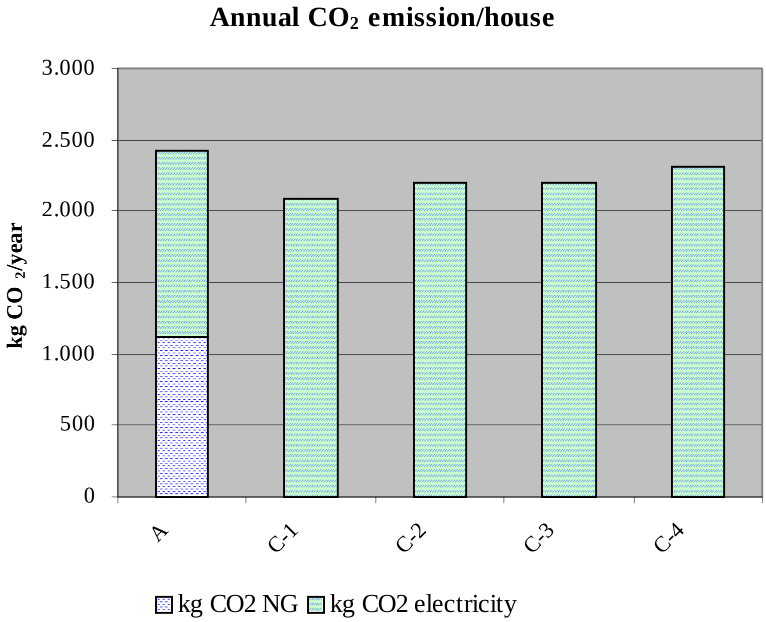

Figure 4.10 *Total CO_2-emissions all-electric systems*

In table 4.7, the values for the Δ$/Δ$CO_2$ ratio are given. Clearly the system with only a heat pump is the most attractive. Because of the lower system costs and the low Δ$/Δ$CO_2$ ratio, system C-3 is considered to be the best option of these four for the all-electric district.

Table 4.7 *Costs per kg* CO_2 *reduced with respect to the conventional system (average/house/year)*

System	Configuration	Extra costs [$]	kg CO_2 reduced [kg CO_2]	Costs/kg CO_2 reduced [Δ$/Δkg CO_2]	Quadrant
C-1	EHP	1161	326	3.56	1
C-2	EHP + heat buffer	1111	227	4.89	1
C-3	EHP + small electrical heater	819	221	3.70	1
C-4	EHP + large electrical heater	809	106	7.63	1

Summarising the results, the following conclusions can be drawn. Compared to C-1:

1. Substantial CO_2-reduction possible, but the investment cost for the heat pump are high
2. The heat losses in the buffer result in higher CO_2 emissions
3. The total cost do reduce slightly when a buffer is used, but the lower investment are offset by larger heat losses
4. The annual fixed costs are lower with an electrical heater, but the energy costs increase
5. Electrical heaters have a large impact on the CO_2-reduction. With a smaller heater (6.2 kW/house) 32% of the reduction potential is lost, with a larger heater (8.1 kW/house) this is 67%

The system that will be used as reference for the further discussed systems is C-3. This is the result of a trade of between the extra investment costs and the CO_2 reduction, which are for this system the best.

4.2 Hydrogen systems versus reference systems

4.2.1 Base-load systems

An alternative for using the SOFC as a micro-CHP unit is the PEMFC. As discussed in chapter 2, the PEMFC operates preferably on pure hydrogen. In this study, hydrogen is produced on one location in the district to eliminate the need for distributed fuel processing.
A large number of configurations have been considered. Both base load and load following configurations have been analysed. Base load operations minimise the investment cost per kWh of electricity generated, while load following optimises heat utilisation. In this section first the base load configurations will be discussed. The conventional system and the SOFC system are both used in this comparison.

Fuel cells operating in base load produce a constant amount of heat and electricity. Both in the districts with natural gas (SOFC) and the hydrogen (PEMFC) as the energy carrier, fuel cell systems in base load have been considered. In this section a comparison is made on cost and emissions among these base load systems with a small fuel cell. In table 4.8 and 4.9, respectively the discussed systems and their starting points are given.

Table 4.8 *Discussed systems*

System	Configuration
Ref	Heater
B-3	SOFC + small heat buffer
D-2	PEMFC + small heat buffer + H_2 burner
D-6	PEMFC + small heat buffer +EHP + electrical heater

Table 4.9 *Starting points of systems: conventional system, B-2, D-2 & D-6*

		Conventional	B-3	D-2	D-6
Fuel cell	kW_e/house		0.32	0.32	0.32
Heater	kW_e/house	10	8.8	8.8	
Electrical heater	kW_e/house				7.2
Heat pump	kW_e/house				2.0
Heat buffer	MJ/house		7.7	7.7	7.7

Providing all the produced energy can be used in the district, this mode ensures maximum utilisation of the fuel cell. This is attractive, because the investment costs of the unit are relatively high. However, depending on the size of the fuel cell, the heat or electricity demand for the district can be higher or lower than the produced amount.
In case the net demand of the district is higher than the heat produced by the fuel cell, an additional heating device (burner or heat pump) is required. Heat that cannot be used directly can be stored in a heat buffer. When the buffer is full the heat is disseminated. The presence of a heat buffer requires therefore a control strategy to optimise the storage and utilisation of heat.

In figure 4.11, this strategy is shown for a hydrogen system with a hydrogen burner as additional heating device. If there is a net demand, the fuel cell heat is primarily used to cover the heat demand followed by the stored heat in the buffer. If the buffer level is at or below 15% of its nominal capacity, the hydrogen burner is switched on to

1. cover the remaining part of the heat demand and
2. fill the buffer until the 30% storage level is reached.

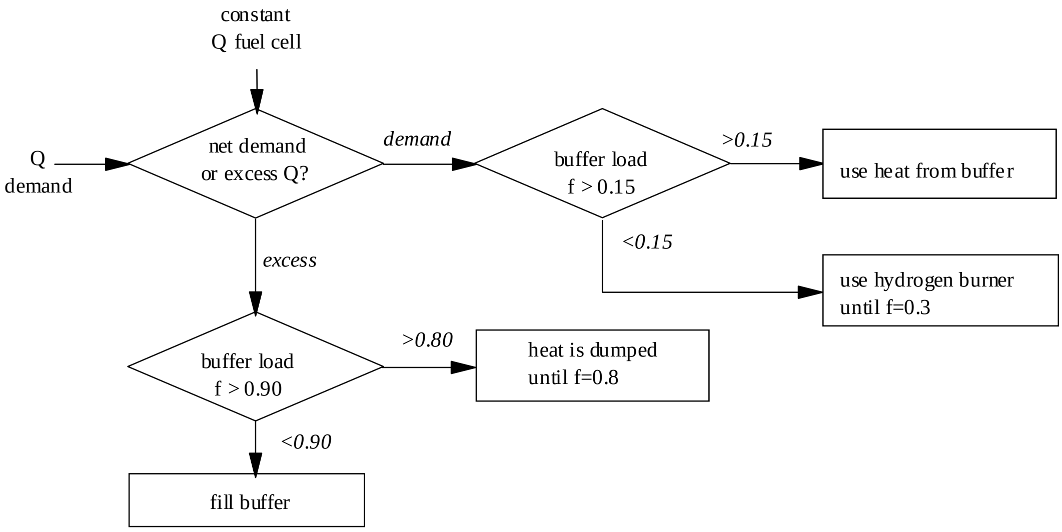

Figure 4.11 *Control strategy for a base-load hydrogen system with a hydrogen burner and a heat buffer*

The second point is to minimise the utilisation of the unit because of the lower overall efficiency of the heater. If, on the other hand, the buffer level exceeds 90% no heat can be stored in the buffer and the excess is disseminated.

In figure 4.12, the annual total costs per household are given for the systems given in table 4.8. The total annual costs of the hydrogen systems are higher than the natural gas systems. Due to the simplicity of the SOFC systems, the total costs are relatively low. In the hydrogen system the configuration is more complex. System D-2 is closest to system B-3, since both have a conventional heater as co-heater. The total energy consumption of both systems is almost similar, the main differences occur in the investment cost of the system units. This indicates that the higher investment costs of the more complex hydrogen systems are not compensated by a substantial reduction in the energy costs.
First of all, the PEM fuel cell is considered 30% more expensive than the SOFC. The uncertain character of both cost assumptions should be taken into account. Secondly, the steam reformer is assumed to operate continuously and, as a consequence of the variable demand pattern, hydrogen has to be temporarily stored. The high-pressure vessels are not cheap and therefore do have a relative high contribution to the costs.
In system D-6 the hydrogen burner is replaced by the heat pump (and source). Because the heat pump and source are far more expensive than the burner, the total system cost increase. The heating device alone makes up 53% to the annual fixed costs (depreciation and O&M).

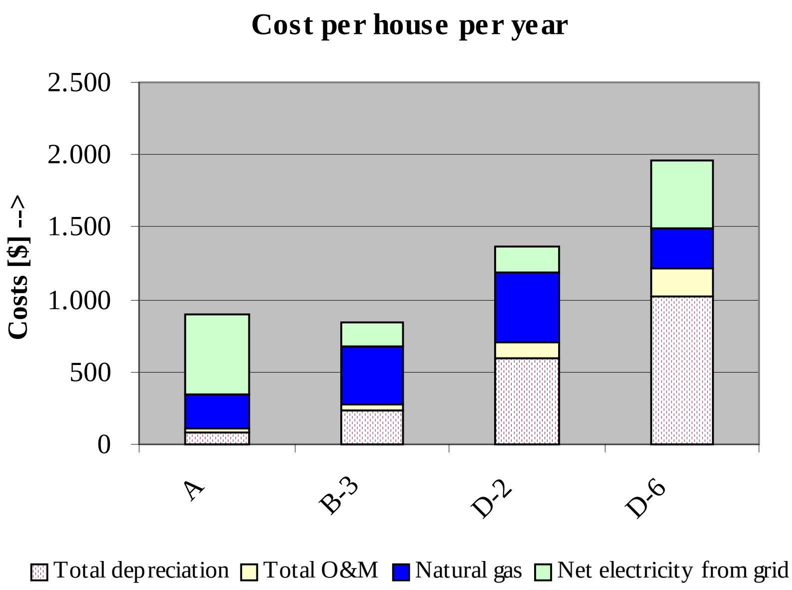

Figure 4.12 *Annual total costs per house per year for base-load fuel cell systems*

The breakdown of the annual depreciation cost is given in figure 4.13. It is clear that for the hydrogen systems the steam reformer and the heat pump are the units that determine the annual cost. Because of the electric heat pump in system D-6, a smaller steam reformer can be used than in D-2 since only hydrogen has to be produced for the fuel cell (in D-2, extra production for the hydrogen burner is required).

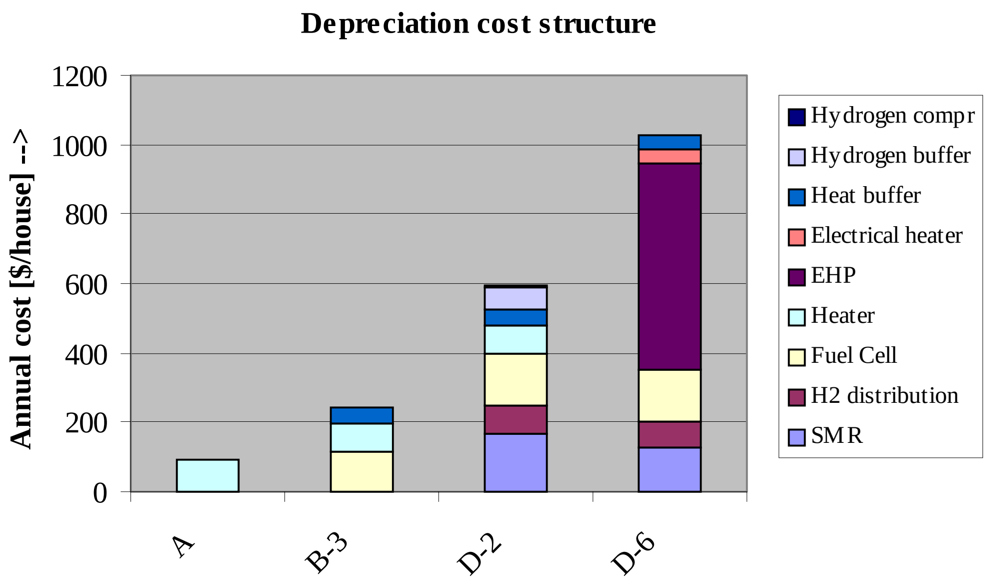

Figure 4.13 *Cost structure of the annual depreciation of four different districts*

Similar to the previous section, an overview for the total electricity and heat production is given in figure 4.14 and 4.15. Due to the lower thermal efficiency of the PEM fuel cell (40% versus 50% for the SOFC), less heat is lost. The electrical heater is only used to supply heat at peak times.

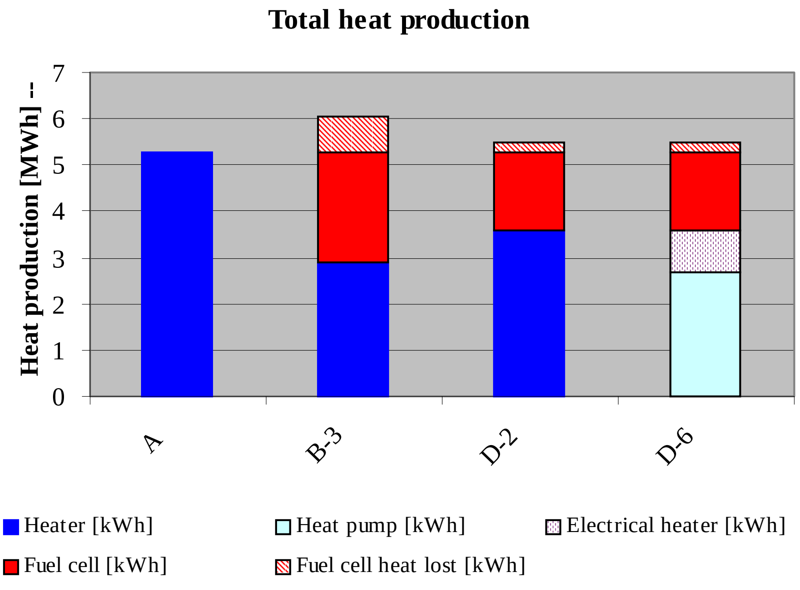

Figure 4.14 *Distribution of the total heat production. Hatched area's show the heat losses*

Installing a heat pump in the energy system influences the electricity demand. Since the heat pump converts electrical energy into thermal energy, the total demand increases and more electricity is purchased from the central grid. Because of the increased demand, a larger part of the produced electricity by the fuel cell can be used directly and less has to be exported (see figure 4.16). However, because electricity is more expensive than natural gas the energy costs will increase.

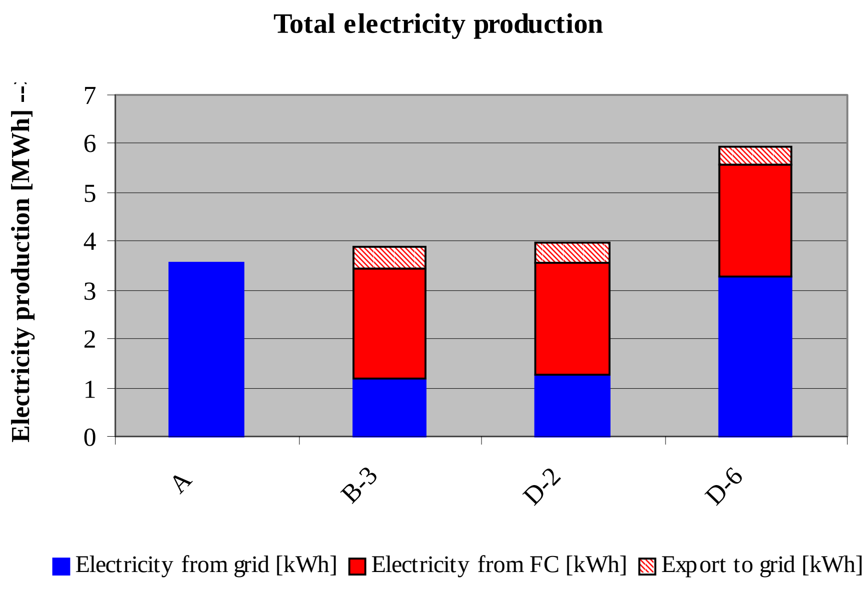

Figure 4.15 *Distribution of the total electricity production. Hatched area's show the electricity exported to the grid*

In the previous section, a comparison among the discussed systems was made on basis of total CO_2 emissions. The evaluated SOFC systems all lay in the second quadrant (see appendix B); both cost and CO_2 emissions were lower than the conventional system. This performance is mainly due to the simplicity of the system and the limited investment required by using a rather small fuel cell.

