REDUCTION OF RESIDENTIAL CARBON DIOXIDE EMISSIONS THROUGH THE USE OF SMALL COGENERATION FUEL CELL SYSTEMS

Technical Study

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Background

Combined heat and power systems (CHP) enable users to operate with increased overall efficiency thus reducing consumption of fossil fuels and green house gas emissions. This study investigates the potential of fuel cell based CHP systems in domestic and small commercial applications to reduce green house gas emissions. Fuel cells in this application have advantages of very low emissions and potentially higher power to heat ratios than other CHP systems.

Study approach

The study was undertaken by the Systems Analysis and Technology Evaluation (STE) Department of the Institute of Energy Research (IEF) at the ForschungZentrum Jülich, Germany.. The recent trends in energy consumption and CO_2 emissions for the EU 25[1] in the industry, residential and commercial sectors were first analysed to get a good understanding of the baseline situation and the typical energy consumption trends in developed countries. The main part of the study consisted of four steps. Firstly, the characteristics of all types of CHP systems on or moving to the worldwide market including those based on fuel cell technology were researched and documented. In the second part the characteristics of heat and power consumption in houses were analysed for three climatic zones; cold, temperature and warm. This analysis was based on both a top down and bottom up approach. In the latter, estimates of heat consumption were made based on the size and insulation standards of typical housing units and then compared with the overall consumption of energy for heating in the sector as a validity check. The third step was to analyse the moment to moment consumption patterns of heat and electricity in order to estimate how fuel cell and other CHP systems would perform in practice. This information was then used to calculate the emission savings which could be made when fuel cell and other CHP systems were applied in place of the conventional system of supplying centrally generated electric power for the electrical loads and gas for heating and hot water. In the fourth and final step assessments were made of how great the uptake of fuel cell CHP systems to 2050 would be and hence what overall contribution they could make to greenhouse gas emission reduction. The potential of the fuel cell systems was then compared with other CHP alternatives. The work was largely based on European energy and building statistics but is considered generally applicable to OECD countries. The full analysis was not extended to the commercial/industrial sector due to lack of readily available information on the diverse applications in this sector.

Results and Discussion

Trends in energy consumption and emissions

Figures for energy consumption in the EU 25 as published by EUROSTAT 2007[2] were reviewed in order to understand the basic trends in the industrial, residential and commercial sectors. In the period 1990 -2004 overall energy consumption in the 25 countries which now make up the EU

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[1] *EU 25 are the 15 original countries in the European Union plus the 10 countries who recently accessed.*

[2] *EUROSTAT is the Organisation which produces and publishes official statistics for the European Union*

rose by 7.6% but the residential sector climbed by 15% and the commercial sector by 29%. There was also a considerable switch to gas in the residential sector and significant increases in electricity consumption which was up by 31%. Likewise, the commercial sector in the EU shows a similar pattern of significant increase with the clean fuels electricity and gas gaining significant market share. The ratio between electricity and power consumption is a key parameter when considering the potential of CHP systems in the EU. Also of importance in assessing the contribution to emission reductions is the baseline emission characteristics with which the technology will compete. For the EU25 statistics the average figures for electricity and thermal energy production are calculated using emission factors for the average EU fuel and energy mixes in 2004 and were electrical 0.35kgCO_2/kWh$_{el}$ and thermal 0.37 kgCO_2/kWh$_{th}$ Charts showing all of the trends are to be found in the main report.

The advantages of CHP

Combined heat and power (CHP) means the simultaneous generation of thermal and electrical power in one system. In comparison to separate generation of heat in a domestic heating system and drawing of electricity from the public electricity grid, CHP-systems have the potential to save primary energy. The main reason for this energy saving potential is the use of the waste heat which is normally rejected by thermal energy conversion systems. For small decentralized CHP-systems (often termed micro-CHP), avoiding network losses is an additional positive aspect. Figure 1 below illustrates the potential savings in primary energy when the requirements are 1 unit of electrical power to 2 of thermal energy. The conventional system in this case uses 53% more primary energy based on typical central power generation and transmission with 35% efficiency. Even if the electricity system efficiency is pushed up to 50% the conventional system would use 27% more primary energy.

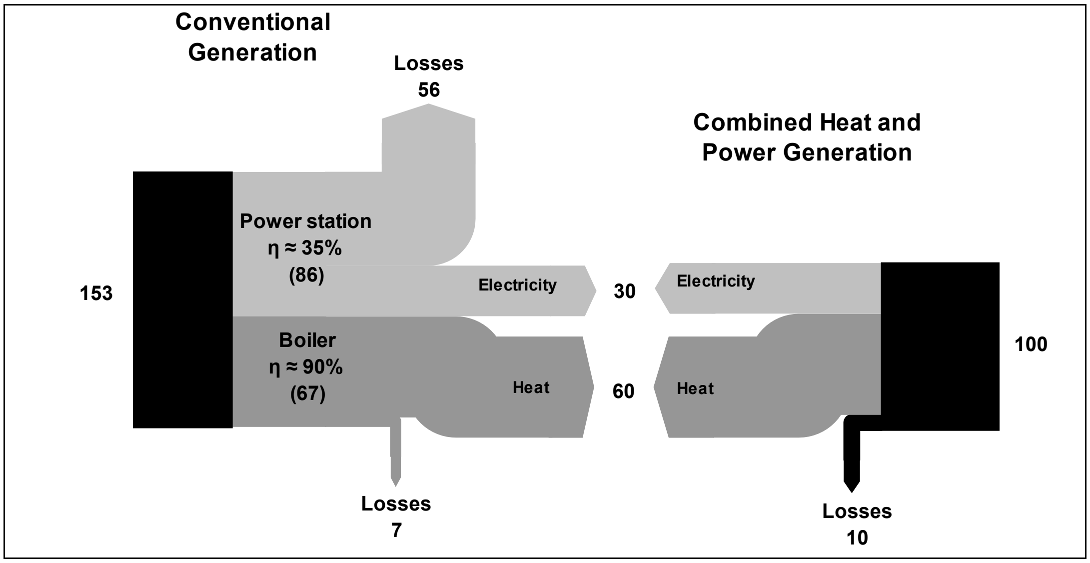

Figure 1 Comparison of Conventional and CHP system energy balance

Survey of available micro CHP technologies

Micro CHP systems have been developed based on electricity generation using at least 5 methods listed below. Examples of the characteristics of systems based on all of these apart from the organic Rankine cycle were obtained and selected data from the range of available systems was subsequently used in the estimation of abatement potential. The number of specific designs for which data was collected is shown in brackets.

- Fuel cells (20)
    - Alkaline (1)
    - Proton exchange membrane (PEM) (7)
    - Solid oxide (SOFC) (5)
    - Molten carbonate (4)
    - Phosphoric acid (3)
- Internal combustion engines (3)
- Stirling engines (4)
- Micro gas turbines (5)
- Organic Rankine Cycle (No commercial examples found)

The models investigated were as follows: (Note: more extensive details of their characteristics and performance and pictures of the units are to be found in the main report)

Intensys produce the PULSAR-6 alkaline fuel cell with an electrical capacity of 6Kwe

The 7 PEM fuel cells reviewed range in capacity from 1 to 5Kw$_e$ and are made by the following manufacturers:-

Vaillant-PlugPower	5Kw$_e$
Inhouse 4000	4Kw$_e$
Viessmann - HEVA II	2Kw$_e$
Baxi Innotech -Beta 1.5	1Kw$_e$
Matsushita Electric Industrial	1Kw$_e$
Toyota-Aisin	1Kw$_e$

The 5 SOFC systems reviewed are all small capacity:-

Ceramic Fuel Cell Ltd NetGen^{Plus}	1Kw$_e$
Hexis -Galileo 1000N	1Kw$_e$
Acumetrics-AHEAD	1Kw$_e$
MTS/Elco/Acumetrics	1Kw$_e$
Kyocera/Osaka Gas	0.7Kw$_e$

These PEM and SOFC fuel cell based systems listed above are the main contenders for the domestic CHP market. The main competitor at this power output level is the Sterling engine based CHP system of which 3 examples investigated.

Whispergen Mk5	1Kw$_e$	Gas fired
Solo Stirling 161	2 – 9.5Kw$_e$	Gas fired
Sunmachine	1.3-3Kw$_e$	Wood pellets

Reciprocating internal combustion engine systems are also available with outputs suitable for the domestic market:-

Senertec (Baxi) –DachsSEplus	5 - 5.5 Kw$_e$
PowerPlus Technologies (Vaillant) Ecopower	1.3 - 4.7 Kw$_e$
Honda -GE160V	1 Kw$_e$

Molten carbonate (MCFC) and phosphoric acid fuel cells (PAFC) are also available but the commercially available units are larger in size and are more suited to the small commercial CHP market. Finally a number of systems based on micro gas turbines are available in the larger capacity ranges. These were not used in the detailed analysis of abatement potential and their characteristics are listed in the main report.

Heat and power demand in the domestic sector

Heat demand

The heat and power demand was analysed for two types of dwelling, single family houses and multi family housing units in which a heating system is shared, for example in a block of flats or a terrace of houses. Using a "bottom up" approach the heat requirements over the year were estimated for a "standard" single family house using data on the areas of walls roof and windows and insulation coefficients taken from the applicable standards. These calculations were made for three different climatic zones based on the "heating degree days" profiles for three representative countries namely Finland (cold), Germany (moderate) and Greece (warm). This resulted in typical heating load curves as shown in Figure 2.