Because the hydrogen systems are more complex and therefore more expensive, it is not expected that de $\Delta\$/\Delta CO_2$ ratio stays in the second quadrant. From table 4.10 it can be concluded that this is indeed the case.
Not surprisingly, system D-2 is situated in the fourth quadrant, indicating that the system is more expensive but there is a reduction in the CO_2 emissions. The system is more expensive and produces more CO_2 than the conventional system. This higher CO_2 emissions are on the account of the hydrogen burner. In figure 4.16 the conventional system, D-2 and D-6 are schematically shown. A large part of the energy is lost at the reformer, which cannot be compensated by the burner. The heat pump, on the other hand, does compensate for this loss (see system D-6) resulting in a higher overall system efficiency.

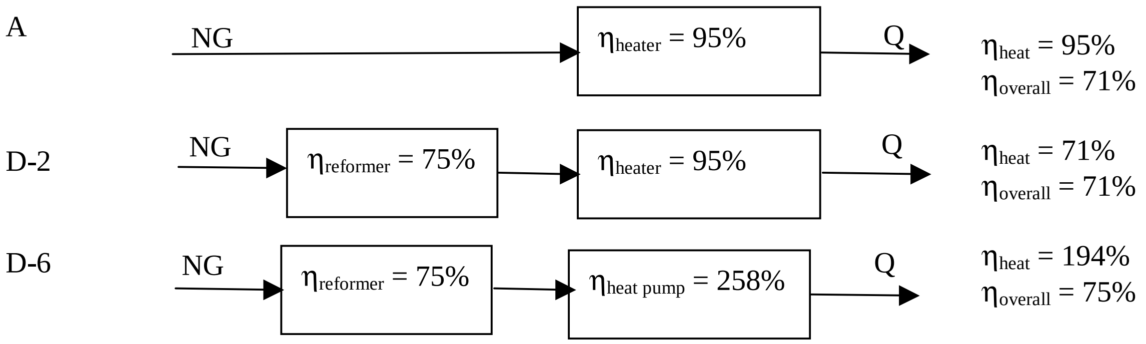

Figure 4.16 *Schematic representation of the overall system efficiency of two hydrogen systems (D-2 and D-16) versus the conventional system (A).*

The hydrogen district with the heat pump returns better results. The costs are high, but the CO_2 emissions are much lower than the conventional system.

Table 4.10 *Costs per kg* CO_2 *reduced with respect to the conventional system*

System	Configuration	Extra costs [$]	kg CO_2 reduced [kg CO_2]	Costs/kg CO_2 reduced [$\Delta\$/\Delta$kg CO_2]	Quadrant
B-3	SOFC + small heat buffer	-55	263	-0.21	2
D-2	PEMFC + small heat buffer + H_2 burner	469	-183	-2.57	4
D-6	PEMFC + small heat buffer +EHP + electrical heater	1072	106	10.14	1

The total heat losses in the system depend on the size of the fuel cell and the heat buffer. Here a 100-litre storage vessel for the heat buffer is assumed, which is reasonable for domestic purposes. The size of the fuel cell is therefore important. So far, the results have been discussed for the smaller fuel cell (0.32 kW/house). The amount of heat produced is rather low and can therefore be used completely in the district. From the results of system D-2 it can be concluded that using a hydrogen burner as an additional peak heater is not beneficial for the total CO_2-emissions. Since producing heat with the fuel cell is more efficient than using the hydrogen burner, using a larger fuel cell should be more efficient. For the base load system (system D-4) the energy flow diagram is shown in figure 4.17. This system is similar to system D-2, though with a larger fuel cell.

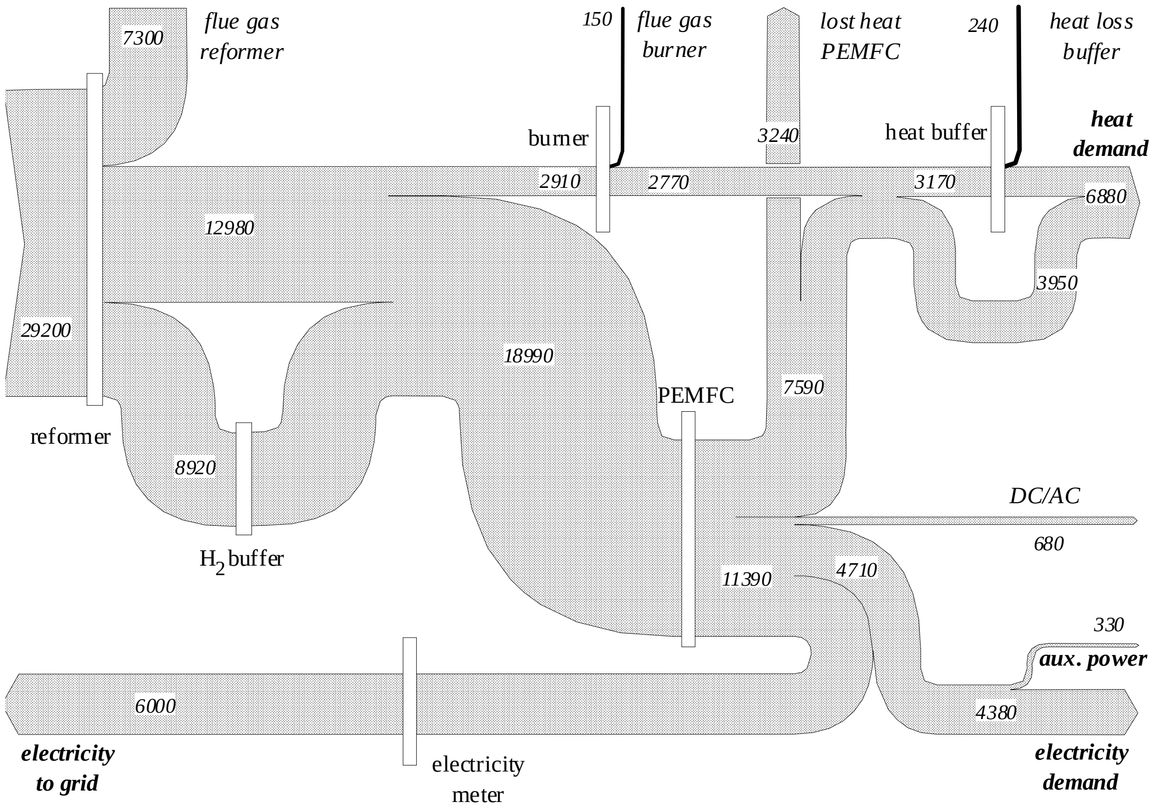

Figure 4.17 *Sankey diagram of system D-4 (numbers are shown in MWh/year)*

In the diagram the large heat losses by the fuel cell are clearly shown. For this case almost 43% of the produced heat in the fuel cell is disseminated. Excess heat produced by the fuel cell is disseminated when the demand is low. Since the fuel cell is operating continuously, electricity is still produced. The effect of co-generation is lost when the heat cannot be used and electricity is produced less efficient than the central power plant. Especially here where there is no net exchange with the grid and the electricity demand is fully covered by the fuel cell. Because of this lower electrical efficiency and the large fuel cell, the total system efficiency decreases as well. Here the efficiency amounts to 61%, 10 percent points lower than the conventional system. For the calculation of this efficiency it is assumed that the 6000 MWh does not have to be produced at the power plant, hereby saving 10909 MWh natural gas.

In table 4.11, the costs per kg CO_2 reduced with respect to the conventional system are shown for the discussed systems.

Table 4.11 *Costs per kg* CO_2 *reduced with respect to the conventional system*

System	Operation mode and size fuel cell	Configuration (excl. large heat buffer)	Extra costs [$]	kg CO_2 reduced [kg CO_2]	Costs/kg CO_2 reduced [$\Delta\$/\Delta$kg CO_2]	Quadrant
B-3		SOFC + small heat buffer	-55	263	-0.21	2
D-2	Base load (0.3 kW)	PEMFC + H_2 burner	469	-183	-2.57	4
D-4	Base load (1.0 kW)	PEMFC + H_2 burner	689	-325	-2.12	4
D-6	Base load (0.3 kW)	PEMFC +EHP + electrical heater	1072	106	10.14	1
D-8	Base load (1.0 kW)	PEMFC +EHP + electrical heater	1258	-210	-5.99	4

Summarising this paragraph the following conclusions can be drawn.

1. The total annual costs of the simulated hydrogen systems are higher than the natural gas systems
2. Important factors in the annual fixed costs are the steam reformer and the heat pump
3. The energy consumption for the natural gas and hydrogen systems with a small fuel cell is almost similar for all presented cases
4. The electricity demand is increased by the use of a heat pump. In this case more electricity from the fuel cell can directly be used in the district (without selling it).
5. Using a hydrogen burner as additional heating device appears to have a negative effect on the system efficiency. More hydrogen (and thus natural gas) is consumed resulting in a higher CO_2 emissions
6. Because of the high efficiency of the heat pump, the CO_2-emissions of the system with a heat pump is lower than the ones with a hydrogen burner.

4.2.2 Load-following systems

Until now, the differences between base load and load following operation of the PEM fuel cell have not been considered. If a system is using a CHP-unit the contribution to the total heat and electricity production is to be maximised. In this way, the contribution of the hydrogen burner or heat pump can be decreased. Increasing the fuel cell size results in a large loss of the produced heat if the cell is still operating in base load. To reduce this large heat loss, load following operation is considered.
In contrast to the base load fuel cell, the electrical efficiency of the load following fuel cells depends on the demand pattern. In part load operation the fuel cell has a higher electrical efficiency (η_e = max 66%) than in full load (η_e = 60%). Because the PEM fuel cells are heat load following, the maximum amount of heat is obtained at full load operation. To ensure that the maximum amount of heat is produced, the fuel cells operate primarily in base load. When the storage of the heat buffer is full, the fuel cell is switched to load following.
In table 4.12 & 4.13, the discussed hydrogen systems and their starting points are given. Four of the systems have a hydrogen burner as co-heater and the other four a heat pump and electrical heater.

Table 4.12 *Discussed systems*

System	Operation mode and size fuel cell	Configuration (excl. large heat buffer)
D-2	Base load (0.3 kW)	PEMFC + H_2 burner
D-4	Base load (1.0 kW)	PEMFC + H_2 burner
D-6	Base load (0.3 kW)	PEMFC +EHP + electrical heater
D-8	Base load (1.0 kW)	PEMFC +EHP + electrical heater
D-10	Load following (0.3 kW)	PEMFC + H_2 burner
D-12	Load following (1.0 kW)	PEMFC + H_2 burner
D-14	Load following (0.3 kW)	PEMFC +EHP + electrical heater
D-16	Load following (1.0 kW)	PEMFC +EHP + electrical heater

Table 4.13 *Starting points of PEMFC systems (base load and load following)*

		D-2 (BL)	D-4 (BL)	D-10 (LF)	D-12 (LF)	D-6 (BL)	D-8 (BL)	D-14 (LF)	D-16 (LF)
Fuel cell	kW_e/house	0.32	1.00	0.32	1.00	0.32	1.00	0.32	1.00
H_2 Heater	kW_e/house	8.8	8.07	8.8	8.2				
Electrical heater	kW_e/house					6.23	6.46	6.23	6.15
Heat pump	kW_e/house					3.00	2.31	3.00	2.31
Heat buffer	MJ/house	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7

BL = base load; LF = load following

Decreasing the heat losses of the system (and thus increasing the total efficiency) can be achieved by using a heat load following PEMFC. In figure 4.18 the control strategy of the heat buffer is shown.
This strategy shows high similarity with the base-load variant. To maximise the contribution of the fuel cell, the fuel cell is primarily operating in base load. The problem with the base-load system was the high waste of heat caused by operating at full load if the buffer is full. The load following mode is thus used when the buffer is almost full (70%). Within these boundaries (between 70% and 90% of the buffer volume) the fuel cell only produces the requested amount of heat, providing the size of the fuel cell is large enough. Similar to the base-load case, an additional heater is required to supply heat when the net demand is higher than the production. When the heat buffer is empty (15%), the heater is used to fill the buffer up to 30%.

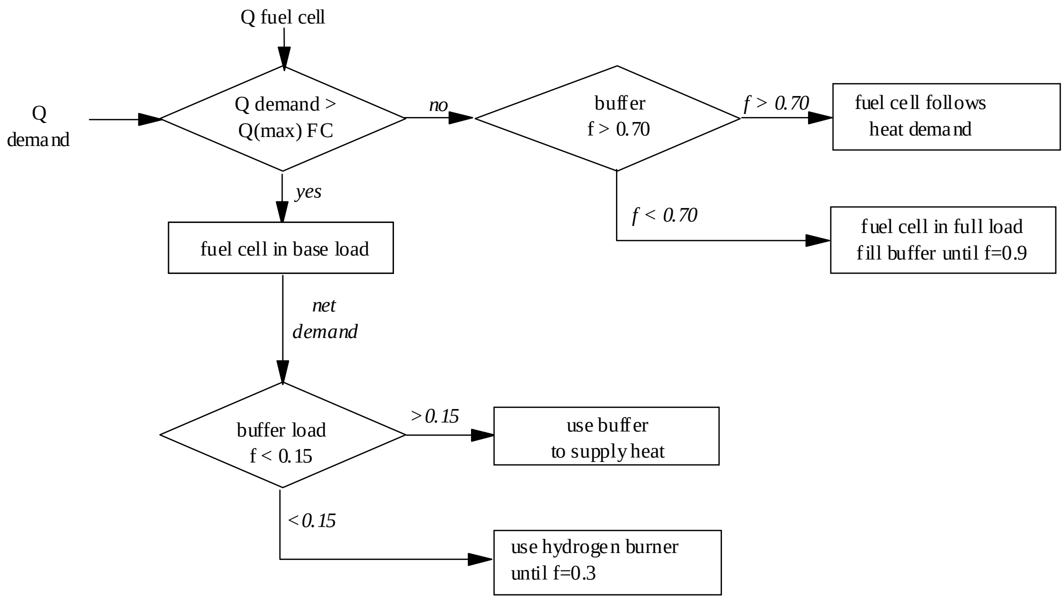

Figure 4.18 *Control strategy for a heat buffer in a base-load hydrogen system with a hydrogen burner*

In figure 4.19, the eight configurations are shown for the above mentioned systems. For small fuel cells, hardly any benefit is obtained by using another operating mode. This is because the heat losses are relatively small in these systems. The largest part of the hatched area's for those systems represent the standard heat loss of the heat buffer.
Load following operation does become more important with increasing fuel cell size. Comparing the systems D-4 with D-12 or D-8 with D-16, a much larger amount of heat is disseminated for the base load systems.

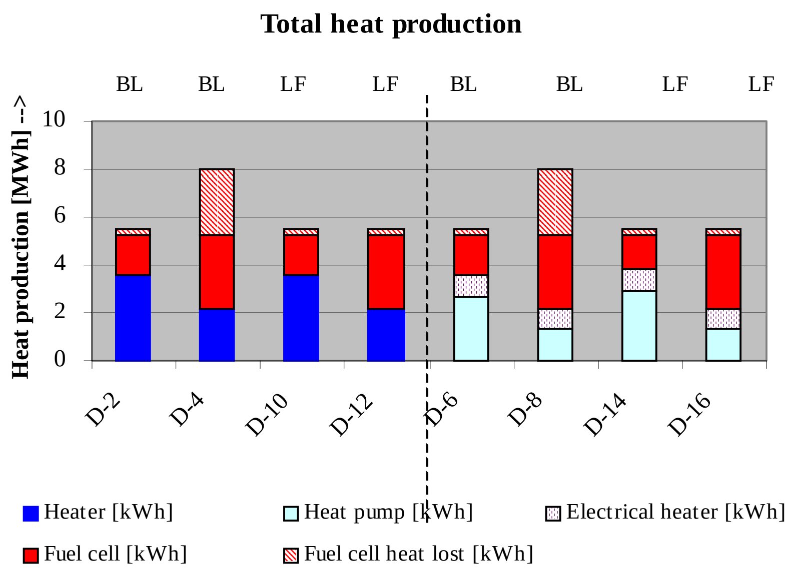

Figure 4.19 *Heat production base-load and load-following PEMFC's*

Concluding from figure 4.19, the operation mode is hardly of influence for the small fuel cells. All the produced heat can be used in the system and the heat losses can be directed to the heat buffer losses. In the further evaluation between base load and load following, attention is focused on the larger fuel cell systems (D-4, D-8, D-12 and D-16).

Similar to the heat production, figure 4.20 gives the electricity production for the four options. Larger fuel cells export a larger amount of electricity to the grid. Because the presented PEM fuel cells are heat load following, the fuel cells are switched from base load to load following when the heat buffer is full and therefore export less electricity to the grid than the base load fuel cells.

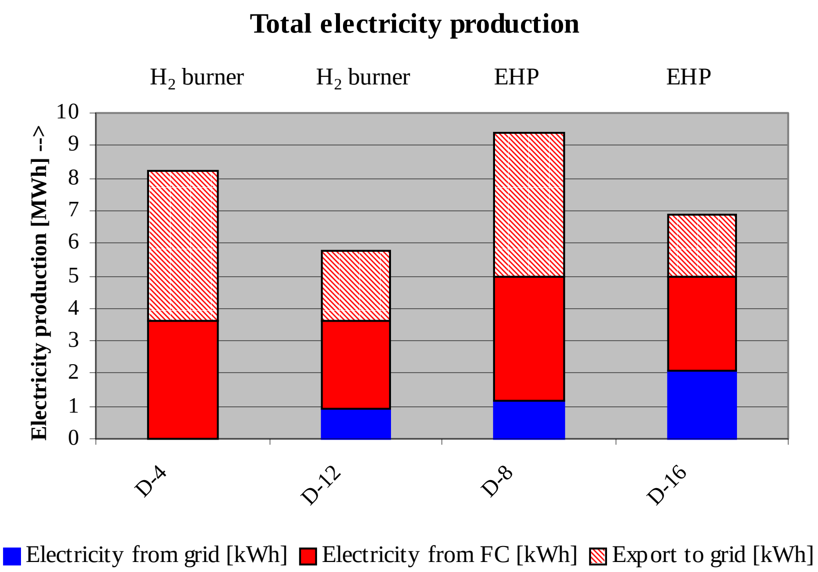

Figure 4.20 *Electricity production base-load and load-following PEMFC's (1kW$_e$)*

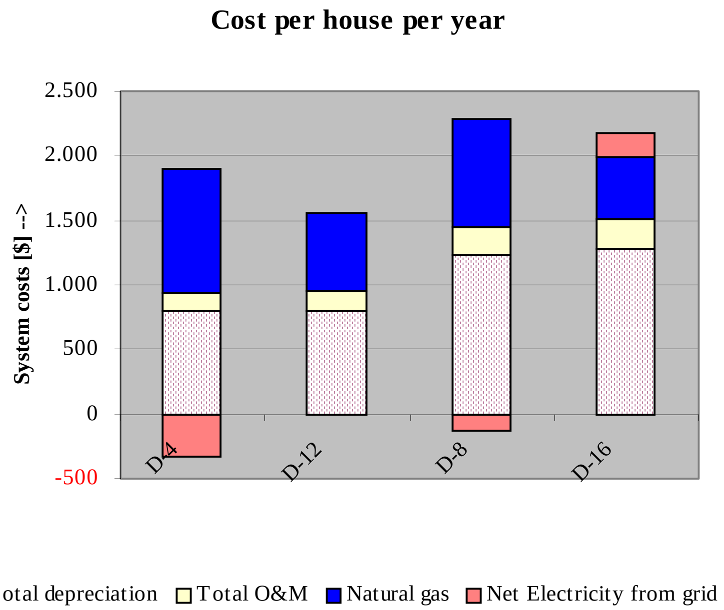

Figure 4.21 *Comparison 1 kW$_e$ base load versus load-following PEMFC's*

In figure 4.21, the system costs are given. All the discussed fuel cell systems in this section do export electricity to the grid. In figure 4.22, the energy costs for the systems D-2, D-4 and D6, D-8 are shown. It can be seen here that the large increase in natural gas costs is compensated by the decrease in electricity costs.

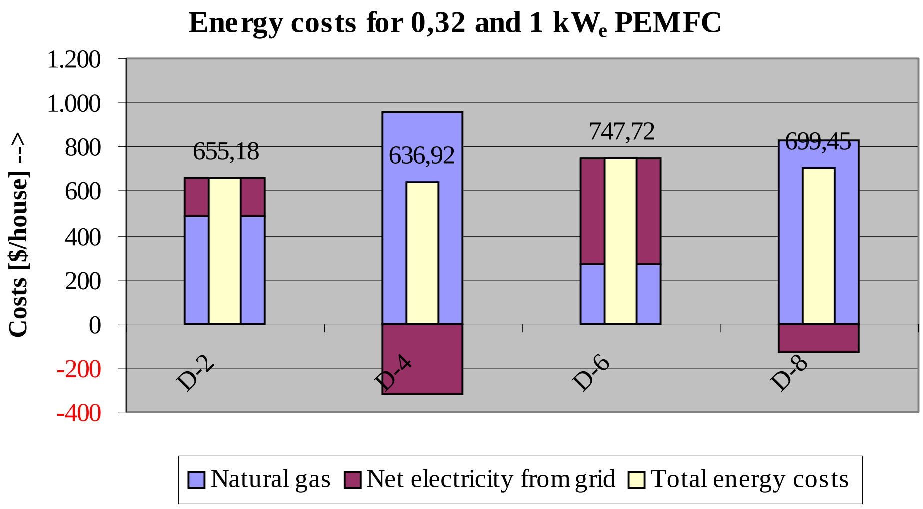

Figure 4.22 *Cost build up for the total energy costs for 1 kW$_e$ PEM fuel cell systems*

For the systems with a hydrogen burner as a co-heater, a larger fuel cell is not beneficial for the base load options. In order to operate continuously, the hydrogen consumption for the larger fuel cell system is higher. This higher demand automatically involves higher hydrogen production cost because a larger reformer is required to cover the demand. As a consequence the natural gas consumption increases also. Although for the 1kW fuel cell systems a larger reformer is required, the increase in capacity is for that reason lower than for the base load cases.

For the other four systems, where co-heating is obtained via a combination of a heat pump and an electrical heater, the capital costs are higher. Because the energy consumption of these systems is

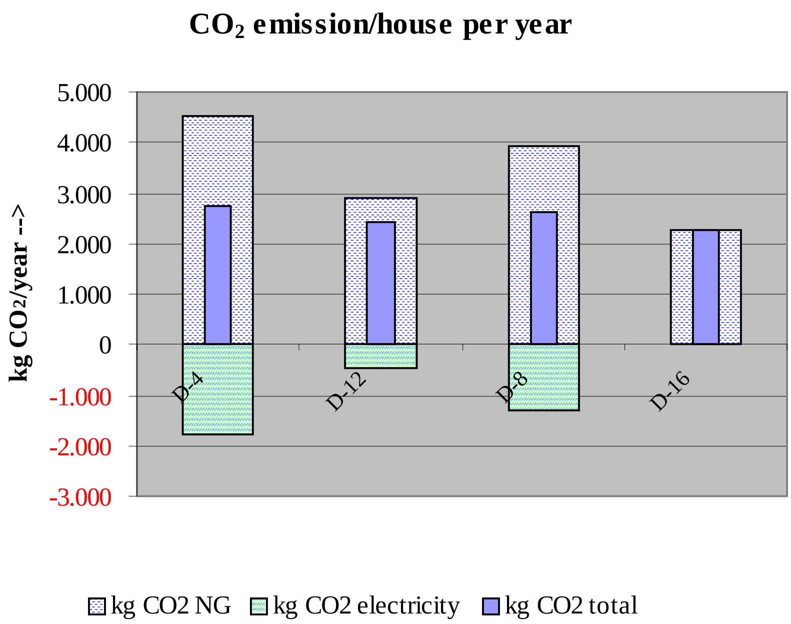

Figure 4.23 *Carbon emissions of base load and load following PEMFC systems*

more or less similar, the contribution of the energy cost to the total cost is consequently lower (29% versus 41% for the H_2 burner systems).
In figure 4.23, the total CO_2-emissions for the discussed systems is shown. Most of the 1 kW PEMFC systems (D-4, D-12 and D-8) have a negative CO_2-emissions. Because the net exchange of electricity with the grid is negative, the production is higher than the demand, less electricity can be produced in the gas fired power plant. The CO_2 reduction is then shifted from the district to the central power plant. Still, these systems have higher CO_2-emissions since producing electricity with the fuel cell while disseminating the heat is less efficient than a conventional power plant.

In the previous section, the Sankey diagram was shown for system D-4, a PEMFC base load system with a 1 kW/house fuel cell. To be able to compare the results, the same diagram is shown in figure 4.24 for the load following system D-12.
The fuel cell heat losses have been reduced to zero in this system. The only heat losses that occur in the system are the losses because of the heat buffer. The net hydrogen demand in this operation mode is lower than the base-load case. As a consequence a smaller reformer can be used to cover the H_2-demand. This reduces the consumption of the primary energy source and increases the overall efficiency to 70%.

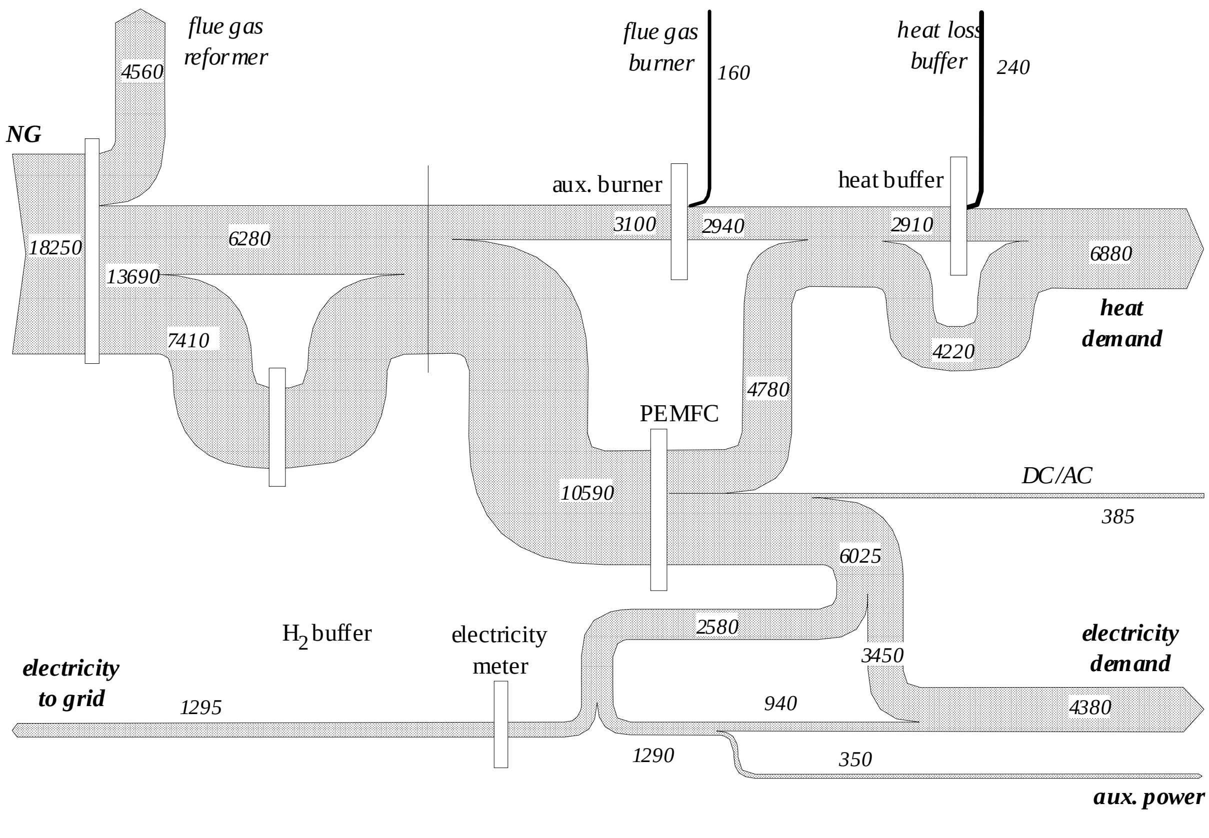

Figure 4.24 *Sankey diagram of system D-12 (numbers are shown in MWh/year)*

The calculated $\Delta\$/\Delta CO_2$ ratio is shown in table 4.14. Concluding from these data, the load following systems with a heat pump are the most attractive with respect to the $\Delta\$/\Delta CO_2$ ratio.

Table 4.14 *Costs per kg* CO_2 *reduced with respect to the conventional system*

System	Operation mode and size fuel cell	Configuration (excl. large heat buffer)	Extra costs [$]	kg CO_2 reduced [kg CO_2]	Costs/kg CO_2 reduced [Δ$/Δkg CO_2]	Quadrant
D-2	Base load (0.3 kW)	PEMFC + H_2 burner	469	-183	-2.57	4
D-4	Base load (1.0 kW)	PEMFC + H_2 burner	689	-325	-2.12	4
D-6	Base load (0.3 kW)	PEMFC +EHP + electrical heater	1072	106	10.14	1
D-8	Base load (1.0 kW)	PEMFC +EHP + electrical heater	1258	-210	-5.99	4
D-10	Load following (0.3 kW)	PEMFC + H_2 burner	490	-222	-2.20	4
D-12	Load following (1.0 kW)	PEMFC + H_2 burner	667	8	87.63	1
D-14	Load following (0.3 kW)	PEMFC +EHP + electrical heater	1148	101	11.37	1
D-16	Load following (1.0 kW)	PEMFC +EHP + electrical heater	1281	142	8.99	1

BL = base load; LF = load following

Summarising this paragraph the following conclusions can be drawn.

1. For small fuel cells no benefits are obtained by using another operating mode
2. The base load operating systems with a large fuel cell emit a large part of the produced heat; for base-load systems the use of large fuel cells is not attractive.
3. The excess production of both heat and electricity are much smaller in the heat load following systems
4. Exporting electricity is in most cases unattractive
5. Using a hydrogen burner as an additional heater, larger reformers are required. The size of the reformer can be decreased by operating in base load and/or using a heat pump instead of the burner
6. The most attractive option is to use a small PEMFC operating in load following with a heat pump as additional heating device

4.2.3 Performance of the PEMFC systems versus the all-electric system

In the all-electric and some of the hydrogen districts, a heat pump is used to supply partly or completely the district heat demand. In this section, these systems are compared in terms of cost and emissions. In table 4.15 & 4.16, the discussed systems and their starting points are given.

Table 4.15 *Discussed systems*

System	Configuration (excl. heater)
C-3	EHP + electrical heater
D-6	PEMFC (BL) + large heat buffer +EHP + electrical heater
D-14	PEMFC (LF) + large heat buffer +EHP + electrical heater

Table 4.16 *Starting points of the systems: conventional system, C-3,D-6 &D-14*

		Conventional system	C-3	D-6 (BL)	D-14 (LF)
Fuel cell	kW_e/house			0.32	0.32
Heater	kW_e/house	10			
Electrical heater	kW_e/house		6.15	6.23	6.23
Heat pump	kW_e/house		3.08	3.00	3.00
Heat buffer	MJ/house			7.7	7.7

BL = base load; LF = load following

The results of the calculations are shown in figure 4.25 and 4.26. The cost bars in figure 4.25 are each build up of the depreciation, operating and maintenance (O&M) and total energy costs. The major contribution to the fixed costs is caused by the heat pump, which has its effect on the depreciation and O&M costs.
The costs of the all-electric district are lower, since no investments have to be made for hydrogen production and storage.

The overall efficiency of the all-electric system is higher than the hydrogen systems, where a large part of the efficiency is lost at the production of hydrogen. The total CO_2-emissions of the H_2 systems is lower than the conventional but higher than system C-3. In table 4.17, the extra costs with respect to the conventional system, which have to be made for the extra CO_2-emissions reductions are given.