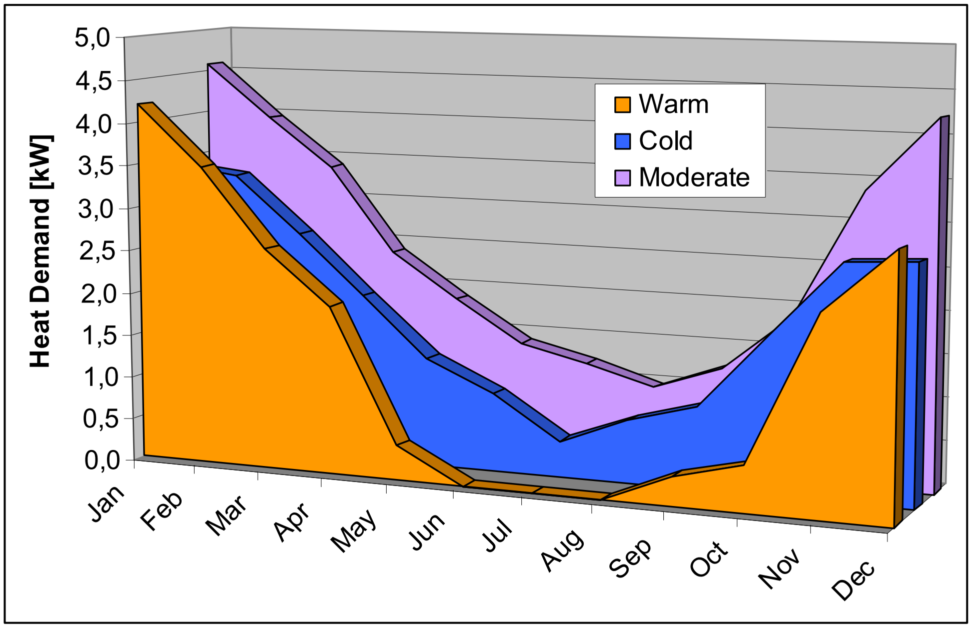

Figure 2. Heat demand single family house from bottom up analysis for 3 climatic regions

The validity of this approach was checked by doing a "top down" calculation which uses total thermal energy demand for the countries concerned combined with information on the number of houses and the split between single and multifamily. Comparison of the results from this approach showed agreement to within roughly 13-16%, the bottom up estimates being consistently higher. Over time the heat demand in houses is expected to change. A major effect will be the rapidly improving standards of insulation in new houses. Figure 3 illustrates the changes which have occurred historically and the very low heat losses per unit area of a house which are expected to be reachable in the future. There is a balancing trend however towards having an increasingly large amount of the living space per house heated. There is evidence that floor areas of newer houses are slowly declining but the effect of increased area heated applies to the whole of the housing stock. The net result is a slight increase of expected heat demand per house over time.

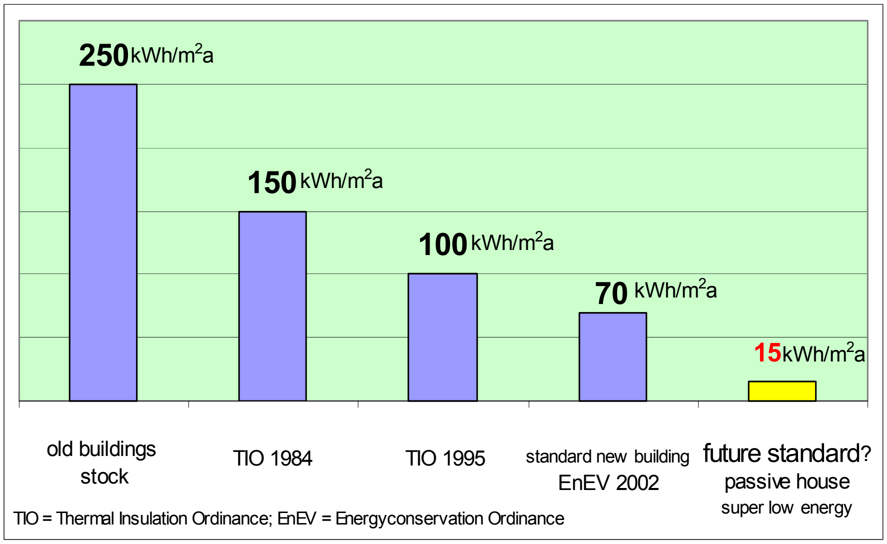

Figure 3 Trends in insulation standards

Electrical demand

The overall performance of a CHP system is very dependent on the balance between the electrical and thermal power demands. For domestic housing the electrical load varies considerably as shown in the example in Figure 4 below which is based on measurements every 15 minutes. Notice that for the aggregate of 83 units in a multi-family house the load is more evenly spread. Because electricity is difficult and expensive to store any calculations on CHP in the domestic application should ideally be based on much more frequent data on the electrical consumption. The researchers found a severe lack of such short time scale data. An example for one single family house in which power was measured every 10 seconds was found and data from this source was used to simulate electrical consumption using a random simulation model. Such data would be important for a power led CHP system. However for the calculations of CO_2 abatement potential a heat lead system is adopted and a small hot water storage is included which has the

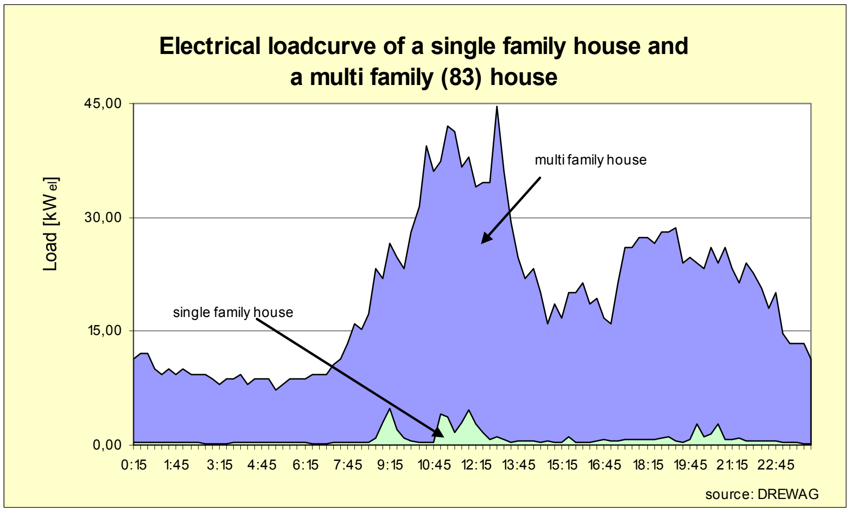

Figure 4 Typical daily household electrical load – 15 minute measurement interval

effect of smoothing out the heat production from the CHP system. Surplus electricity is exported to the grid. Based on typical heat and electrical load profiles the operating hours of the chosen systems were calculated including details of the requirements to stop and start and to use a peak burner for any shortfall in thermal output.

Emission reductions and costs per unit

General parameters

Based on the heat demand for typical single and multi-house units the annual emission reduction and emission reduction costs for these units are calculated. The results of these calculations are dependent on a number of parameters which are expected to change over time. For example the emissions of CO_2 for grid produced electricity, the cost of its production, the cost of micro CHP systems are all expected to change in the period up to 2050. Figure 5 which is based on data from the IEA for the OECD region shows the changes expected in these parameters compared to a base year 2010. The parameters are incorporated into the overall model to calculate emission reductions and costs.

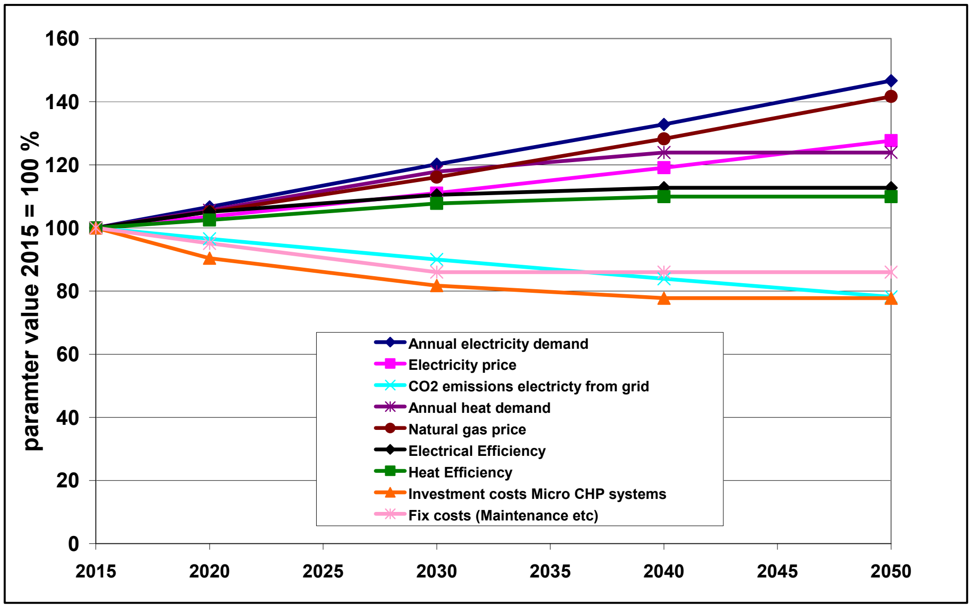

Figure 5 How key parameters are expected to vary with time

Fuel cell performance

The average performance of SOFC and PEM fuel cells currently available is shown in the left hand side of the table below. It is expected that these values will be significantly improved by the time the devices enter the mass market and in the columns on the right show the values assumed for the calculation future emission abatement potential. Note in particular the significantly higher electrical efficiency of the SOFC and somewhat improved overall efficiency of the PEM fuel cells.

Current average efficiency [%]				Efficiency for calculations		
Type	**electric**	**thermal**	**overall**	**electric**	**thermal**	**overall**
SOFC	35.8	46.8	82.5	45	30	80
PEMFC	29.7	44.1	73.9	30	50	80

The calculation of relative performance per unit for different types of fuel cell CHP as compared to competing systems is shown in the following charts (Figures 6 & 7). The results are shown for periods 10 years apart from 2010 to 2050. For the multi family house the comparison is made between a CHP based on an internal combustion engine and a low temperature PEM. For the single family house the comparison is between a Sterling engine type CHP a SOFC and a PEFC. In all cases but one there is a slight increase with time as a result of the scenario assumptions. In the case of the PEFC in a single family house there is a slight decrease in savings in later decades because improvements in the reference grid electricity emission factor start to outweigh the benefits from the relatively small amount of CHP electricity which this type of unit produces.

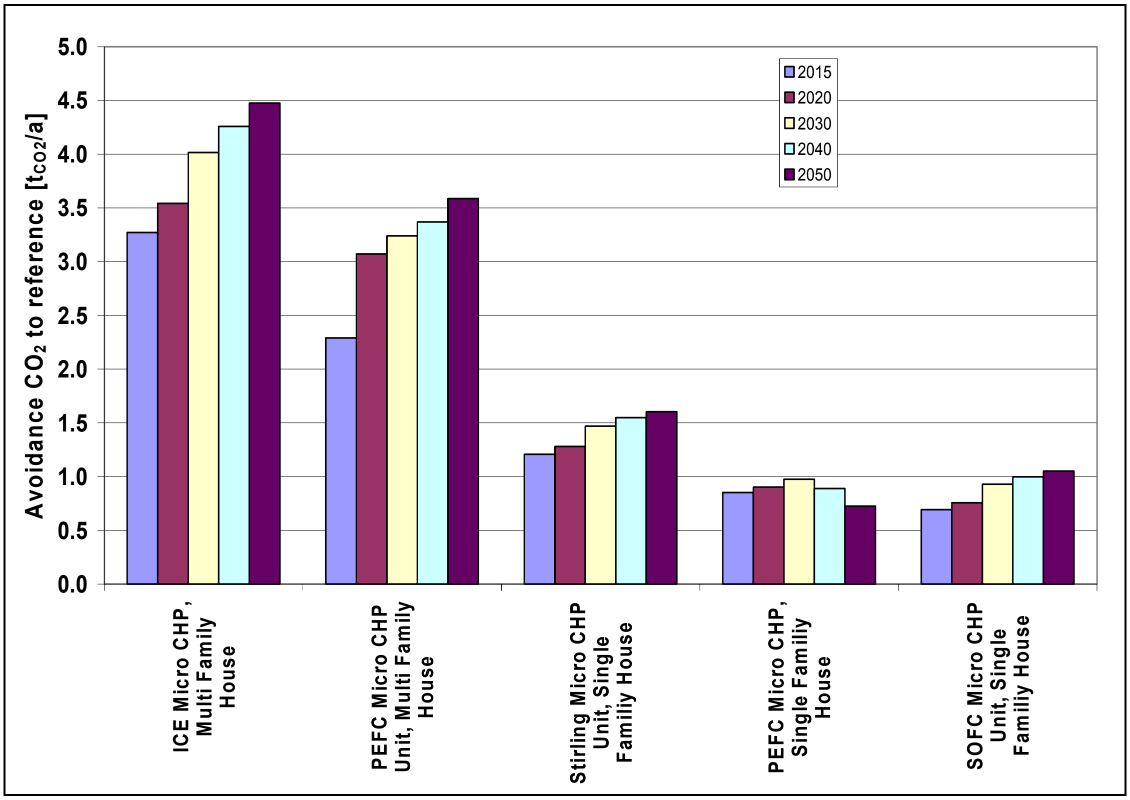

Figure 6 Abatement potential of various CHP systems per housing unit

The corresponding chart (Figure 6) for the avoidance costs shows that economies of scale play a significant role so that the abatement costs for multi-family houses are much lower or negative than for single family houses. Also the relatively high cost of very small fuel cell systems makes for rather high avoidance costs. All of the above figures are based on the assumption that starting and stopping the units does not affect their assumed overall efficiency. Because of the high operating temperature some restrictions were brought in for the SOFC system so that in the simulation the unit could not be restarted for some hours after a shutdown. It is evident that unless there can be major cost breakthroughs the fuel cell systems are at a serious cost disadvantage compared to competing CHP systems based on Sterling engines.

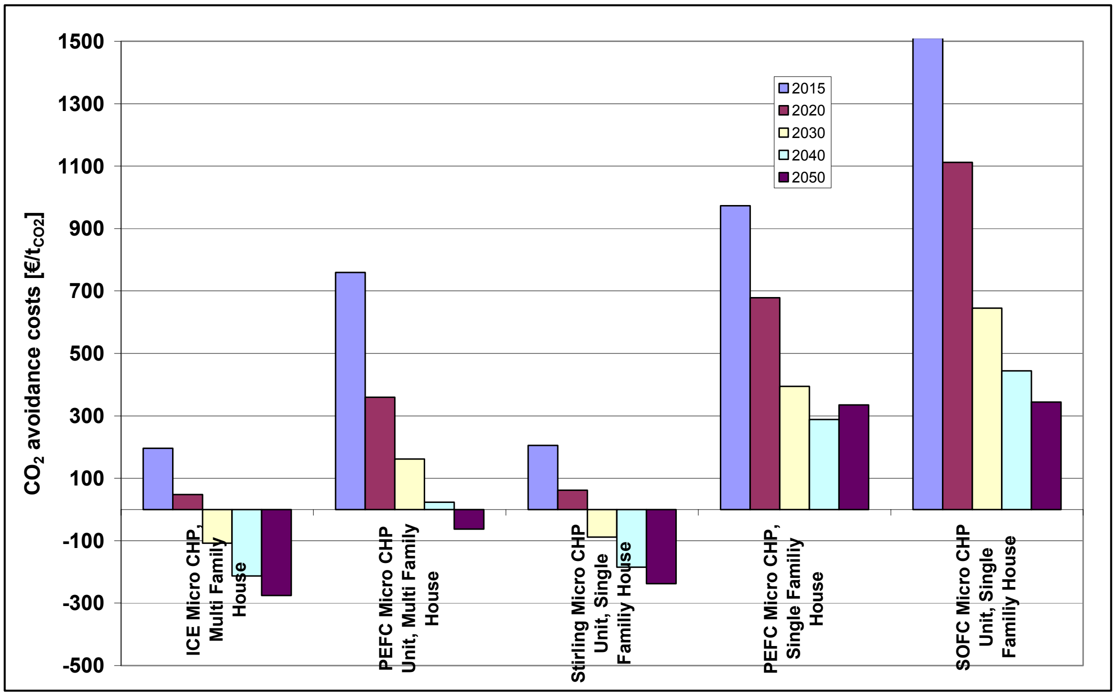

Figure 7 Cost per ton of CO$_2$ abatement using various CHP systems

Market penetration

In order to build up full scenarios for which abatement costs and amounts can be calculated it is necessary to make estimates of the number and capacity of fuel cell CHP systems which will be sold into the market. The study uses results for a market survey of heating appliances for the world market made by Bosch Thermotechnik GmbH in 2006.[3] This makes projections as to the total market and also the make up of that market. After examining information from manufacturers on progress with the development of fuel cell micro CHP systems it was considered reasonable to expect significant market entry in the OECD by about 2014. Considering the breakdown of the market and the competitiveness of other systems two cases for market penetration were selected, a low case of just 5% and a high case of 20%. A standard logistic function was used to assess the trajectory of the penetration. This was calibrated so that full market share was reached by 2030 being achieved by an initial exponential rise followed by a levelling off which is typical of such markets. Post 2030 the technology was assumed to maintain a constant share of the total market which continues to grow steadily through to 2050. The trajectories are illustrated in Figure 8.

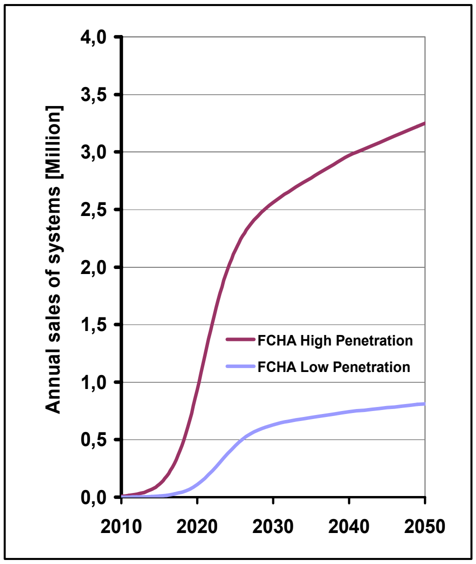

Figure 8 Market penetration profiles

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[3] BBT (2006) *Marktreport 2006 - Energie effizienter nutzen*. BBT Thermotechnik GmbH, Bosch Gruppe. www.bosch-thermotechnik.de/sixcms/detail.php?id=2326456, 2006

Overall abatement potential

Having established all these conditions the total potential for the OECD market was estimated. This is considered to be the realistic extent of the market with capability to adequately support deployment of this technology for domestic consumers. Under these assumptions the CO_2 reduction from the deployment of Fuel Cell Heating Appliances in the residential sector can reach between 14 to over 50 million tonnes of CO_2 per year by 2050. The trend in this potential is illustrated in Figure 9. To put this amount in perspective it should be noted that this corresponds to a reduction of emissions of between 1% and 4 % of the emissions in the residential sector of the OECD. Whilst significant this is a relatively modest contribution and is rather sensitive to the key parameters on which the scenario calculations are based. For consideration of different climatic zones in the OECD an arithmetic average system for the warm, moderate and cold zone was used. The CO_2 avoidance of the systems to the reference is calculated for the OECD mix of power plants with average emissions for grid electricity derived from IEA data[4].