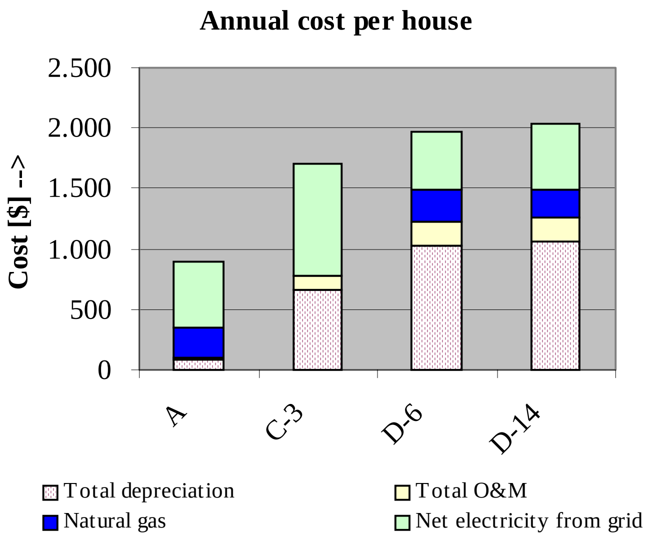

Figure 4.25 *Total annual costs for systems with a heat pump and an electrical heater*

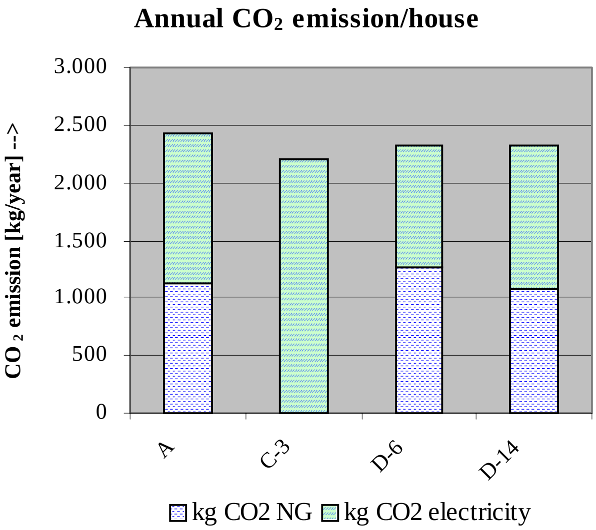

Figure 4.26 *Total annual CO_2-emissions for systems with a heat pump and an electrical heater*

Summarising this paragraph the following conclusions can be drawn.

1. Heat pump is an expensive device and has a large influence on the total capital costs
2. The absence of devices for hydrogen production and storage make the all-electric system cheaper than the hydrogen systems
3. The overall efficiency for the all-electric system is higher than the hydrogen system. A large part of the energy is lost at the conversion from natural gas to hydrogen (reformer)

Table 4.17 *Costs per kg* CO_2 *reduced with respect to the conventional system*

System	Configuration (excl. heater)	Extra costs [$]	kg CO_2 reduced [kg CO_2]	Costs/kg CO_2 reduced [Δ$/Δkg CO_2]	Quadrant
C-3	EHP + electrical heater	819	221	3.70	1
D-6	PEMFC (BL) + large heat buffer +EHP + electrical heater	1072	106	10.14	1
D-14	PEMFC (LF) + large heat buffer +EHP + electrical heater	1148	101	11.37	1

BL = base load; LF = load following

4.3 Summary: Costs and emissions overview systems

An overview of the CO_2 emissions and the total annual costs of the discussed systems is given in table 4.18.

Table 4.18 *Overview emissions and cost of the simulated systems*

Systems	Total CO_2 emissions [kg CO_2/house.year]	Total system costs [$/(house*year)]	Costs/kg CO_2 reduced [Δ$/Δkg CO_2]	Quadrant
A	2422	893	-	
B-1	2306	828	-0.56	2
B-2	2185	824	-0.29	2
B-3	2159	838	-0.21	2
B-4	2413	955	7.12	1
B-5	2351	972	1.11	1
B-6	2334	988	1.08	1
C-3	2201	1712	3.70	1
D-2	2605	1362	-2.57	4
D-4	2747	1582	-2.12	4
D-6	2316	1965	10.14	1
D-8	2632	2151	-5.99	4
D-10	2644	1383	-2.20	4
D-12	2414	1560	87.63	1
D-14	2321	2041	11.37	1
D-16	2280	2174	8.99	1

5 RESULTS ADVANCED HYDROGEN OPTIONS

The efficiency in the configurations in the previous chapter, is limited mainly by two factors. On one hand there are economic restrictions. The second limitation is technical: the calculations shown that a critical point in all the hydrogen systems is the conversion step from natural gas to hydrogen. With the selected 75% efficiency, the margin for the hydrogen systems to perform better than the conventional system is limited. In this chapter first the potential efficiency increase which can be obtained by cost reduction is considered. Subsequently a two solutions to the technical limitation of the losses in the reformer are considered: increasing the efficiency of the reformer (section 5.2) and using part of the heat produced in the reformer (section 5.3).

5.1 Increasing efficiency by reducing cost

The high cost estimates for the equipment in the hydrogen system limit the efficiency. For example, the assumed cost of the fuel cell has led to the selection of small fuel cells (0.32 and 1 kW). Increasing the fuel cell size will increase efficiency. Similarly the size of the heat pump has been reduced by using an electrical heater for peak loads. Again a penalty is paid in the form of a lower efficiency. Therefore, by reducing the cost of the components the trade-off between investment and efficiency changes. In other words it will be possible to increase the efficiency by reducing the mayor cost components.

To illustrate this point the CO_2 reduction has been calculated for larger fuel cell size using a the PEMFC combined with a hydrogen burner (systems D-10 & D-12) . The results are shown in figure 5.1. If the fuel cell is 0.32 kW, the hydrogen burner delivers slightly more than 70% of the heat and the remaining 30% is delivered by the fuel cell. At 1 kW stack size, the contribution of the burner decreases to 43%. For this size the system emits the same amount of CO_2 as the conventional reference system (decrease CO_2 emission = 0%). To reduce the emissions the fuel cell size should be larger. The figure shows the emission reduction increases to 13% (compared to the conventional reference system) at 5 kW stack size.

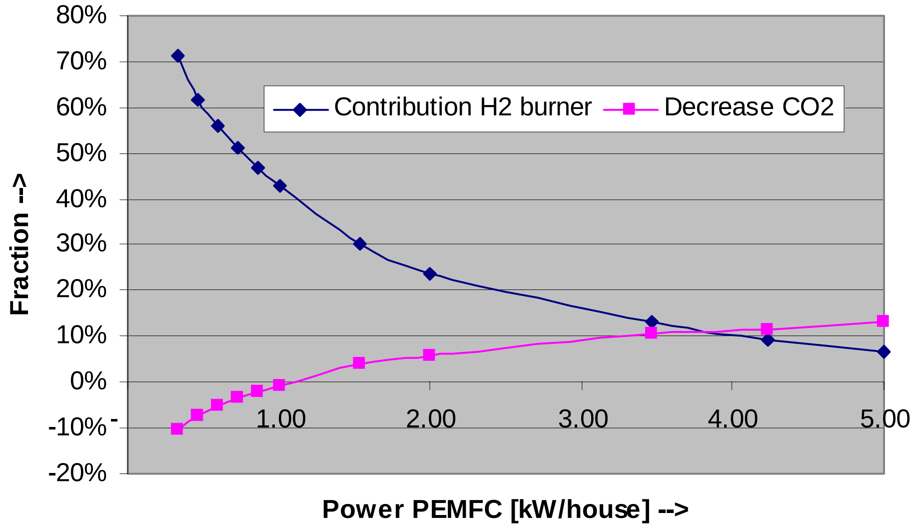

Figure 5.1: *Influence of the stack size on the reduction of the CO_2 emission compared to the conventional reference system*

Another example is the electrical heater which is used to reduce investment cost for the electrical heat pump. Figure 5.2 shows the CO_2 emissions for the hydrogen system with a heat pump (D-16) with an electrical heater and without. In the latter case (D-16/EHP), the CO_2 emission is 14% lower than the reference case, which is a substantial improvement over the 6% calculated for the system with a electrical heater (D-16/EHP+EH).

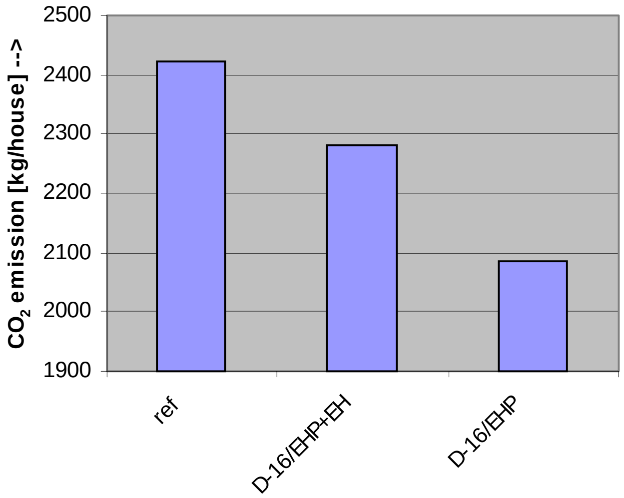

Figure 5.2: *Influence of the electrical heater(EH) on the system with an electrical heat pump (D-16 / EHP)*

Both examples illustrate that the potential CO_2 emission for the technology is much higher than indicated in the previous chapter, but strongly impacted by the investment cost.

5.2 Influence of the steam reformer efficiency

Based on the analysis of the results in the previous chapter, it is clear that the performance of the hydrogen systems can be improved with a higher reformer efficiency. A more efficient conversion reduces the consumption of the primary energy source and consequently the total CO_2 emissions. With improved heat integration and other techniques, reformer efficiencies of up to 80% (LHV) are achievable. When coupled to a gas turbine pre-heater, an overall efficiency of 85% may be achievable. Because of the potential benefits of costs and CO_2-emissions this option has been considered as well. In this section this effect is shown for system D-16 (see table 5.1).

Table 5.1 *Discussed systems*

System	Configuration (excl. heater)
C-3	EHP + electrical heater
D-16	PEMFC +EHP + electrical heater (η_{CH4-H2} ref. = **75%**)
D-16(80)	PEMFC +EHP + electrical heater (η_{CH4-H2} ref. = **80%**)
D-16(85)	PEMFC +EHP + electrical heater (η_{CH4-H2} ref. = **85%**)

In figure 5.3 the total CO_2-emissions of system D-16 with respectively a SMR efficiency of 75%, 80% and 85% are shown. The data for the conventional system and the all-electric system are shown in respectively the first two bars. As is seen in the figure (the last two bars), an efficiency increase of 5% reduces the CO_2-emissions with 137 kg (from 2280 kg to 2143 kg), which is a 6% reduction on an annual base. For the reformer operating at 85% efficiency these values are 268 kg and 12% respectively.

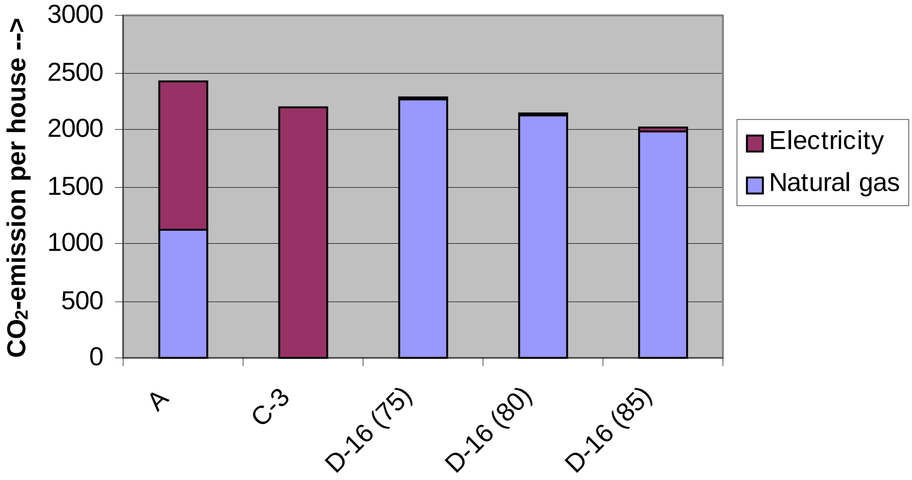

Figure 5.3 *CO_2-emissions for PEMFC systems*

The relative contribution of the electricity import from the grid to the total CO_2-emissions decreases with the presence of the fuel cell in the system. The electricity import from the grid in the conventional system contributes for 48% to the total CO_2-emissions. In the two fuel cell systems, represented by the last two bars this contribution reduces to 0.9%.
In table 5.2, the $\Delta\$/\Delta CO_2$-ratio is shown for the presented systems. A five percent efficiency increase for the reformer results in a fifty percent lower ratio.

Table 5.2 *Costs per kg* CO_2 *reduced with respect to the conventional system*

System	Configuration (excl. heater)	Extra costs [$]	kg CO_2 reduced [kg CO_2]	Costs/kg CO_2 reduced [$\Delta\$/\Delta$kg CO_2]	Quadrant
C-3	EHP + electrical heater	819	221	3.70	1
D-16	PEMFC +EHP + electrical heater (η_{CH4-H2} ref. = **75%**)	1281	142	**8.99**	1
D-16(80)	PEMFC +EHP + electrical heater (η_{CH4-H2} ref. = **80%**)	1252	279	**4.49**	1
D-16(85)	PEMFC +EHP + electrical heater (η_{CH4-H2} ref. = **85%**)	1263	411	**3.07**	1

5.3 Utilisation of the reformer heat

The reformer in the hydrogen systems converts natural gas to hydrogen with an efficiency of 75% (see table 5.3). This means that 25% of the energy input is lost at this conversion step and influences the total system efficiency. With this, it is difficult for the hydrogen systems to compete with the natural gas systems in terms of efficiency. The feasibility of hydrogen systems can therefore be improved by finding a way to utilise the reformer heat. Because of transport, convection/radiation losses and temperature differences of the waste gasses, it is not possible to use all the heat of the reformer. It is assumed that the exported steam can be used for the heat distribution, which is approximately 15% of the total energy output. In figure 5.4, a schematic representation of the split district is given. Part A consists of 910 houses and the energy (heat and electricity) is supplied by a 2 kW fuel cell primarily. The heat in part B (390 houses) is supplied by a heat grid.

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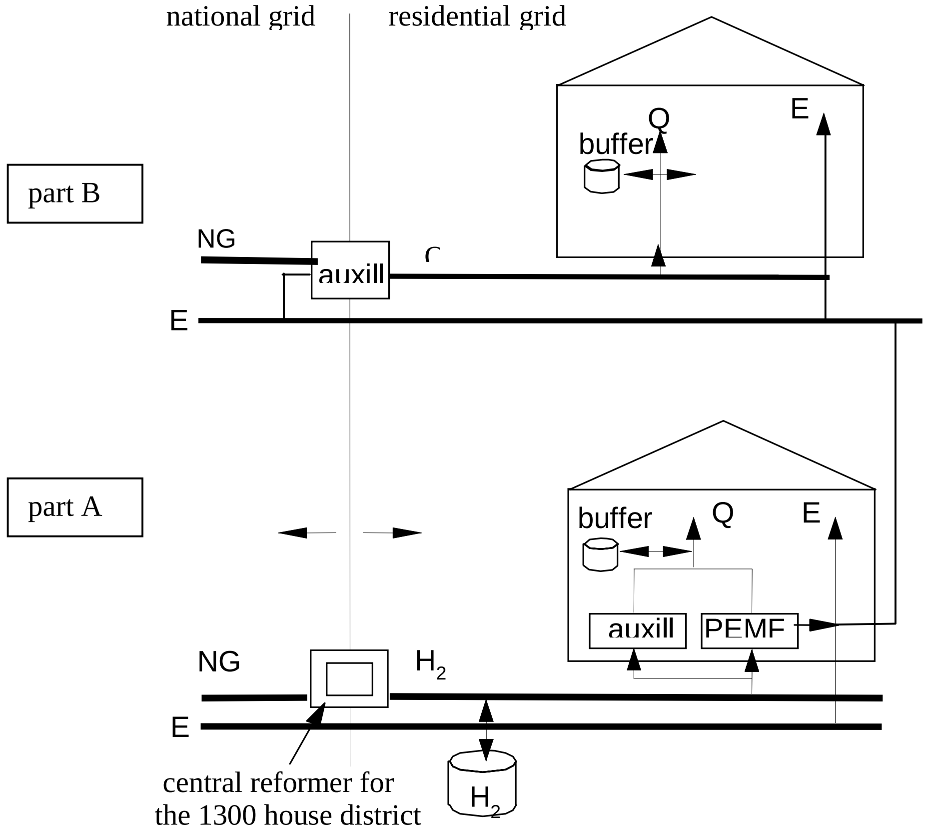

Figure 5.4 *Schematic representation of the district with hydrogen and heat as energy carriers*

If the heat of the reformer is to be used in the district, a heat distribution grid is required. However, the amount of generated heat by the reformer is not sufficient to supply the complete district with heat. The district has been divided in two separate parts (A and B) each with a different energy system. Section A uses a hydrogen grid similar to the system in the previous section and section B uses the heat grid which if fed by the reformer and by an additional source for heat. In table 5.3, the units for the complete districts are shown.

Table 5.3 *Simulated systems*

System	Part	Distri-bution	PEMFC	Central Electric heat pump	Central NG burner	Domestic H_2 burner	Domestic heat buffer	Domestic H_2 buffer
1	A	H_2	x			x	x	x
	B	heat			x		x	
2	A	H_2	x			x	x	x
	B	heat		x	-		x	

LF = load following

Part A

Part A resembles the previously discussed hydrogen systems. Hydrogen is produced by the centralised steam reformer and transported to this part. The hydrogen is converted with PEM fuel cells to heat and electricity and an additional hydrogen burner is installed as co-heater to cover peaks in the demand pattern. The fuel cells are placed in each house and are heat load following. Because co-generation of heat and power is more efficient than separate production, the fuel cells are deliberately oversized. The excess produced electricity that cannot be used in this part is exported to the part B of the district to cover the demand. Extra required electricity is purchased from the grid.

Part B

The energy system of part B is different from part A. Heat is supplied by a heat distribution grid and the required amount is produced centrally by two separate sources. Primarily, a part of the heat of the steam reformer is used. Secondly, a centralised natural gas heater or heat pump (see next section) produces the additional required heat. In the houses only a heat buffer is available to store the heat from the grid.
The electricity is provided by the fuel cells in part A and the remaining is purchased from the central grid.

Heat pump

Although a lot of experience is available in the heat pump field for domestic purposes, hardly any experience is available for large centralised heat pumps. In the Netherlands no such systems exist, but in Scandinavia a limited amount of megawatt heat pumps (electricity driven) are present. Near Gotheborg, Sweden, a heat pump district heating plant is build with four heat pumps having a total power of 160 MW. One of these pumps produces 55MW of thermal energy under good conditions and is known to be world's largest heat pump. The COP value of this pump is 3.0 [10].
Because a centralised heat pump is used in one of the systems, a COP-value of 3.0 is assumed here as well.

The number of houses that are connected to a heat grid is determined by the size of the reformer. Based on the simulated hydrogen systems, a reformer that converts approximately 2500 kW of natural gas is required for the demand patterns of the district. On an annual basis the reformer produces 2000 MWh of thermal energy. With respect to the total heat demand of 6879 MWh, this is approximately 30%. Based on this, it is assumed that 390 houses (or 30% of the district) are supplied with heat from a central heat grid. In the next two sections two systems (E-1 and E-2) are discussed.
A natural gas heater (E-1) or an electric heat pump (E-2) supplies extra heat for the heat grid.

5.3.1 Split district with a centralised natural gas co-heater

The advantage of dividing the district in two parts is that the excess produced electricity in part A can be used in part B. This enables the use of a relative large fuel cell in part A, that produces a large part of the heat demand. The total efficiency increases because electricity is produced in a more efficient way than a conventional power plant (all the produced heat can be stored). In figure 5.5, a Sankey diagram is shown for the divided district with a 2 kW fuel cell/house.

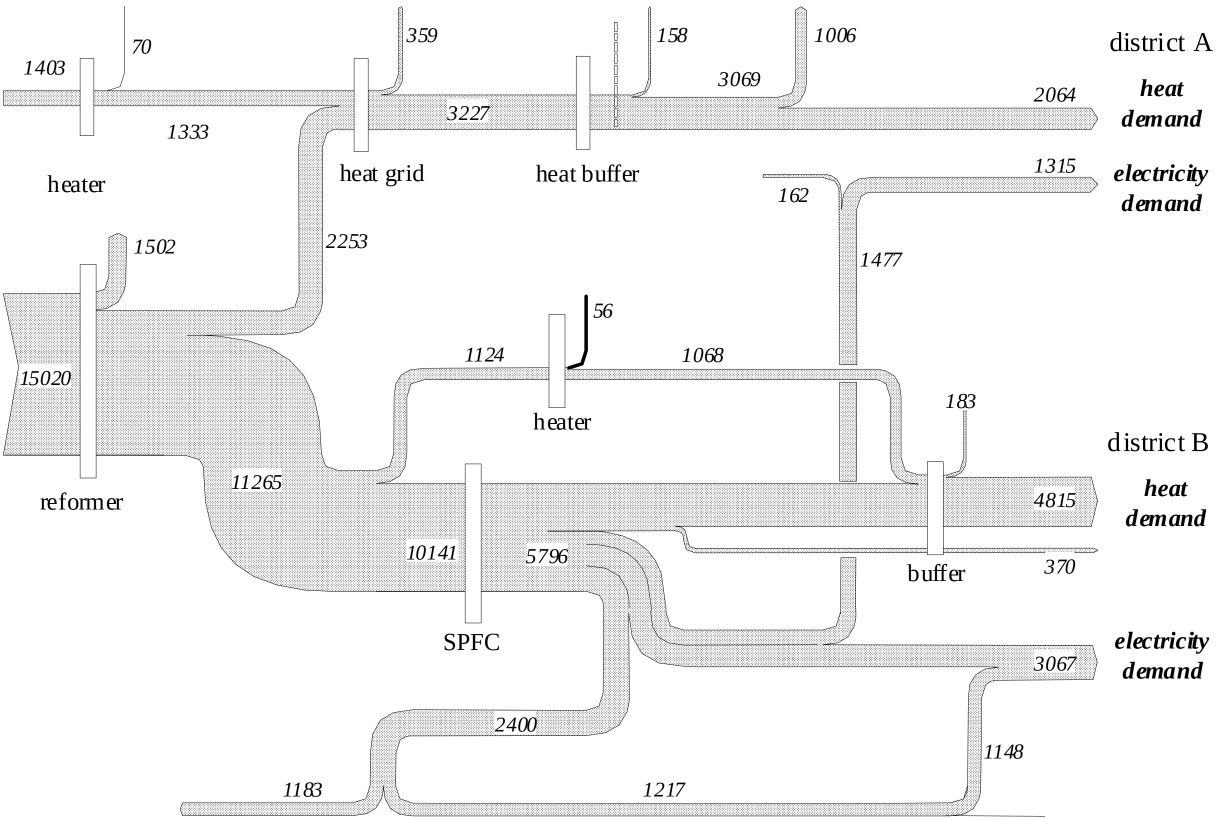

Figure 5.5 *Sankey diagram of the split district*

To reduce the costs of the system, a hydrogen burner is used in part A to function as additional heater. The contribution of the heater to the total heat production is approximately 30%, the remaining is produced by the fuel cell. This contribution is 13% lower compared to system D-12, the all hydrogen system with a hydrogen burner as additional heater. Using a larger fuel cell (2 kW/house instead of 1 kW/house) therefore reduces the contribution of the hydrogen burner and increases the efficiency of the system. Apart from this, almost 59% of the produced electricity by the fuel cell is exported to part B of the district, where it is used to cover the electricity demand of that part. The net exchange with the grid is therefore much lower than the all-hydrogen systems (9% is exported to the grid in E-1 versus 24% in system D-12).

Part B is connected to a heat grid where a part of the heat generated by the reformer is used to supply the heat. Losses in this part are mainly accountable to the 10% in the heat grid. Other losses are buffer losses (5%) and heat from the reformer that cannot be used or stored in the buffer (23%). It is assumed here that a buffer containing 400 litres of water is placed in each house in part B. Assuming that the returned amount of electricity saves the production at the gas-fired power plant, the overall efficiency can be calculated and is 80%.

It is interesting to compare the divided district E-1 with the three of the previously discussed systems: system B-3, D-12 and D-16. In table 5.4 and 5.5, four systems are given.

Table 5.4 *Discussed systems*

System	Configuration
B-3	0.32 kW_e SOFC + large heat buffer
D-12	1 kW_e PEMFC (LF) + H_2 heater
D-16	1 kW_e PEMFC (LF) + heat pump
E-1	split district + NG heater

LF = load following

Table 5.5 *Starting points of systems B-3, D-12, D-16 and E-1*

		B-3	D-12	D-16	E-1
Fuel cell	kW_e/house	0.32	1.00	1.00	2.00
H_2-heater	kW_{th}/house		8.20		9.07
CH_4-heater	kW_{th}/house	8.85			10.26
Electrical heater	kW_e/house			6.15	
Heat pump	kW_{th}/house			2.31	
Heat buffer	MJ/house	7.70	7.70	7.70	8.24 (A)
					16.67 (B)
SMR	MW_{NG}		4.50	2.30	5.00

Of the discussed districts with a single energy carrier (natural gas, electricity or hydrogen), system B-3 is the most economic and efficient energy system. It is therefore interesting to compare system E-1 with this system. In fact, the feasibility of the advanced system E-1 depends on the performance with respect to this natural gas based alternative. The systems D-12 and D-16 are more or less similar to part A in the system and makes comparison easier. Benefits of splitting the (hydrogen) district can be discerned clearly.

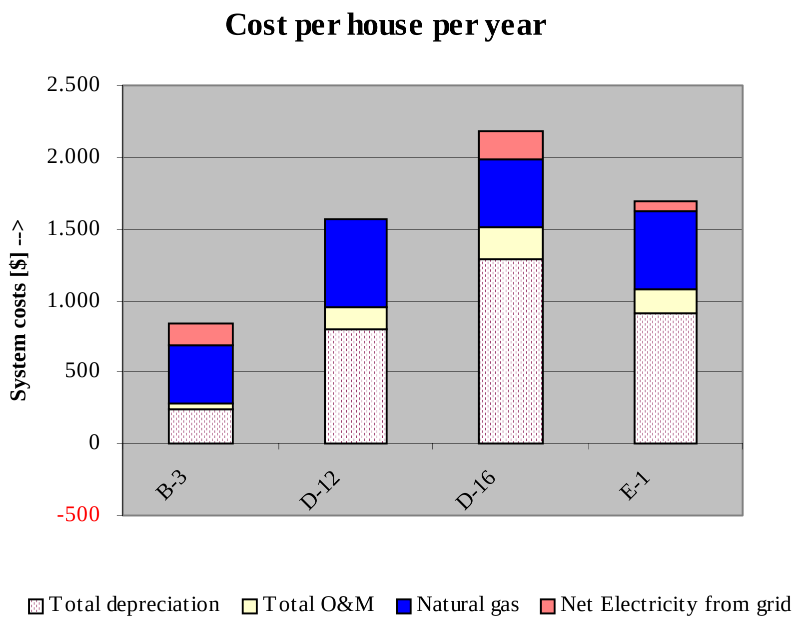

Figure 5.6 *Total system cost for the systems B-3, D-12, D-16 and E-1*

Like in the previous paragraph, the systems are compared on the total costs of the system and the total CO_2-emissions. In figure 5.6, the costs of the mentioned systems are shown.
Due to the simplicity of the natural gas district, system B-3 is the cheapest of all. Interesting is the rather large reduction in costs with respect to the hydrogen systems. System D-16 is 30% more expensive than E-1, while system D-12 is slightly cheaper. The largest part of the cost in system D-16 is for the account of the heat pump in each house. Dividing the districts means that the total heat demand in part B is split accordingly. In contrast to the systems D-12 and D-16, a larger fuel cell is used in part B. The net hydrogen demand is therefore higher and a larger reformer should be used to supply the necessary hydrogen. The larger reformer causes the slight change in the capital and energy costs. Due to the more efficient use of the produced electricity of the fuel cell, less electricity is exported to the grid.
Figure 5.7 shows the total CO_2-emissions. A remarkable result is the emissions of the divided district, which is with 2210 kg CO_2 per house per year the best performing system. Although all shown system configurations (except D-12) have a lower CO_2-emissions than the conventional system (2422 kg CO_2/house per year), it is clear that better results are obtained by dividing the district. Using the heat of the reformer and excess electricity of the fuel cell in a part of the district does reduce the energy consumption. Less natural gas for extra heat and hydrogen has to be converted. Next to that, the electricity production by using large fuel cells is more efficient than a conventional power plant (providing the produced heat can be used).
The total system efficiency, which can be defined as the quotient of the total energy required (heat + electricity) and the total energy (NG) input, is for system E-1 10% higher than the conventional system and 6% higher than D-16. (E-1= 78%; D-16 = 75%; ref = 71%; B-3 = 80%)

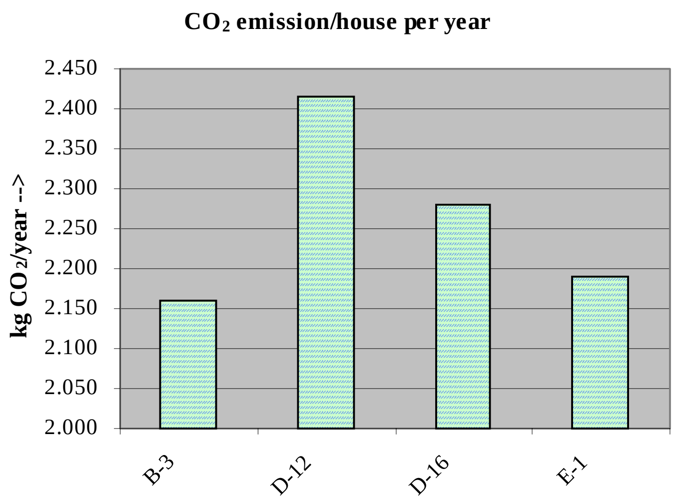

Figure 5.7 *Total CO_2-emissions for the systems B-3, D-12, D-16 and E-1*

A better indication for the performance of system E-1 is given by the $\Delta\$/\Delta CO_2$ ratio, which is shown in table 5.6. For the hydrogen systems, E-1 is the best choice; a large amount of CO_2 is reduced against relatively low extra costs.

Dividing the district in two parts influences the synergy of the system. The total system cost of E-1 slightly increase compared to system D-12, but the CO_2-emissions reduces substantially. Generating electricity in one part of the district and using it in the other part before exporting it to the grid is attractive. The $\Delta\$/\Delta CO_2$ ratio decreases from -48.58 (D-12) to 3.44 \$/kg (E-1).

Table 5.6 *Costs per kg* CO_2 *reduced with respect to the conventional system*

System	Configuration	Extra costs [$]	kg CO_2 reduced [kg CO_2]	Costs/kg CO_2 reduced [Δ$/Δkg CO_2]	Quadrant
B-3	0.32 kW_e SOFC + large heat buffer	-55	263	-0.21	2
D-12	1 kW_e PEMFC H_2 heater	671	-14	-48.58	4
D-16	1 kW_e PEMFC + heat pump	1281	142	8.99	1
E-1	split district + NG heater	799	232	3.44	1

Sensitivity analysis system E-1

Because the reformer is hydrogen demand following, the heat produced cannot be used in the district at all times. As can be seen in the figure almost 45% of that heat is lost (the natural gas co-heater is heat load following). Especially in the summer time, when the heat demand is relatively low and the hydrogen demand still exists, a large part of the reformer heat is lost. Different parameters have been varied to determine how the utilisation of the reformer heat can be increased

Size of the steam methane reformer versus the size of the hydrogen buffer

Between the steam reformer and the hydrogen buffer a certain balance exists. The reformer produces hydrogen and fills the buffer. When the buffer is full the reformer is switched off until at a certain level it is switched back on again. If a large capacity reformer is used, a small hydrogen buffer will be sufficient but the reformer is switched on and off frequently. Increasing the size of the buffer is therefore beneficial for both the size as the operating conditions of the reformer.

A smaller reformer results in a lower reformer heat flow to the heat grid in part B and a higher natural gas consumption. The latter is because the co-heater has to produce the remaining part of the heat required. As a result less heat is disseminated and the utilisation of the reformer heat increases from 51 – 60% (see table 5.7).

As can be seen in the table, increasing the hydrogen buffer volume decreases the total CO_2-emissions of the system.

Table 5.7 *Influence hydrogen buffer on reformer size and* CO_2*-emissions*

Size of the H_2-buffer [m^3]	Size of the reformer [kW NG]	CO_2-emissions [kg CO_2/year.house]	CO_2-reduction [%]	d$/d$CO_2$ ratio [$/kg CO_2]	Utilisation of the reformer heat [%]
150	6500	2203	9.1	3.69	51
250	5000	2189	9.6	3.43	55
375	4250	2171	10.3	3.19	58
500	3500	2155	11.0	2.98	60

Size of the fuel cell versus the size of the hydrogen burner

A hydrogen burner and a PEM fuel cell produce the heat in part A. Because of the rather inefficient hydrogen burner, it is preferred to maximise the production by the fuel cell. In table 5.8, the results are shown for a 1, 2 and 3 kW fuel cell in each house. In case of the small fuel cell, the hydrogen burner contributes for 39% to the total heat production. For the 3 kW fuel cell this contribution is decreased to 14%.