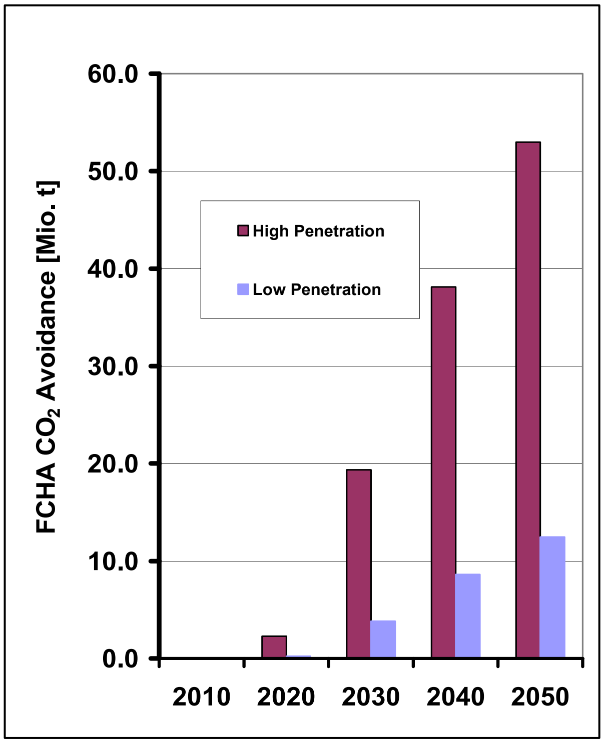

Figure 9 Potential CO_2 emission reduction from domestic fuel cell CHP systems in the OECD

Expert Reviewers Comments

The expert reviewers found the report to be detailed and thorough. Some were concerned about the rather small potential emission reductions which were calculated and felt that the assumption of a purely heat lead system was too restrictive and that better results might result if better use was made of the electrical capacity. On the other hand another reviewer commented that the reduction figures for Sterling engine CHP found from practical tests were much lower than the predictions in this report. The reason was considered to be that the overall efficiency of such micro CHP systems is considerably reduced in practice by frequent stops and starts. Thus results based on performance information for steady state operation could be seriously misleading. The same reviewer also commented that the need to have a hot water storage tank to smooth out the thermal heat production was a serious disadvantage in the domestic market place where space in domestic properties is at a great premium. This could render the assumptions for future market penetration rather optimistic.

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[4] IEA Energy Technology perspectives 2006, Scenarios & Strategies to 2050. OECD. www.iea.org.
IEA World Energy Outlook 2006. OECD/IEA.

It was commented that the insulation standards chosen for analysis of heating requirements in the moderate and cold regions were rather stringent compared to what might be typical in the OECD. Also, that the heat insulation calculations had not taken account of heat losses due to ventilation which can be significant. A more sophisticated calculation of heat loads for typical housing units would be possible but ultimately when totalised this has to agree with measured total actual residential consumption figures. It is on these latter figures on which the projected savings are based.

Reviewers also cautioned that consumer behaviour might work to reduce the calculated emission cuts since the availability of cheaper heat after a CHP system was installed would encourage its more profligate use.

There was general disappointment that fuel cell CHP systems seemed to offer so little potential for reduction of emissions but also acceptance that there were good reasons for this conclusion. It was also noted that the natural gas system might need to be significantly extended to supply the energy needed for distributed generation of electricity and given the limited emission reduction potential a better option would be to go for central decarbonisation with distribution of either hydrogen or more electricity. It was commented that fuel cells might come into their own if there was a hydrogen distribution system. However consideration of such a change in infrastructure was beyond the scope of this report.

Reviewers also commented that the report had not been able to make predictions for the reduction potential in the commercial facility market. This shortcoming is recognised but the sector is considered to be much more diverse that a convincing estimate of potential emission reductions would require a much more extensive survey of the opportunities, which could not be undertaken with the resources available for this study.

Conclusions

The main conclusion is that fuel cell CHP systems can only be expected to make a small contribution to emissions reductions in the domestic housing energy market in the future. Their potential contribution is very sensitive to the carbon intensity of the electrical power supply and if this decarbonises substantially would eliminate any of the advantages for domestic CHP systems consuming natural gas.. Fuel cell CHP systems still suffer from high projected costs compared to competing CHP systems and unless this disadvantage can be effectively addressed they will struggle in the cost sensitive domestic market place.

The report has not looked at the potential for fuel cell CHP were centrally produced hydrogen to become widely available. This would tend to improve their performance relative to competing systems. However analysis of this type of system would require development of rather speculative scenarios involving a shift to a hydrogen economy. There would be potential competition from a clean electricity based economy perhaps involving more extensive use of heat pumps which again would be a rather speculative scenario on which to base calculations.

Recommendations

It is recommended that no further work is done on analysis of the potential of fuel cell systems to reduce emissions for the time being.

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in der Helmholtz-Gemeinschaft

Research Report

05
2007

Reduction of Residential Carbon Dioxide Emissions through the Use of small Cogeneration Fuel Cell Systems

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Institute of Energy Research (IEF)
Systems Analysis and Technology Evaluation (STE)

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Reduction of Greenhouse Gas Emissions through the Use of Fuel Cells Producing Combined Heat and Power

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Executive Summary

To find answers to the question, can fuel cell technology contribute to carbon dioxide emission reduction, possible fields of application in the energy consumption sectors household, commercial and industrial sector are analysed. The fuel cell technologies are compared with today's and future conventional technologies, to find out the application potential and the corresponding carbon dioxide emission reduction.

Keywords

Fuel cell, industrial energy consumption, process heat, energy sector household, commercial sector, energy technologies

Contribution to

Report of the project "Reduction of Greenhouse Gas Emissions through use of Fuel Cells producing combined Heat and Power (IEA/CON/06/133) funded by the IEA Greenhouse Gas R&D Programme

I Introduction

The global energy supply is a very large growth market. Because of the increasing world energy consumption and the decreasing resources availability there is an enormous demand for more efficient processes and technologies.

Big efforts are being made and are necessary to improve heat and especially electricity generation which, worldwide not only has a low efficiency but also emits an enormous amount of carbon dioxide, which is seen as one of the main reasons for climate change.

Today's structures of centralised power generation are expected to be changed as far as possible towards a more decentralised structure located near to consumers which opens up possibilities to improve energy efficiency and to reduce energy generation losses. Fuel cells belong to that group of technologies which are predestined for combined heat and power production, which would improve the fuel (and therefore resource) utilisation. Because of the electrochemical reaction principle of fuel cells as opposed to the thermal combustion processes used in other combined heat and power production technologies, the fuel cell is characterised not only by particularly high electrical efficiencies of more than 50% but also by very low emissions. Their technical realisation and application could be an essential step towards a sustainable and resource conserving energy supply system.

The following chapters will analyse the possibilities for fuel cell house heating systems to enter the residential sector by analysing the market conditions and consumers requirements. The goal is to find out if the application of the small CHP systems can contribute to the reduction of carbon dioxide emissions.

With regard to emission reduction, the report concentrates on the comparison of central electricity generation versus distributed electricity generation. The distributed electricity generation is regarded as combined heat and power generation only in order to maximise the utilisation of fuels and thus reducing CO_2 emissions. For the stationary applications it seems to be unrealistic for the next 40 years to think about a worldwide widespread hydrogen infrastructure because of the existence of sufficient final energy infrastructures like natural gas or liquefied petrol gas. Therefore the report focuses on natural gas applications with connection to the local distribution grid. Because of concentrating on natural gas as final energy other micro CHP units like Stirling engines or internal combustion engines are possible counterparts too.

II Final energy consumption and carbon dioxide emission by sector, EU25

On the basis of the statistical data of [EUROSTAT 2007], the final energy consumption in the sectors industry, residential and commercial (service) were analysed to determine overall trends and relationships. The EU25 region was selected because a good cross section of situations in OECD countries and the existence of a comprehensive supporting database. The corresponding carbon dioxide emissions are calculated using specific carbon dioxide emission factors for the various sources of energy.

II.1 Energy consumption EU25

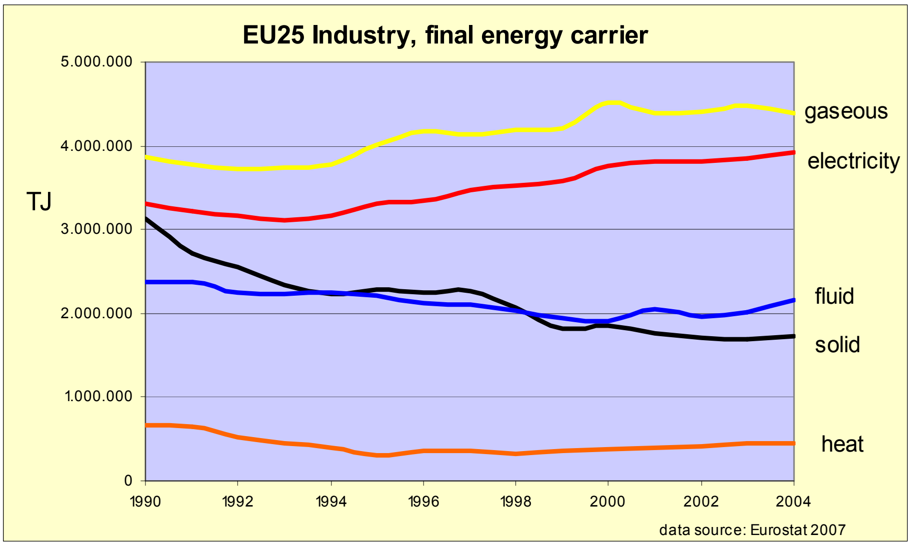
In total the final energy consumption of the three sectors rose by 7.6 percent from 1990 to 2004, but a more detailed look at each sector shows different developments. While the final energy consumption in the industrial sector decreased by 5%, it rose by 16% in the residential sector. In the commercial sector the consumption increased between 1990 and 2004 by 22%, whereby the commercial (service) sector has only a share of ~11% at the total final energy consumption.

The individual developments of the different final energy carriers in the industrial sector are shown in Figure II-1.

In the industrial sector the consumption of gas and electricity rose further despite relative economic stagnation. In total the gas demand increased by 13%. The highest increase, 38%, happened in the food, drink & tobacco industry followed by 26% in the non-metallic mineral products industry. A decrease of 20% occurred in the iron & steel branch.

The total industrial electricity demand increased by 10% with some much higher increases in specific sectors. Notably the paper & printing industry was responsible for 48% and the food, drink & tobacco industry for 32% of the overall increase.

The reduction by 42% for solid fuels is mainly caused by the reduction (-25%) in the iron & steel industry and in the non-metallic mineral products industry (-25%). The reduced demand for liquid final energy carrier is mainly caused by its declining use in the food, drink & tobacco industry as well as in the engineering & other metal industries.

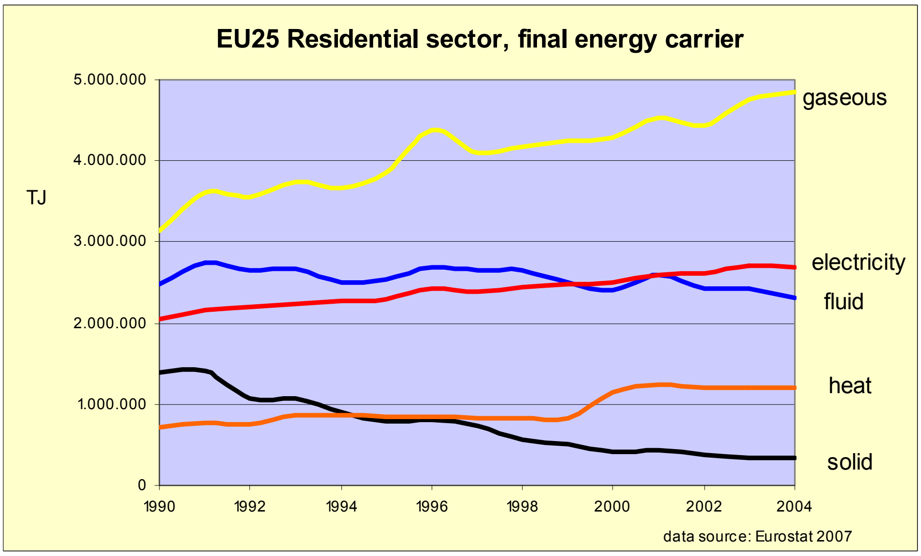


Source: [Eurostat, 2007b], IEF-STE

Figure II-1: Final energy consumption in the industrial sector by fuel, EU25

The energy supply mix in the residential sector is dominated by gas (mainly natural gas), see Figure II-2. Starting from the leading position (in 1990 a share of 32%) gas sales expanded by ~54 % up to 2004 so that it then held a share of 42%. The reason for that development is the fact, that new buildings are usually equipped with gas heating systems instead of heating oil systems, direct electricity heating systems or connections to district heating. This fact also explains the stagnation and subsequent moderate reduction of heating oil consumption.

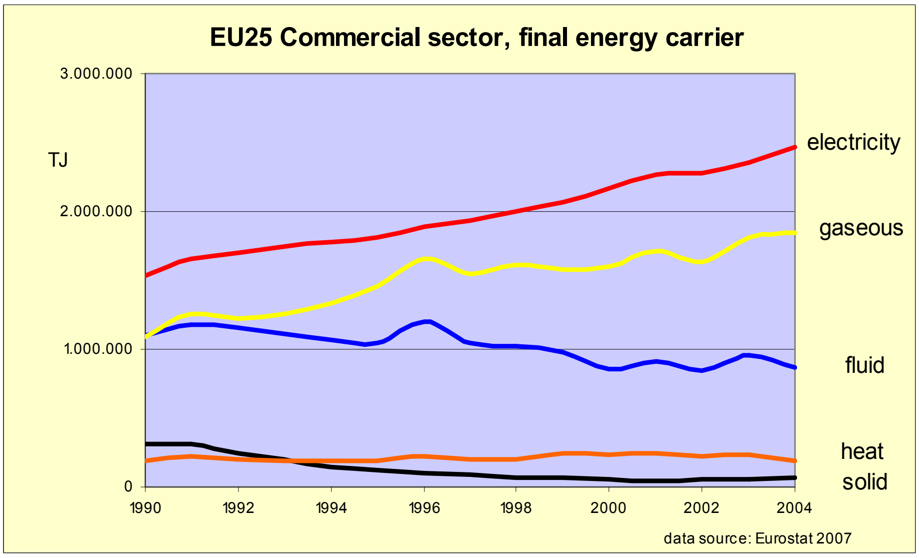
Electricity consumption rose by 31% during the period analysed because of higher electrification levels and more electrical devices in households.



Source: [Eurostat, 2007b], IEF-STE

Figure II-2: Final energy consumption in the residential sector, EU25

The development in the commercial sector is characterised by a 29% increase in energy consumption between 1990 and 2004. Electricity and natural gas profited from this and gained market share. Electricity now has a share of ~45% and gas 34%. Electricity clearly enhanced its leading position. The gradual reduction of liquid and solid energy carriers and of heat is not large in real numbers. As in the other sectors this development highlights the growing demand for clean and efficient energy carriers.



Source:[Eurostat, 2007b], IEF-STE

Figure II-3: Final energy consumption in the commercial sector, EU25

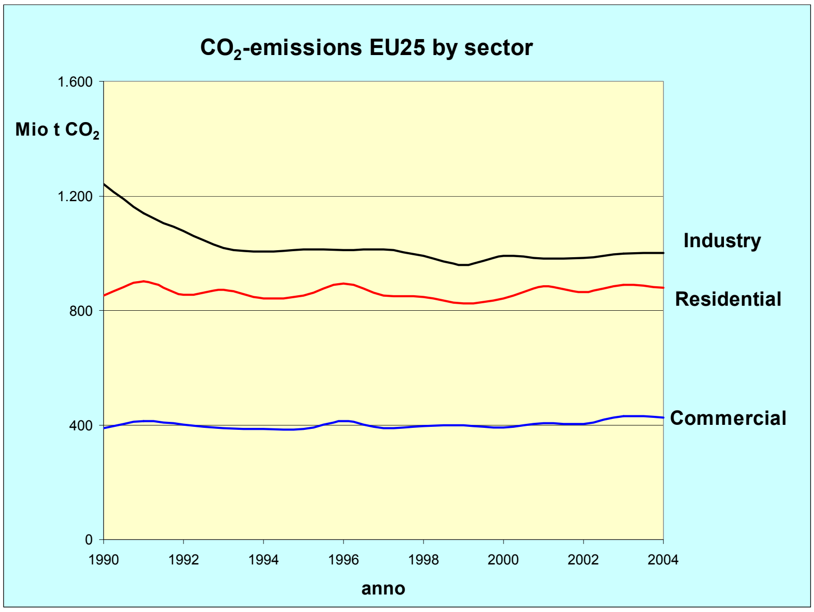
II.2 Carbon dioxide emission

The carbon dioxide emissions are determined from the amount of fuel and the corresponding specific carbon dioxide factors. The carbon dioxide factors are stoichiometrically calculated from the carbon content of a fuel (M(C) = 12.0110 g/mol, $M(O_2)$ = 31.9988 g/mol and $M(CO_2)$ = 44.0098 g/mol).

The main fossil energy sources for electricity and heat production are hard coal, coke, lignite, refinery gas and liquefied petroleum gas as well as gas/diesel oil, residual fuel oil, natural gases and derived gases. The calculated carbon dioxide amount was split between power and heat generation, so that a share for electricity and a heat production resulted. The specific carbon dioxide emission factor for the generation of one kWh of electricity was calculated by using the complete electricity production in EU25 including that which was generated by wind, solar, water, nuclear power or by burning biomass etc. The value for 2004 was 0.35 $kgCO_2/kWh_{el}$.

The specific carbon dioxide emission factor for thermal energy is derived based on the emissions from heating plants and the emission share of combined heat and power plants which is allocated to the producing thermal energy. For 2004 a value of 0.37 $kgCO_2/kWh_{th}$ was calculated.