Table 5.8 *Influence fuel cell on CO_2-emissions*

Size of the fuel cell [kW/house]	CO_2-emissions [kg CO_2/year.house]	CO_2-reduction [%]	d\$/dCO_2 ratio [\$/kg CO_2]	Utilisation of the reformer heat [%]	Fraction heat demand covered by fuel cell [%]
1	2308	4.7	5.34	59	64
2	2189	9.6	3.43	55	82
3	2125	12.3	3.23	53	89

Influence of the heat buffer in the district with the heat grid (part B)

Minimising the unused heat fraction in part B can be achieved by increasing the size of the heat buffer in that section. In the basic configuration a 400-liter water vessel is placed in each of the houses in part B. Using larger vessels can be beneficial as long as the heat losses of the vessel are not too large. In table 5.9, the results are shown for a 615 and a 1230-liter vessel. Clearly increasing the size of the buffer is beneficial for the CO_2-emissions and the utilisation of the reformer heat. Interesting is that the $\Delta\$/\Delta CO_2$ ratio remains more or less constant. The increase in costs is compensated for the decrease in CO_2-emissions.

Table 5.9 *Influence heat buffer part B on the CO_2-emissions*

Size of the heat buffer [litres/house]	CO_2-emissions [kg CO_2/year.house]	CO_2-reduction [%]	d\$/dCO_2 ratio [\$/kg CO_2]	Utilisation of the reformer heat [%]
400	2189	9.6	3.43	55
615	2185	9.8	3.43	60
1230	2177	10.1	3.42	73

Efficiency of the reformer

It is likely that new developments in reactor design will result in higher efficiencies for steam methane reforming. Here, the effect of a five to ten-percent higher efficiency is shown in table 5.10. Comparing these results with the previous ones, a larger overall effect on the CO_2-emissions is achieved by higher reformer efficiency. Roughly a 10 percent more efficient reformer means a ten percent CO_2-reduction.

Table 5.10 *Influence reformer efficiency on the CO_2-emissions*

Size of the reformer [kW NG]	CO_2-emissions [kg CO_2/year.house]	CO_2-reduction [%]	d\$/dCO_2 ratio [\$/kg CO_2]	Utilisation of the reformer heat [%]
75.0	2189	9.6	3.43	55
77.5	2119	12.5	2.54	60
80.0	2045	15.6	1.95	68
85.0	1939	19.9	1.45	81

5.3.2 Split district with a centralised electric heat pump as co-heater

As is shown in the previous section, using the heat of the reformer in a part of the district reduces the total CO_2 emissions of the hydrogen systems. Although an efficient natural gas burner is used in E-1, even further emission reduction can be achieved by using a centralised electric heat pump. Placing the heat pump at a central point outside the district has three reasons:

1. Because of the larger scale of the unit, a better heat integration and transfer can be achieved. This leads to a higher COP value (COP = 3.0) compared to domestic smaller heat pumps (here COP = 2.58).
2. Since a heat grid is already available, it is easier to supply heat directly to the grid
3. A central position enables easier installation and annual maintenance. This is because only a single heat source is required rather than a source for each (couple of) house(s).

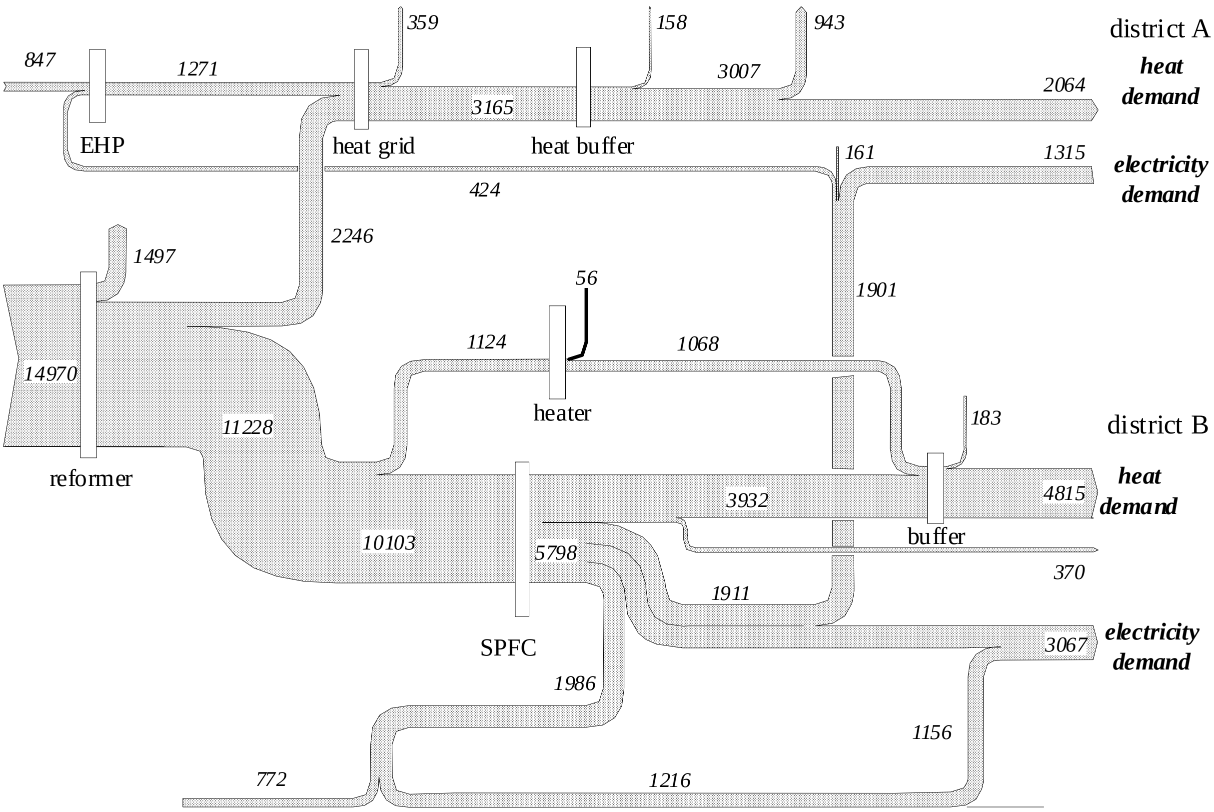

Figure 5.4 *Sankey diagram system E-2 (split district with central heat pump)*

For the interpretation of the simulation results, a comparison is made between the systems B-3, D-16, E-1 and E-2 (see table 5.11 and 5.12). The energy flow diagram is shown in figure 5.4.

Table 5.11 *Discussed systems*

System	Configuration
B-3	0.32 kW_e SOFC + large heat buffer
D-16	1 kW_e PEMFC + heat pump
E-1	split district + NG heater
E-2	split district + EHP

Table 5.12 *Starting points of systems B-3, D-16, E-1 and E-2*

		B-3	D-16	E-1	E-2
Fuel cell	kW_e/house	0.32	1.00	2.00	2.00
H_2-heater	kW_{th}/house			9.07	9.07
CH_4-heater	kW_{th}/house	8.85		10.26	
Electrical heater	kW_e/house		6.15		
Heat pump	kW_{th}/house		2.31		10.26
Heat buffer	MJ/house	7.70	7.70	8.24 (A) 16.67 (B)	8.24 (A) 16.67 (B)
SMR	MW		0.90	5.00	4.00

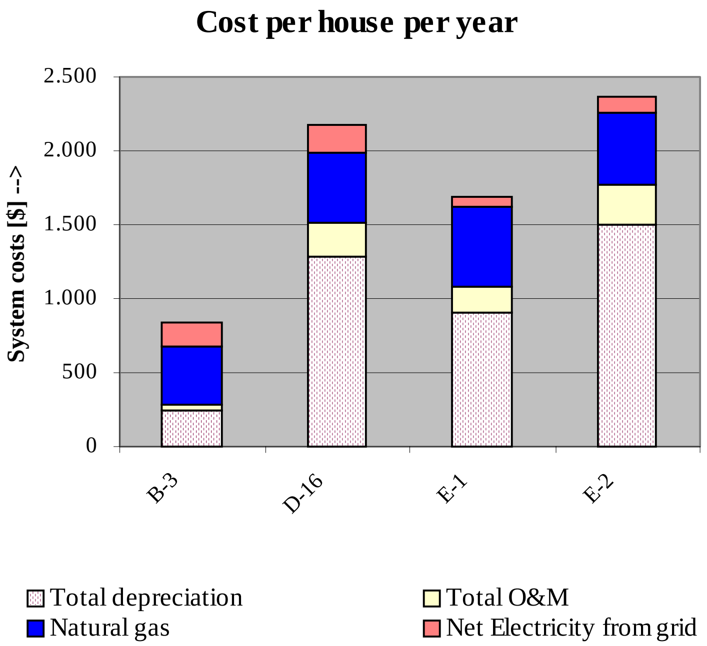

Figure 5.5 *Total system cost for the systems B-3, D-12, D-16 and E-1*

Compared to E-1, the cost of E-2 are higher that is mainly caused by the central heat pump. In terms of costs, this makes the system comparable to D-16. Here the peaks in the heat demand are covered completely by domestic heat pumps and electrical heaters, which explains the higher electricity import from the central electricity grid. In E-2, less electricity is imported due to the better synergy in the system; direct utilisation of excess electricity in the district before exporting it to the grid.

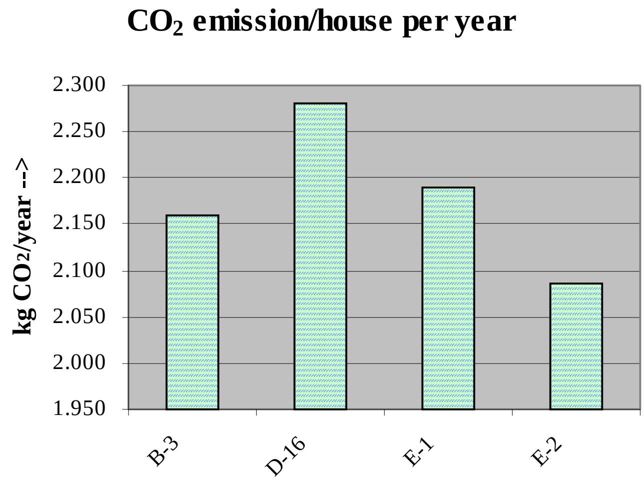

Figure 5.6 *Total CO_2-emissions for the systems B-3, D-16, E-1 and E-2*

Figure 5.6 shows the CO_2-emissions for the discussed systems. A centralised heat pump is clearly beneficial to the CO_2 emissions; the emissions are even lower than system B-3. Since only the natural gas heater in E-1 has been replaced by the heat pump in E-2, the latter unit causes the extra 103-kg CO_2 reduction.

As has been shown in the previous sections, the $\Delta\$/\Delta CO_2$ ratio shows the relation between the system cost and the CO_2-emissions (see table 5.13). Despite the reduction of CO_2 (5%) compared to E-1, the system cost with the heat pump increase more (40%) and a higher ratio is the result.

Table 5.13 *Costs per kg* CO_2 *reduced with respect to the conventional system*

System	Configuration	Extra costs [$]	kg CO_2 reduced [kg CO_2]	Costs/kg CO_2 reduced [$\Delta\$/\Delta$kg CO_2]	Quadrant
B-3	0.32 kW_e SOFC + large heat buffer	-55	263	-0.21	2
D-16	1 kW_e PEMFC + heat pump	1281	142	8.99	1
E-1	split district + NG heater	799	232	3.44	1
E-2	split district + EHP	1477	335	4.41	1

6 CONCLUSIONS AND DISCUSSION

1.1 Discussion

In this study the use of hydrogen as an energy carrier for a residential area is considered. The hydrogen based district assumes the use of a hydrogen grid which is supplied with hydrogen by a reformer. PEM fuel cells in each house convert the hydrogen gas to electricity and heat. The benefits and disadvantages for the hydrogen based systems are evaluated by comparing with systems using other energy carriers: natural gas and electricity. For districts with a natural gas/electricity infrastructure, both the conventional system, having a natural gas heater and electricity supply from the grid, as a more advanced version based on the use of a combined heat and power SOFC system are evaluated. The district with an “all-electric” infrastructure uses an individual electric heat pump (EHP) to supply heat.

Analysis of the calculation results for the hydrogen systems
For the hydrogen based systems a broad range of configurations are evaluated. Fuel cells in a combined heat and power (CHP) system supply both heat and power in a ratio depending on the efficiency of the fuel cell. However, this heat to power ratio is not necessarily equal to the ratio of demand: this proves to be an important issue for the hydrogen systems. The houses in the district demand more heat than electricity, while the fuel cell, when operating on hydrogen, produces more electricity than heat. As a result, covering the complete heat demand with the fuel cell results in a large excess production of electricity. Although the electricity can be sold to the central grid, the economy of selling electricity is poor[5]. On the other hand, sizing the fuel cell on electricity demand with the fuel cell means that additional heating is required. Because of the large impact of the fuel cell size, configurations with different sized fuel cells are evaluated. Furthermore, different systems are considered for supplying additional heat: systems with a hydrogen burner and systems with a heat pump as an additional heat source. The method of operation (base-load and heat load following[6] operation) is examined. To optimise the system performance not only the size of the fuel cell but also the size of heat and hydrogen buffers and the reformer have been varied.

In natural gas based systems additional heat is produced as efficiently as it is produced in the reference system (same technology). But using a hydrogen burner for producing additional heat is strongly lowers the efficiency of the system. Burning hydrogen for additional heat is much more unfavourable than burning natural gas for additional heat because the limited efficiency of the steam reformer (75% LHV). If hydrogen is used to produce electricity the losses in the reformer are compensated by the higher efficiency of the end-use (the fuel cell on hydrogen has an efficiency which is 25..35% higher than the fuel cell on natural gas). However, if hydrogen is burned to produce heat, the losses in producing the hydrogen are not compensated by a higher efficiency and therefore the total efficiency for heat production using hydrogen is considerably lower than the efficiency of heat production in the conventional system.
The efficiency of the systems with an electrical heat pump to supply the additional heat is higher than for the other configurations, but using a heat pump strongly increases the cost of the system in our calculations. In these calculations the assumption has been made that every house is provided with a complete heat pump system (electric heat pump and ground heat exchanger). Therefore, although the heat which has to be supplied by the electric heat pump is much lower in the hydrogen system than in the all electric system, the cost do not decrease significantly. This makes the specific cost of the heat pump in the hydrogen system even higher than normal.

[5] For the calculations we assumed that the price for selling to the grid is half the purchasing price: this is not pessimistic
[6] In load-following mode the PEMFC follows the heat demand when the buffer is full. When the heat buffer is not full the PEMFC operates in base-load. In this way dumping heat is prevented.

Load following or base load operation influences both investment cost and the CO_2 emissions of the system. Base load operation maximise the utilisation of a costly component: the fuel cell. However, two factors make base load operation unattractive:

- the selling price of electricity compared to the cost of natural gas makes it unattractive to operate the fuel cell if the heat produced in the fuel cell is not utilised;
- Because the efficiency of electricity generation (approximately 45% in the hydrogen system) is lower compared to the efficiency of the electricity delivered by the grid (52%) the CO_2 emissions increase if the fuel cell operates without utilising the heat produced in the fuel cell.

However, for small fuel cells hardly any benefits are obtained by switching from base-load to load following. The heat buffer is large enough to store the produced heat and as a result the fuel cell can continue operating at its nominal capacity.

Selection of a advanced systems for comparison
For both types of systems (SOFC and all-electric), the case which was used for the comparison with the hydrogen system was carefully considered.

- *Advanced natural gas reference system*
  If natural gas is the energy carrier, a solid oxide fuel cell is an attractive option. The most important consideration is the size of the fuel cell. The fuel cell is considered to operate in base load. Because the varying heat demand a relatively large fraction of the heat produced cannot be used directly and is lost. To maximise the utilisation of the heat produced, the fuel cell is sized on the annual electricity demand[7]. This leads to a small SOFC-CHP system (0.38 kW_e) with a heat buffer to store part of the excess heat. Because the heat losses of the heat buffer increase with size there is a trade-off between the losses and energy saved by using the buffer, which leads to the selection of 100 litre boiler for each household.
- *All-electric district*
  In the all-electric district the size of the heat pump is the main issue. The specific investment costs for the heat pump are high. Options to reduce the capacity of the heat pump which have been considered are using a large heat buffer or an electrical heater to reduce peaks in the heat demand. The size of the heat buffer is limited by the relative large heat loss, resulting in a substantial increase in energy consumption and CO_2-emissions. Electrical heaters are inefficient but cheap but also have a large impact on the CO_2-reduction. Based on these considerations a system with a small electrical peak heater and a small heat buffer has been selected.

Comparison of hydrogen system and reference systems
The CO_2-emissions and the cost ranges for all systems are given in figure 6.1 and 6.2. The two first ranges indicate the results for the advanced references: the natural gas SOFC system (NG|SOFC) and the all-electric system with electrical heat pump and a small heater (E|EHP|EH). The other lines in the figures indicate the results for different configurations of the hydrogen systems (H2|…). Results are shown for both operation modes, (heat) load following and base load operation ((LF / BL) and both methods of additional heat production, the hydrogen burner and the electric heat pump (H2B / EHP). The lines in the figures indicate the range of results due parameter variations (fuel cell size, buffer size, etc.) within the four basis configurations. The results for the hydrogen based systems can be explained primarily by considering how the heat demand is met in the system. All the systems with a hydrogen burner have a low overall efficiency. The most efficient system is achieved by operating in load following with a heat pump.

The lower CO_2 emission reductions in figure 6.1 for the hydrogen systems are mainly caused by the trade-off between efficiency and investment cost. For instance for the calculations two fuel cell sizes were used (0.38 kW and 1 kW) based on the strong increase in costs expected for larger systems. However, it should be realised that much higher CO_2 emission reductions can be achieved by using larger fuel cells because in that case a larger part of the heat production can be covered by the fuel cell. For example, by increasing the size of the fuel cell system to 5 kW, the CO_2 emission can be

[7] The fuel cell size is selected to cover the electricity demand 50% of the time: this corresponds approximately to the average annual electricity demand

reduced by 13% for a system with a hydrogen burner. Similarly the use of an electrical heater in combination with the heat pump, decreases the investment cost strongly. But much higher reductions (14%). can be achieved for the fuel cell system with a heat pump by eliminating the electrical heater.

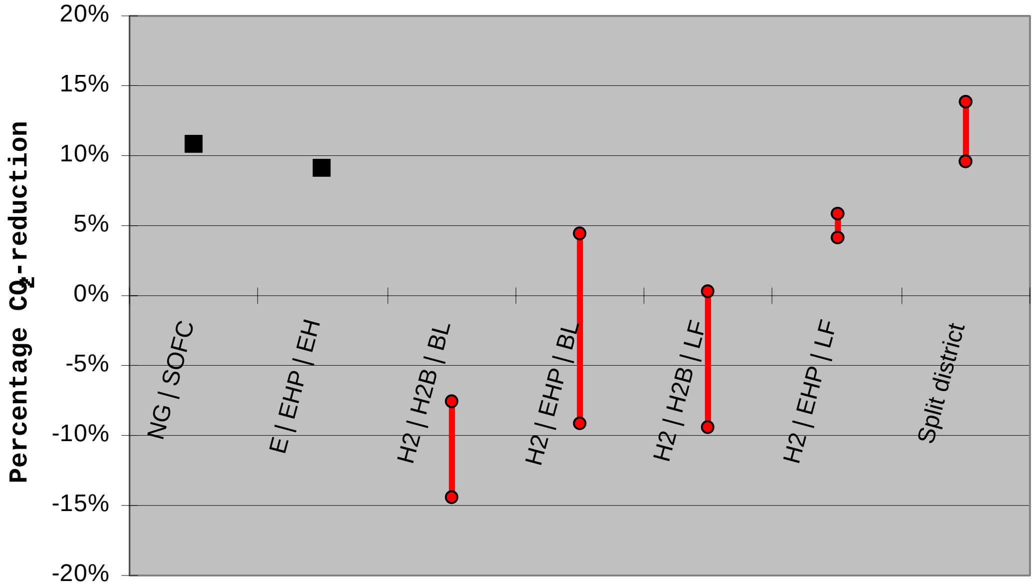

Figure 6.1 *CO_2-reduction range for the simulated systems*

The hydrogen systems as a whole consists of a large number of conversion steps. Because of this complexity the hydrogen systems are expensive. The major cost components are the reformer, the fuel cell. In those systems where a heat pump is present, it is the most costly component[8]. Although the high-pressure hydrogen buffer vessels are expensive, the contribution to the annual fixed costs is not very large. Investment cost and distribution of cost over the different components depends strongly on the type of the system. Using a hydrogen burner for example, requires a much larger reformer or larger hydrogen buffers, because the hydrogen supply systems has to be designed for peak-loads. On the other hand base load operation with a EHP leads to optimum use of the reformer and correspondingly lower cost for the hydrogen production system.

Advanced hydrogen systems

The difference in the ratio between heat and electricity production and heat and electricity demand, was reason to consider some advanced options. The performance of the system can be improved strongly by using a more efficient reformer. If the efficiency of the reformer increases from 75% to 80% LHV, the CO_2 emission reduction relative to the reference system increases from 6% to 11%. Another way to minimise the losses as a result of the hydrogen production process is to recover part of the heat from the reformer. In the advanced systems the district is split in two separate parts. In one section hydrogen is used as the energy carrier and other section a heat grid is used which utilises part of the heat from the reformer. The remaining heat required for the heat grid is either produced with a natural gas burner or with an centralised electrical heat pump. The CO_2-emissions reduction is for the two calculated systems is 10% (for the system with a natural gas heater) and 14% (for the system with an electrical heat pump) respectively.

[8] In absolute terms the reformer costs more but the investment is distributed over 1300 households

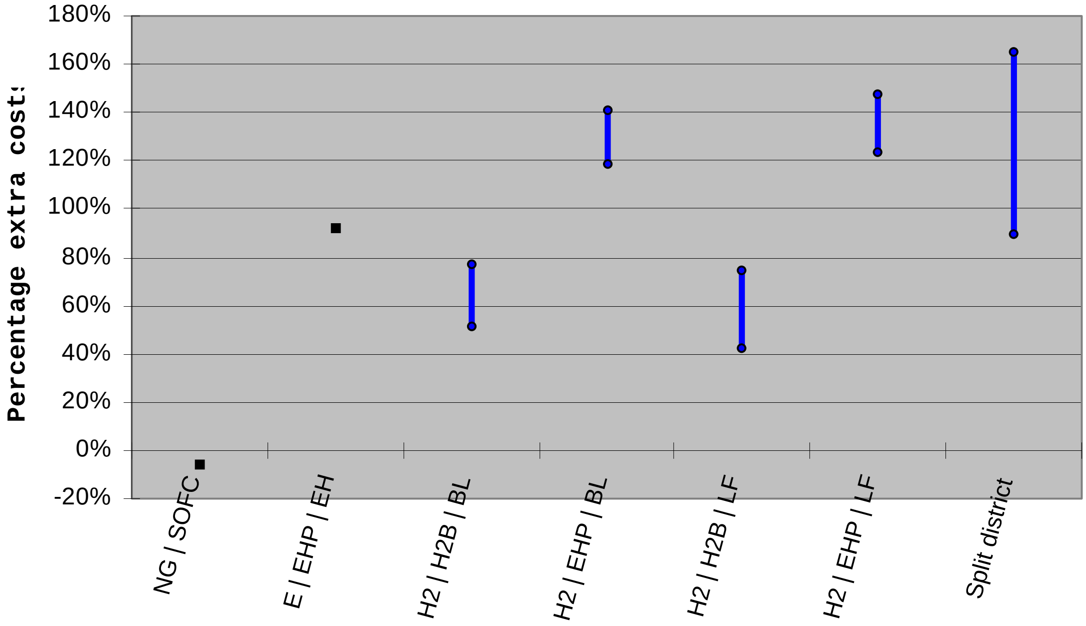

Figure 6.2 *Extra cost range for the simulated systems*

6.2 Conclusions

The purpose of the study is to identify the technological and economical barriers for using hydrogen as an energy carrier in a residential district. Having identified these barriers, efforts can be made to reduce or eliminate them through:

- Improvement of the design of a H_2-based residential energy system
- Identification of the research needs (technical and economical)
- Identification of possible demonstration projects

Improvement of the design of a hydrogen-based residential energy system

The study shows that the design of the system is a critical issue. If the set-up of the energy system is not well thought out, the energy use of the system may even be higher than the energy use of the conventional system. On the other hand, by optimising the system design, primary energy demand and CO_2 emissions can be reduced considerably (10…15%).

The most important issue in the design of the hydrogen based energy systems is efficiency of the additional heat supply. For systems with a hydrogen burner, the emphasis of the design should be on minimising the amount of hydrogen to the burner for example by optimising the fuel cell size and control strategy or by considering dual fuel (hydrogen/natural gas) systems. If a heat pump is used the main issue is cost reduction. The smaller size of the heat pump which is required has not lead to substantially lower cost for the system in this study. A more advanced system design, for example by optimising the use of the ground source (e.g. by sharing one source for several household) and development of smaller heat pumps, could lead to considerably lower cost for the system. Moreover, more efficient use of the heat pump can be achieved by integrating the heat pump and fuel cell system.

The production of hydrogen in the reformer is the weak link in the system because of the efficiency of the reforming process. Improvements of the system efficiency can be achieved by process integration, for example by combining hydrogen production with electricity production: using a gas turbine to deliver heat to the reformer or by using internal reforming high temperature fuel cells for hydrogen production.

Identification of the research needs (technical and economical)
The most influential parameter in the design is the efficiency of the steam methane reformer. Research should therefore mainly be focused on the design of more efficient hydrogen production systems.
Cost reduction is a large issue. One issue is technology development, for example hydrogen production processes more suited (i.e. cost effective) for the specific scale. The other issue is the need to develop more dedicated components. Integration of fuel cell system with other components (heat pump, heat buffer, burner) should reduce cost. Other components of interest are small-scale heat pumps and fuel cell systems specifically for operation on hydrogen. Hydrogen storage is also important. Due to the relatively low energy density that can be stored in the high-pressure vessels, large volumes are required. Other or improved means of storage will be beneficial to both costs and storage volume.

Identification of the possible demonstrations
Analysis can show the potential of the concept of using hydrogen in a residential area, and the benefits in terms of efficiency and reduced emissions. Whether such a potential can be realised can only be determined in the end by bringing the concept to life. This calls ultimately for a demonstration project to determine the potential in a real environment, with real limitations to infrastructure, real regulations and real consumer behaviour and perception. However, before such a step can be taken the aspects as safety, maintenance, start-up and shutdown times, etc. need to be demonstrated for residential application.

Hydrogen production is the central issue. For the future decentralised application of hydrogen, smaller reformers are required with higher efficiencies. For transportation applications operational experience for small hydrogen production will be obtained units in the coming years, which could be useful for stationary applications. Combining hydrogen production for stationary and mobile applications could be interesting. Ultimately one of the most important reasons for creating a hydrogen infrastructure is the role hydrogen as an energy carrier can play in the sustainable energy system. In particular the concept of hydrogen for residential applications can be advanced by demonstrating those technologies which could aid such a transition, for example decentralised hydrogen production from natural gas with CO_2 capture and sequestration or decentralised hydrogen production from biomass or waste.

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APPENDICES

A. COST CALCULATION CONVENTIONAL SYSTEM

The capital costs of the different components are determined on basis of a certain scale that is scaled up or down, in other terms the simulations determine the scale of the components. For example, the reference situation that only consists of a heater:

The heater capital costs are based on 1300 heaters of 10 kW. The costs are determined on basis of a 12 kW system scaled down to 10 kW with scaling factor 0.7.

Capital costs heater		
cost/kW_12KW	75 USD/kW	[4]
scale factor	0.7	
kW Installed /house	10 kW	
kW Installed	13000 kW	

	USD/KW	USD/Energy system	USD/House
Heater	79	1029000	792
Total	79	1029000	792

For the heater, the capital depreciation is based on a 15-year period and an interest rate of 7.5%, so the annual capital depreciation per house is USD 792. The O&M rate are set to 2% resulting in 106 USD/house.

Capital depreciation	Years	Interest	Depreciation USD/Energy system	Depreciation USD/House
Heater	15	7.5%	117000	90
Totals			117000	90

A 2% share of the capital cost of the heater is assumed for O&M, resulting in 20000 USD/Energy system and 15 USD/Year/House.

O&M	O&M USD/Energy system	O&M USD/House
2%	21000	16
	21000	16

In the conventional system, all electricity is imported from the grid and therefore the heater is the only capital cost unit. The energy costs for both electricity and natural gas are given below.

Energy consumption	/Energy system	/House	USD/Energy system	USD/House
NG (Nm^3)	821000	632	308000	237
Electricity (kWh)	4624000	3557	716000	551
Total			1024000	788

The total cost per/household/year for energy are summed below:

Totals	USD/Energy system	USD/House
O&M+Depreciation	137000	106
Energy consumption	1024000	788
	950000	894

B. THE $\Delta\$/\Delta CO_2$ RATIO AND THE QUADRANT

An indicative number showing the relationship between CO_2 emissions and system costs is the ratio of the extra costs versus the amount of CO_2 reduced (further referred as $\Delta\$/\Delta CO_2$):

$$\frac{\Delta\$}{\Delta CO_2} = \frac{Cost_{\ optional\ system} - Cost_{reference}}{CO_{2\ reference} - CO_{2\ optional\ system}}$$

The result of the $\Delta\$/\Delta CO_2$ ratio is either negative or positive. However, in both cases two interpretations are possible. If for example $\Delta\$/\Delta CO_2 = -5.85$, it can either be concluded that the cost of the optional system are lower, but there is still a CO_2-reduction or the other way around. A similar reasoning is applicable for a positive ratio result. This means that four different situations can be defined. With respect to the conventional system, the

1. New system is more expensive but there is a reduction in the CO_2 emissions
2. New system is cheaper and there is a reduction in the CO_2 emissions
3. New system is cheaper but there is no reduction in the CO_2 emissions
4. New system is more expensive but there is no reduction in the CO_2 emissions

Those four items can be more easily interpreted if it is visualised in four quadrants. This is shown in figure 2.3. Here the numbers of the quadrants correspond to the numbers in the list.

Quadrant 2	**Quadrant 1**
$\Delta CO_2 > 0$ $\Delta\$ < 0$ $\Delta\$/\Delta CO_2 < 0$	$\Delta CO_2 > 0$ $\Delta\$ > 0$ $\Delta\$/\Delta CO_2 > 0$
Quadrant 3	**Quadrant 4**
$\Delta CO_2 < 0$ $\Delta\$ < 0$ $\Delta\$/\Delta CO_2 > 0$	$\Delta CO_2 < 0$ $\Delta\$ > 0$ $\Delta\$/\Delta CO_2 < 0$

Figure B.3 *Quadrant system for d$/d$CO_2$*

C. DETAILED SYSTEM INFORMATION

6.3 Reference systems

6.3.1 Natural gas based energy system (A & B)

6.3.1.1 The conventional system (A)

Heat for the reference system is generated with a central heating system and electricity is withdrawn from the grid. In the following tables the unit specifications of the heater and the power plant are given. The simulation results are tabulated in table D-3.

Table D-1: Unit specifications of the heater

Parameter	Value	unit
Efficiency	95	%
Nominal power	13000	kW/district

Table D-2: Unit specification power plant

Parameter	Value	unit
Efficiency	55	%

Table D-3: Simulation results of the conventional system

	Reference system	
Demand per year	Per Energy system	Per Residence
Total heating demand [kWh]:		
Heater [kWh]	**6879000**	**5292**

Total electricity demand [kWh]	**4624000**	**3557**
Buy peak [kWh]	2572000	1978
Sell peak [kWh]	-	-
Buy base [kWh]	2052000	1578
Sell base [kWh]	-	-
Total carbon emission [kg CO_2]	**3149000**	**2422**
heating	1457000	1121
electricity	1692000	1301

6.3.1.2 Solid Oxide Fuel Cell systems (B)

Heat for the SOFC system is partly generated with a central heating system and partly with a fuel cell. Electricity that is not produced with the fuel cell is withdrawn from the grid. In the following tables the unit specifications of the fuel cell, the heat buffer and the simulation results are given. The specifications of the other units remain unchanged.