Figure II-4 shows the development of the carbon dioxide emissions by sector for the EU25 between 1990 and 2004.



Source:[Eurostat, 2007b], IEF-STE

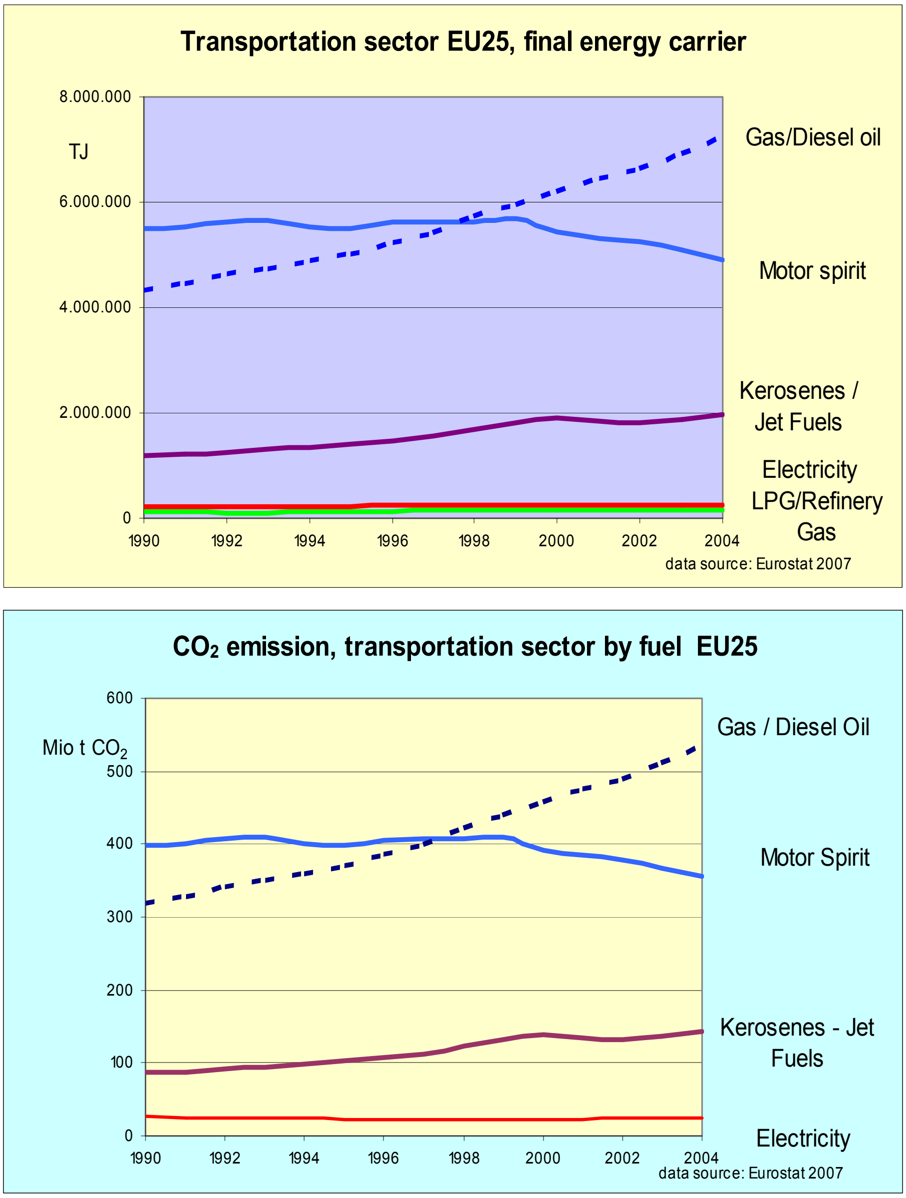
Figure II-4: Development of the CO_2 emission by sector, EU25

A clear decline can be seen for the industrial sector. It seems to be caused mainly by the reduced demand for solid and liquid fuels. That reduction more than compensated the influence of the increasing demand for gas and electricity.

The CO_2 emission curve for the residential sector shows little fluctuation. The growing consumption did not cause any significant growth in CO_2 emissions because solid and fluid fuels were substituted by natural gas, which burns with lower emissions. The same can be said for the commercial sector.

An additional figure finishes this analysis of sectoral CO_2 emissions; Figure II-5 shows the consumption of fuels in the transportation sector, upper chart, and the corresponding CO_2 emission in the lower chart.

The change in the leading fuel at the end of the nineties is remarkable. Diesel oil displaced motor spirit (gasoline, petrol) as the main energy carrier. This is for two reasons: The first is the growing number of passenger cars with diesel engines, which substituted gasoline driven passenger cars, and the second is the growing demand for freight transportation, which is operated in Europe with diesel trucks. A mirror image of that development gives the curves for carbon dioxide



Source:[Eurostat, 2007b], IEF-STE

Figure II-5: Transportation sector, development of fuel consumption and carbon dioxide emission, EU25

emission by fuel. Since 1998 diesel oil is the main source of carbon dioxide emissions in the transportation sector and the 533 Mio t CO_2 in 2004 corresponds with ~16% of the carbon dioxide emission of the final energy consumption in all sectors.

III Combined heat and power technology and fuel cells

The energy supply structure in many industrialised countries is characterised by more or less centralised generation systems. That applies in particular to the generation of electric power. An excellent example is the European electricity transmission network, which connects and supplies 23 countries and ~500 million customers, who consume ~2,300 TWh electric power per year [UCTE, 2007]. A small number of big power plants feed electricity into the network, which is operated by the Union for the Co-ordination of Transmission of Electricity (UCTE). The high reliability of the European electricity supply is ensured by the regulations of the UCTE, which obligates the Transmission System Operator to keep e.g. certain power reserve, which is large enough to compensate an unexpected loss of some GW power plant capacity. This more or less centralised power generation together with relatively long power transmission lines has come under criticism and discussion, as a more decentralised combined electricity and heat generation seems to have environmental benefits. That requires a heat consumer nearby with a continuous heat demand to avoid a discontinuous plant operation. The heart of such a decentralised supply system would be combined heat and power generation systems, which are operated near to consumer sites and which have smaller capacities than the typical centralised power plants.

In the following chapter some general information about the technological background is given. CHP-systems and their advantages are discussed at the beginning followed by descriptions of the current status of fuel cell technologies.

III.1 Combined heat and power systems

III.1.1 CHP Technology

Combined heat and power (CHP) means the simultaneous generation of thermal and electrical power in one system. In comparison to the separate generation of heat in a domestic heating system and drawing of electricity from the public electricity grid, CHP-systems have the potential to save primary energy. The main reason for this saving potential is the use of the waste heat which is normally rejected by thermal energy conversion systems. For small decentralized CHP-systems, avoiding network losses is an additional positive aspect. Figure III-1 compares the typical fuel input needed to produce 30 units of electricity and 60 units of heat using conventional separate heat and power generation on the left side and CHP technology on the right side.

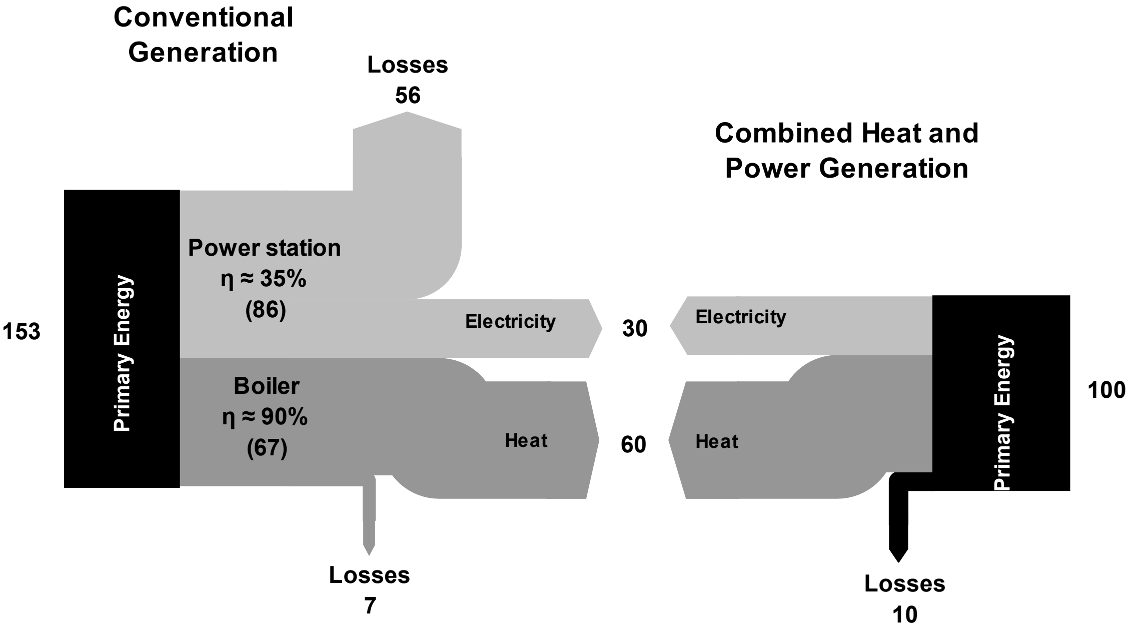


Figure III-1: Conventional vs. CHP

Because of the simultaneous generation and the very limited and expensive possibilities to store electricity immediate utilisation of the electrical power is needed.