Table D-4: Unit specifications of the SOFC for the district

Parameter	Value	Unit
Electric efficiency	45	%
Thermal efficiency	35	%
Minimum partial load	0	-
Nominal power	362	kW

Table D-5 ***Unit specifications of the Heat buffer for the district***

Parameter	Value	Unit
Nominal capacity	10000	MJ (120 liter H_2O/residence)
Initial filling fraction	0.4	-
Heat loss	0.01	1/h

Table D-6 *Overview simulated systems per house*

System	Configuration (excl. heater)
B-1	0.32 kW_e SOFC
B-2	0.32 kW_e SOFC + 3.80 MJ heat buffer
B-3	0.32 kW_e SOFC + 7.70 MJ heat buffer
B-4	1 kW_e SOFC
B-5	1 kW_e SOFC + 3.80 heat buffer
B-6	1 kW_e SOFC + 7.70 heat buffer

Table D-7 *Sizes of the units in the SOFC systems (B)*

	B-1	**B-2**	**B-3**	**B-4**	**B-5**	**B-6**
Heater [kW]						
KW Installed (district) [kW]	13.000	11.500	11.500	10.000	10.000	10.000
Electricity required (district) [kWh]	23.260	19.580	18.810	11.360	9.416	8.931
SOFC						
KW installed	422	422	422	1.300	1.300	1.300
Heat buffer						
Size [MJ]		5.000	10.000		5.000	10.000

Table D-8: Simulation results SOFC system averaged for each house

Model name	**B-1**	**B-2**	**B-3**	**B-4**	**B-5**	**B-6**
Calculated system cost [USD/house]	**828**	**824**	**838**	**955**	**972**	**988**
Total heating demand [kWh]:						
District heat demand [kWh]	5292	5292	5292	5292	5292	5292
Heater [kWh]	**3578**	**3012**	**2894**	**1748**	**1448**	**1374**
Heat pump [kWh]						
Electrical heater [kWh]						
Fuel cell [kWh]	**3160**	**3160**	**3160**	**9731**	**9731**	**9731**
Q steam reformer [kWh]						
Heat stored/emitted [kWh]	**-1447**	**-881**	**-762**	**-6187**	**-5888**	**-5813**
Natural gas required [m3/y]	**1146**	**1078**	**1065**	**2422**	**2386**	**2378**
Total electricity demand [kWh]	**3451**	**3449**	**3448**	**3383**	**3382**	**3382**
Total electricity from grid [kWh]	**1203**	**1202**	**1201**	**2**	**2**	**2**
Buy peak [kWh]	715	715	714	1	1	1
Buy base [kWh]	487	487	487	1	1	1
Total electricity to grid [kWh]	-424	-426	-426	-4857	-4858	-4858
Sell peak [kWh]	-71	-72	-72	-2050	-2051	-2051
Sell base [kWh]	-353	-354	-354	-2807	-2808	-2808
Total electricity fuel cell [kWh]	2673	2673	2673	8238	8238	8238
Net exchange with grid :	778	775	775	-4855	-4857	-4857
Total CO_2 emission [kg CO_2]	**2306**	**2185**	**2159**	**2413**	**2351**	**2334**
heating	2029	1909	1884	4287	4225	4208
electricity	276	275	275	-1874	-1875	-1875

6.3.2 Electricity based Energy system (C)

Heat for the all-electric system is generated with an electric heat pump and electricity is withdrawn from the grid. In the following table the unit specifications of the heat pump are given. The simulation results are tabulated in table D-11. The specifications of the other units remain unchanged.

Table D-9: Unit specifications of the heat pump for the district

Parameter	Value	unit
Carnot efficiency	0.38	-
High temperature	65	°C
Low temperature	15	°C
Nominal power	13000	kW

Table D-10 ***Discussed systems for a house***

System	Configuration
C-1	10 kW Electric heat pump (EHP)
C-2	6.5 kW EHP + 27 MJ heat buffer
C-3	3.1 kW EHP + 6.20 kW electrical heater
C-4	1.9 kW EHP + 8.10 kW electrical heater

Table D-11: ***Simulation results of the all-electric system***

Model name	**C-1**	**C-2**	**C-3**	**C-4**
Calculated system cost [USD/house]	**828**	**824**	**838**	**955**
Total heating demand [kWh]:				
District heat demand [kWh]	5292	5292	5292	5292
Heater [kWh]				
Heat pump [kWh]	**5292**	**5951**	**4846**	**4356**
Electrical heater [kWh]			**445**	**935**
Fuel cell [kWh]				
Q steam reformer [kWh]				
Heat stored/emitted [kWh]	**0**	**-659**	**0**	**0**
Natural gas required [m3/y]	**0**	**0**	**0**	**0**
Total electricity demand [kWh]	**5728**	**5998**	**6015**	**6332**
Total electricity from grid [kWh]	**5728**	**5998**	**6015**	**6332**
Buy peak [kWh]	2943	3071	2944	2972
Buy base [kWh]	2785	2928	3072	3359
Total electricity to grid [kWh]	0	0	0	0
Sell peak [kWh]	0	0	0	0
Sell base [kWh]	0	0	0	0
Total electricity fuel cell [kWh]	0	0	0	0
Net exchange with grid :	5728	5998	6015	6332
Total CO_2 emission [kg CO_2]	**2096**	**2195**	**2201**	**2316**
heating	0	0	0	0
electricity	2096	2195	2201	2316

6.4 Hydrogen based energy system (D & E)

6.4.1 Hydrogen based district (D)

Heat for the hydrogen based PEMFC system is partly generated with an electric heat pump and partly with a fuel cell. Electricity that is not produced with the fuel cell is withdrawn from the grid. In the following tables the unit specifications of the fuel cell, the hydrogen buffer, the steam reformer and the simulation results are given. The specifications of the other units remain unchanged.

Table D-12 ***Discussed systems***

System	Operation mode and size fuel cell	Configuration
D-1	Base load (0.3 kW)	PEMFC + H_2 burner + 3.84 MJ Q buffer
D-2	Base load (0.3 kW)	PEMFC + H_2 burner + 7.70 MJ Q buffer
D-3	Base load (1.0 kW)	PEMFC + H_2 burner + 3.84 MJ Q buffer
D-4	Base load (1.0 kW)	PEMFC + H_2 burner + 7.70 MJ Q buffer
D-5	Base load (0.3 kW)	PEMFC +EHP + electr. heater + 3.84 MJ Q buffer
D-6	Base load (0.3 kW)	PEMFC +EHP + electr. heater + 7.70 MJ Q buffer
D-7	Base load (1.0 kW)	PEMFC +EHP + electr. heater + 3.84 MJ Q buffer
D-8	Base load (1.0 kW)	PEMFC +EHP + electr. heater + 7.70 MJ Q buffer
D-9	Load following (0.3 kW)	PEMFC + H_2 burner + 3.84 MJ Q buffer
D-10	Load following (0.3 kW)	PEMFC + H_2 burner + 7.70 MJ Q buffer
D-11	Load following (1.0 kW)	PEMFC + H_2 burner + 3.84 MJ Q buffer
D-12	Load following (1.0 kW)	PEMFC + H_2 burner + 7.70 MJ Q buffer
D-13	Load following (0.3 kW)	PEMFC +EHP + electr. heater + 3.84 MJ Q buffer
D-14	Load following (0.3 kW)	PEMFC +EHP + electr. heater + 7.70 MJ Q buffer
D-15	Load following (1.0 kW)	PEMFC +EHP + electr. heater + 3.84 MJ Q buffer
D-16	Load following (1.0 kW)	PEMFC +EHP + electr. heater + 7.70 MJ Q buffer

Table D-13 ***Unit specifications of the PEMFC***

	Base load	Part load	
Variable	Value	Value	Unit
Electrical efficiency	0.60	0.66	%
Thermal efficiency	0.40	0.34	%
Cell voltage	750	825	mV
Minimum partial load	0.25 - 0.15	0.25 - 0.15	%
DC/AC conversion efficiency	0.94	0.94	%

Table D-14 ***Unit specifications of the Hydrogen buffer***

Parameter	Value	Unit
Nominal pressure	200	bar
Initial load fraction	0.4	-

Table D-15 ***Unit specifications of the Steam reformer***

Variable	Value	Unit
Hydrogen plant efficiency	75	%
Boiling feed water	0.671	(kg/h)/kW H_2
Cooling water	0.013	(m^3/h)/kW H_2
Electricity	0.014	kW/kW H_2
Export steam	0.328	(kg/h)/kW H_2

Table D-16 *Sizes of the units in the hydrogen based energy system*

	Heater [kW]		**SMR capacity**					**PEMFC**	**EHP**	**Elect. heater**	**Heat buffer**	**H_2 buffer**	**H_2 compr.**
	KW Installed (district) [kW]	Elect. req. (district) [kWh]	Size [kW]	Cooling water [$1e^6$ m^3/a]	Steam [$1e^6$ m^3/a]	Process water [$1e^6$ m^3/a]	Elect. Req. [kWh]	Size [KW]	Size [kW]	kW installed [kW]	Size [MJ]	Size [Nm3]	Size [kW]
D-1	11.500	24.110	2.625	528	13.230	27.060	160.200	422			5.000	107.692	17
D-2	11.500	22.530	2.625	521	13.060	26.710	158.100	422			10.000	107.692	17
D-3	11.000	14.380	3.750	1.040	26.040	53.250	315.200	1.300			5.000	107.692	17
D-4	10.500	13.240	3.750	1.034	25.890	52.940	313.700	1.300			10.000	107.692	17
D-5			703	291	7.280	14.880	88.110	422	3.000	9.000	5.000		
D-6			703	291	7.280	14.880	88.110	422	3.000	9.000	10.000		
D-7			2.167	895	22.430	45.850	271.400	1.300	2.600	8.900	5.000		
D-8			2.167	895	22.430	45.850	271.400	1.300	2.600	8.900	10.000		
D-9	11.500	24.040	2.850	500	12.540	25.630	151.700	422			5.000	107.692	22
D-10	11.500	24.470	2.850	525	13.150	26.880	159.100	422			10.000	107.692	23
D-11	11.500	15.450	3.375	638	15.990	32.700	193.600	1.300			5.000	123.077	35
D-12	11.500	14.720	3.375	660	16.530	33.790	200.000	1.300			10.000	123.077	35
D-13			600	247	6.193	12.660	74.950	422	3.000	9.000	5.000	46.154	7
D-14			600	247	6.193	12.660	74.950	422	3.000	9.000	10.000	46.154	7
D-15			900	355	8.894	18.180	107.600	1.300	2.600	8.900	5.000	46.154	10
D-16			1.725	517	12.940	26.460	156.600	1.300	2.600	8.900	10.000	92.308	18

Table D-17 *Simulation results hydrogen based energy system*

Model name	**D-1**	**D-2**	**D-3**	**D-4**	**D-5**	**D-6**	**D-7**	**D-8**	**D-9**	**D-10**	**D-11**	**D-12**	**D-13**	**D-14**	**D-15**	**D-16**
Calculated system cost [USD/house]	**1350**	**1362**	**1570**	**1582**	**1955**	**1965**	**2135**	**2151**	**1267**	**1383**	**1550**	**1560**	**2000**	**2041**	**2215**	**2174**
Total heating demand [kWh]:																
District heat demand [kWh]	5292	5292	5292	5292	5292	5292	5292	5292	5292	5292	5292	5292	5292	5292	5292	5292
Heater [kWh]	**3709**	**3582**	**2212**	**2128**					**3698**	**3582**	**2213**	**2132**				
Heat pump [kWh]					**2825**	**2686**	**1407**	**1337**					**2871**	**2949**	**2129**	**1342**
Electrical heater [kWh]					**895**	**896**	**805**	**803**					**896**	**911**	**968**	**804**
Fuel cell [kWh]	**1896**	**1896**	**5840**	**5840**	**1896**	**1896**	**5840**	**5840**	**1686**	**1896**	**3172**	**3346**	**1618**	**1618**	**2288**	**3332**
Q steam reformer [kWh]																
Heat stored/emitted [kWh]	**-314**	**-187**	**-2760**	**-2677**	**-324**	**-187**	**-2761**	**-2688**	**-93**	**-187**	**-93**	**-187**	**-93**	**-187**	**-93**	**-186**
Natural gas required [m3/y]	**1306**	**1289**	**2570**	**2558**	**718**	**718**	**2213**	**2213**	**1237**	**1298**	**1578**	**1631**	**611**	**611**	**878**	**1277**
Total electricity demand [kWh]	**3579**	**3577**	**3628**	**3627**	**5606**	**5550**	**4996**	**4968**	**2968**	**3643**	**3650**	**3646**	**5632**	**5688**	**5466**	**4956**
Total electricity from grid [kWh]	**1282**	**1278**	**5**	**6**	**3318**	**3265**	**1173**	**1161**	**770**	**1326**	**1050**	**927**	**3531**	**3745**	**3502**	**2070**
Buy peak [kWh]	768	759	4	4	1302	1265	147	138	770	776	484	450	1362	1523	1231	581
Buy base [kWh]	514	519	1	1	2016	2001	1026	1023	676	549	567	476	2168	2222	2271	1488
Total electricity to grid [kWh]	**-376**	**-374**	**-4615**	**-4617**	**-386**	**-388**	**-4415**	**-4432**	**-180**	**-355**	**-1968**	**-2099**	**-181**	**-338**	**-1347**	**-1912**
Sell peak [kWh]	-59	-59	-1926	-1925	-56	-57	-1872	-1884	-54	-54	-1099	-1123	-57	-51	-798	-1074
Sell base [kWh]	-317	-315	-2689	-2692	-330	-332	-2544	-2548	-126	-301	-868	-976	-124	-288	-549	-838
Total electricity fuel cell [kWh]	2673	2673	8238	8238	2673	2673	8238	8238	2378	2673	4567	4818	2282	2282	3312	4798
Net exchange with grid :	906	904	-4610	-4611	2933	2877	-3242	-3271	590	970	-917	-1173	3350	3406	2155	158
Total CO_2 emission [kg CO_2]	**2635**	**2605**	**2770**	**2747**	**2337**	**2316**	**2643**	**2632**	**2649**	**2644**	**2418**	**2414**	**2304**	**2321**	**2315**	**2280**
heating	2312	2282	4549	4527	1271	1271	3918	3918	2190	2296	2793	2885	1082	1082	1554	2260
electricity	324	323	-1779	-1780	1065	1045	-1275	-1286	459	348	-375	-471	1222	1239	761	20

6.4.2 Advanced hydrogen systems (E)

In the report three advanced hydrogen systems have been discussed. The first system is equivalent to system D-16 (see table D-12) but is simulated with a higher reformer efficiency. The other two systems are E-1 and E-2, where a part of the district uses the heat of the steam reformer.

Table D-18 ***Simulated systems***

System	Part	Distri-bution	PEMFC	Central Electric heat pump	Central NG burner	Domestic H_2 burner	Domestic heat buffer	Domestic H_2 buffer
E-1	A	H_2	x			x	x	x
	B	heat		-	x		x	
E-2	A	H_2	x			x	x	x
	B	heat		x	-		x	

LF = load following

Table D-19 ***Unit specifications of the heater***

Parameter	Value	unit
Efficiency	95	%
Nominal power:		
District	13000	kW
Part B	8250	kW
Central heater (only E-1)	4000	kW

Table D-20 ***Unit specifications of the central heat pump for the split district (E-2)***

Parameter	Value	unit
Carnot efficiency	0.44	-
High temperature	65	°C
Low temperature	15	°C
Nominal power	4000	kW

Table D-21 *Sizes of the units in the advanced hydrogen systems*

	D-16 (80)	E-1	E-2
Heater [kW]			
KW Installed (district) [kW]		12.250	8.250
Electricity required (district) [kWh]		1	1
SMR capacity			
KW Installed [kW]	1.725	3.750	3.000
Cooling water [1e^6 m^3/a]	518	531	530
Steam [1e^6 m^3/a]	12.970	13.310	13.270
Process water [1e^6 m^3/a]	26.510	27.210	27.130
Electricity required [kWh]	156.900	161.100	160.600
Distribution system hydrogen			
Additional costs for H_2 grid	1.148.400	803.880	803.880
Distribution system heat			
Investment per household ($/house)		3.000	3.000
PEMFC			
KW installed	1.300	1.820	1.820
Electric Heat Pump			
KW Installed [kW]	2.600		4.000
Electrical heater			
kW installed [kW]	8.900		
Heat buffer			
Size [MJ]	10.000	14.000	14.000
Hydrogen buffer			
Size [Nm^3]	92.308	76.923	76.923
H_2 compressor			
Size	19	32	32

Table D-22 *Simulation results advanced hydrogen systems per house*

Model name	D-16 (80)	E-1	E-2
Calculated system cost [USD/house]	**2145**	**1692**	**2370**
Total heating demand [kWh]:			
District heat demand [kWh]	5292	5292	5292
Heater [kWh]		**1847**	**822**
Heat pump [kWh]	**1342**		**978**
Electrical heater [kWh]	**804**		
Fuel cell [kWh]	**3332**	**3024**	**3024**
Q steam reformer [kWh]		**1733**	**1728**
Heat stored/emitted [kWh]	**-186**	**-1312**	**-1260**
Natural gas required [m^3/y]	**1199**	**1436**	**1309**
Total electricity demand [kWh]	**4957**	**3627**	**3948**
Total electricity from grid [kWh]	**2070**	**1529**	**1675**
Buy peak [kWh]	580	759	828
Buy base [kWh]	1490	770	847
Total electricity to grid [kWh]	**-1912**	**-2362**	**-2186**
Sell peak [kWh]	-1075	-1251	-1193
Sell base [kWh]	-836	-1111	-993
Total electricity fuel cell [kWh]	4798	4459	4459
Net exchange with grid :	159	-832	-511
Total CO_2 emission [kg CO_2]	**2143**	**2190**	**2087**
heating	2123	2542	2318
electricity	20	-352	-231