CHP systems can follow either the heat or the electrical power demand. Micro-CHP-systems which were treated in this study generally run as heating appliances, providing space heating and warm water in residential, suburban, rural or commercial buildings. Any electricity not consumed is fed into the public grid.

To describe CHP-systems some characteristic values have to be defined. The power to heat ratio is defined as:

$$\sigma = \frac{|P_{el}|}{|\dot{Q}|} \qquad \text{III-1}$$

σ : Power to Heat Ratio

P_{el} : Electrical Power

$\dot{Q}$: Heat Flow

To get the maximum rate of energy saving, the power to heat ratio of the installation (σ_i) and of the demand (σ_d) has to be equal most of the time.

$$\sigma_i = \sigma_d \qquad \text{III-2}$$

In practical appliances such equality is rare so that an additional peak burner and heat storage for supplemental heat demand as well as a connection to the public electricity grid for peak or off-peak[1] current are needed.

Another important value is the efficiency. For a CHP-system, three efficiencies need to be defined: electrical (η_{el}), thermal (η_{th}) and total (η_{to}) efficiency. Even though it is not correct the single overall efficiency for electricity and heat for CHP are often quoted instead of the energy for both energy forms.

$$\eta_{el} = \frac{|E_{el}|}{E} \qquad \text{III-3}$$

$$\eta_{th} = \frac{|Q|}{E} \qquad \text{III-4}$$

$$\eta_{to} = \frac{|Q| + |E_{el}|}{E} \qquad \text{III-5}$$

E : Total Primary Energy Consumption

E_{el} : Electricity Generation

Q : Heat Generation

As the second law of thermodynamics implies that heat cannot be transformed completely into work, the overall efficiency does not describe a system unambiguously. To compare different CHP-systems correctly at least two of these efficiencies are needed.

III.1.2 Different Micro-CHP-Systems

For micro-CHP-systems several technologies have been developed [Simader et al., 2006].

- **Internal combustion engines** are conventional combustion engines coupled with a generator and heat exchangers to recover the heat of the exhaust gas and the cooling cycle.
- **Stirling engines** are thermal engines where the heat is generated externally in a separate combustion chamber (external combustion engines). They are also equipped with a generator and heat exchangers.
- **Micro gas turbines** are small gas turbines belonging to the group of turbo machines up to an electric power output of 300 kW_{el}. In order to raise the

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[1] Feeding surplus electricity into the public grid

electrical output micro gas turbines are equipped with a recuperator (heat/heat exchanger). They are also equipped with a regular heat exchanger in order to use the waste heat from the exhaust gases.

- **ORC:** The Organic Rankine Cycle (ORC) is similar to the cycle of a conventional steam turbine, except for the fluid that drives the turbine, which is a high molecular mass organic fluid. The selected working fluids allow low temperature heat sources to be exploited efficiently to produce electricity in a wide range of power outputs (from few kW up to 3 MW electrical power per unit).

Various other technologies, such as steam engines, thermoelectric devices, etc. are still under development.

While reciprocating units are already commercially available, Stirling engines, ORC and micro-gas turbines are at field-testing or demonstration stage.

Another competitor in this field, which is discussed in depth, are Fuel Cell CHP appliances (see chapter IV).

III.2 Fuel Cell Technology

With regard to the requirements and possibilities in the residential market, two fuel cell types have been investigated, developed and tested in-depth. These are the Proton Exchange Membrane Fuel Cell (PEMFC) and the Solid Oxide Fuel Cell (SOFC) which are described below. Though the Alkaline Fuel Cell type is well proven and used in military and space applications there is little chances of its introduction in the residential sector. A reason for this is that they operate with hydrogen and oxygen because of their sensitivity to impurities in both the fuel and the oxidant. Looking forward a possible future system for residential house heating the High Temperature – PEM is treated briefly at the end of this chapter. A further fuel cell type is the Molten Carbonate Fuel Cell (MCFC), which has been developed in the capacity range of some hundred kW. It is primarily used in the commercial and industrial sectors as well as for combined heat and power production by utilities but not by house owners in the residential sector. The same is true for the Phosphoric Acid Fuel Cell (PAFC). Though this was the first fuel cell to cross the commercial threshold, its spread of application is limited. It is expensive ($ 4,000 – $ 4,500 per kilowatt), the rejected heat has a low temperature level so that it can only be used for room or water heating, but with a capacity of 200 kW it is to large to be used in the private residential sector.

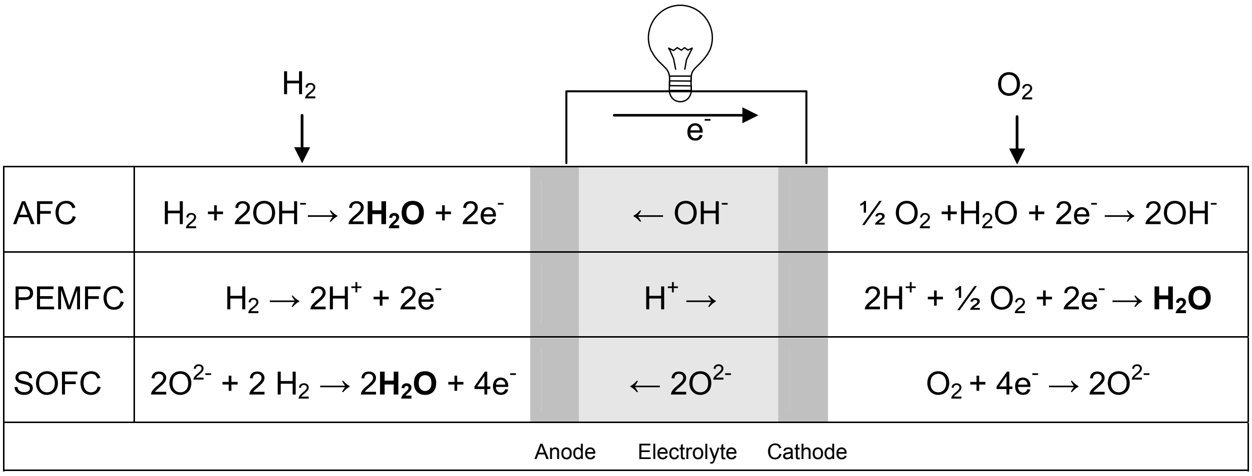
III.2.1 Basics

Fuel cells are electrochemical devices that convert chemical energy in fuels directly into electrical energy, promising power generation with high efficiency and low environmental impact.

The basic fuel cell reaction is the controlled electrochemical reaction between hydrogen (and CO in the case of SOFC's) as the reactant and oxygen as the oxidant. This electrochemical reaction is the reverse of water electrolysis. During this so-called "cold combustion" heat and electricity are released.

Cell

Fuel cells basically consist of three main parts, anode, cathode and a gas tight electrolyte layer which separates these two (see Figure III-2). The electrolyte is either permeable to anions or cations[2]. Hydrogen is fed continuously to the anode and oxygen (normally as air) is fed continuously to the cathode. The exothermic electrochemical reactions take place at the catalytically active electrodes. At the anode the Hydrogen is oxidized[3]. Due to the difference in charge the separated electrons (e^-) flow in an outer electric circuit to the cathode where they react with the oxidant. This electron flow provides electrical energy. Depending on the type of the fuel cell either the remaining cation (H^+ e.g. in PEM fuel cells) or the reduced oxidant (anion e.g. $2O^{2-}$ in SOFC respectively OH^- in the AFC) diffuse because of the concentration gradient through the electrolyte either to the cathode (H^+) or to the anode ($2O^{2-}$, OH^-) and react to form water. In Figure III-2 the main chemical reactions for some fuel cell types are shown.



AFC	$H_2 + 2OH^- \rightarrow 2\mathbf{H_2O} + 2e^-$	$\leftarrow OH^-$	$\frac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2OH^-$
PEMFC	$H_2 \rightarrow 2H^+ + 2e^-$	$H^+ \rightarrow$	$2H^+ + \frac{1}{2} O_2 + 2e^- \rightarrow \mathbf{H_2O}$
SOFC	$2O^{2-} + 2 H_2 \rightarrow 2\mathbf{H_2O} + 4e^-$	$\leftarrow 2O^{2-}$	$O_2 + 4e^- \rightarrow 2O^{2-}$

Figure III-2: Main Chemical Reactions in Different Fuel Cell Types

Performance

Fuel Cells convert chemical energy directly into electrical energy. As the intermediate steps heat and mechanical energy conversion are missing, fuel cells are not limited

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[2] An Ion is an atom or molecule which have lost (e.g. H^+) or gained (O^{2-}) electrons, making them negatively (Anion) or positively (Cation) charged

[3] basic reaction: $H_2 \rightarrow 2H^+ + 2e^-$

by the Carnot efficiency. The maximum useful energy that a fuel cell operating reversibly can deliver at a specific temperature and pressure is given by the change in Gibbs free energy (ΔG) of the electrochemical reaction. The enthalpy change (ΔH), which is equivalent to the heating value of a fuel describes the total thermal energy in a fuel. Thus the thermal efficiency ($\eta_{thermal}$) of a fuel cell is defined as:

$$\eta_{thermal} = \frac{useful\_energy}{total\_energy} = \frac{\Delta G}{\Delta H} \qquad \text{III-6}$$

with: $\Delta G = \Delta H - T\Delta S$

$$\eta_{thermal} = 1 - \frac{T\Delta S}{\Delta H} \qquad \text{III-7}$$

$\eta_{thermal}$: Thermal Efficiency

ΔG : Gibbs Free Energy

ΔH : Enthalpy Change (Heating Value)

ΔS : Entropy Change

T : Temperature

The ideal potential (voltage) of the electrochemical reaction in a fuel cell can be derived from the Gibbs free energy. Equation III-9 is only valid if a reversible ideal fuel cell operates with pure hydrogen and pure oxygen. Some values for the ideal potential are shown in Table III-1.

$$\Delta G = Q \cdot E_{ideal} = z \cdot F \cdot E_{ideal} \qquad \text{III-8}$$

$$\Rightarrow E_{ideal} = \frac{\Delta G}{z \cdot F} \qquad \text{III-9}$$

$$E_{ideal} = \frac{\Delta H}{z \cdot F} - \frac{T\Delta S}{z \cdot F} \qquad \text{III-10}$$

ΔG : Gibbs Free Energy

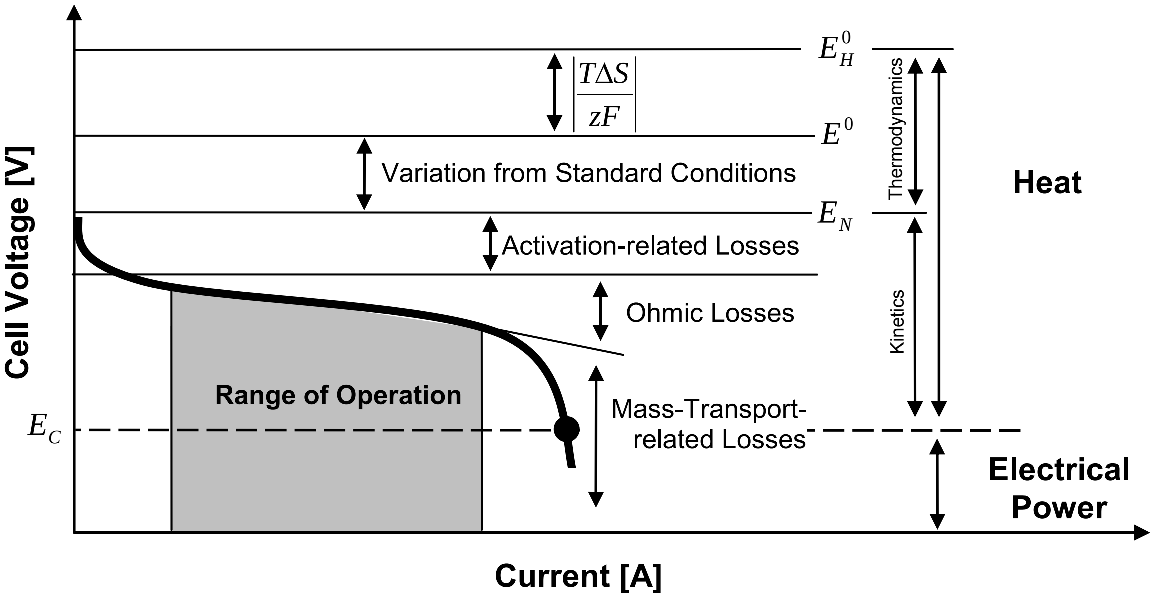
Q : Electric Charge

E_{ideal} : Ideal Potential of the Cell

F : Faraday’s Constant (96,485 C/mol)

z : Number of Electrons participating in the Reaction

In Figure III-3 the voltage/ current characteristic of a typical fuel cell is shown. On the right hand the ratio between heat and electrical power is displayed. The heat production can be divided into a thermodynamic and a kinetic fraction.



Source: [Stolten, 2006]

Figure III-3: Voltage/Current Characteristic of a Typical Fuel Cell

E_H^0 : Heating Value Potential

E^0 : Standard Potential

E_N : Nernst Potential

E_C : Actual Cell Voltage

The thermodynamic fraction consists of three parts. First, if the entropy-term in equation III-10 is zero and the cell operates at standard conditions[4], formula III-11 gives the heating value potential E_H^0 (= 1.253V, for the hydrogen reaction and gaseous water as the product). Also at standard conditions but with respect to the entropic losses the reversible ideal standard potential E^0 (=1.185 V, same conditions as E_H^0) is defined (III-12).

$$E_H^0 = \frac{\Delta H^0}{z \cdot F} \qquad \text{III-11}$$

$$E^0 = \frac{\Delta G^0}{z \cdot F} \qquad \text{III-12}$$

---

[4] 298 K and 1 bar pressure, the indices is “^{0}”

Variations from the standard conditions are considered in the so-called Nernst potential (or open-circuit potential). A basic form to calculate this potential is given in formula III-13.

$$E_N = E^0 - \frac{R \cdot T}{z \cdot F} \cdot \sum_i \nu_i \cdot \ln a_i \qquad \text{III-13}$$

The second term on the right side of this equation takes into account the dependency of the cell potential on pressure and the reactants concentration (for further information see [Stolten, 2006]).

For the basic hydrogen/oxygen-reaction[5] Table III-1 shows the different ideal potentials for some fuel cell types and their temperatures range. With the help of formula III-7 the thermal efficiency ($\eta_{thermal}$) related to the heating value potential can be calculated.

Temperature	**25°C**	**80°C**	**100°C**	**800°CK**
Cell Type	-	PEMFC	AFC	SOFC
E_{ideal} [V]	1.185	1.17	1.16	0.99
$\eta_{thermal}$	0.94	0.93	0.93	0.79
η_{system} [1]	-	0.43 – 0.5	~ 0.6	0.45 – 0.5

Source: [DOE, 2004], [1][Heinzel et al., 2006], own calculations

Table III-1: Ideal Voltage as a Function of Cell Temperature, p=1bar

The comparison between the thermal fuel cell efficiency $\eta_{thermal}$ and the Carnot efficiency η_{Carnot} is shown in Figure III-4. The Carnot efficiency is defined as:

$$\eta_{Carnot} = 1 - \frac{T_l}{T_u} \qquad \text{III-14}$$

T_l : Lower Temperature (Temperature of the Heat Release)

T_u : Upper Temperature (Temperature of the Heat Absorption)

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[5] $H_2 + \frac{1}{2} O_2 \rightarrow H_2O_{gas}$

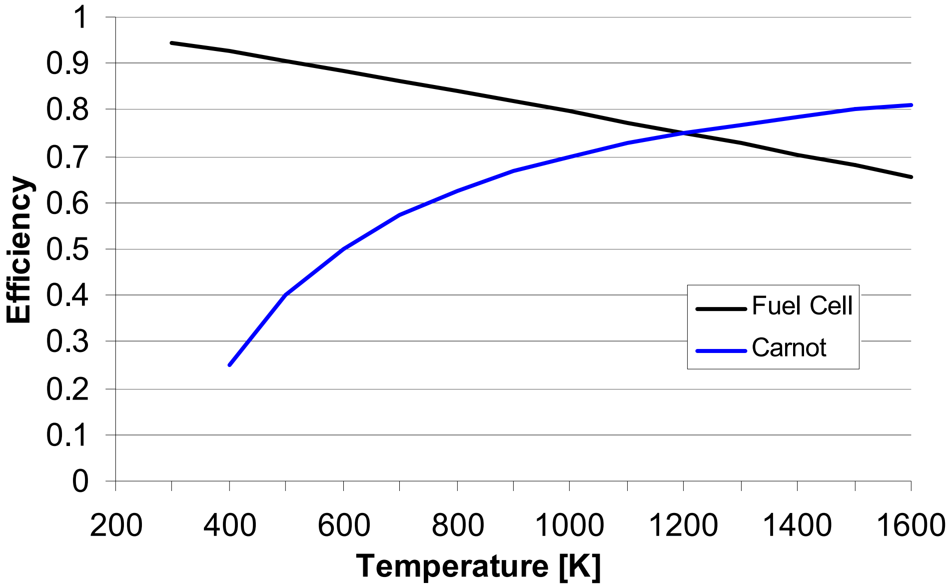


Figure III-4: Thermal and Carnot Efficiency (T_l =300K)

It is obvious that fuel cells can theoretically reach much higher efficiencies in the low temperature region than heat engines. But as indicated in Table III-1 the overall efficiencies for fuel cell systems are much lower. The reasons for this are based on the electrochemical aspects of the cell itself and on the auxiliary system components e.g. pumps, fuel supply, blowers. These aspects are discussed in the following.

The thermodynamic potentials so far described are only defined in the currentless state. If current is flowing, some supplemental **kinetic** phenomena must be taken into account [DOE, 2004] (see Figure III-1).

- **Activation-related losses:** These losses result from the activation energy of the electrochemical reactions at the electrodes. They depend on the respective reactions, the electro-catalyst material and microstructure, reactant activities and weakly on current density.
- **Ohmic losses:** Ohmic losses are caused by ionic resistance in the electrolyte and electrodes, electronic resistance in the electrodes, current collectors and interconnects, and contact resistances. Ohmic losses are proportional to the square of current density, depend on materials selection and stack geometry, and to the temperature as well.
- **Mass-transport-related losses**: These are a result of finite mass transport limitations on the rate of supply of the reactants to the active sites in the electrodes and depend strongly on the current density, reactant activity, and electrode structure.

III.2.2 Fuel Cell Systems

Stationary fuel cell systems require the integration of several components, especially when they are supplied with natural gas. Due to the existing supply infrastructure in many countries, natural gas is, as earlier mentioned, in favour to become the source for hydrogen. Figure III-5 gives an overview of the main components for such a system which are described in the following.

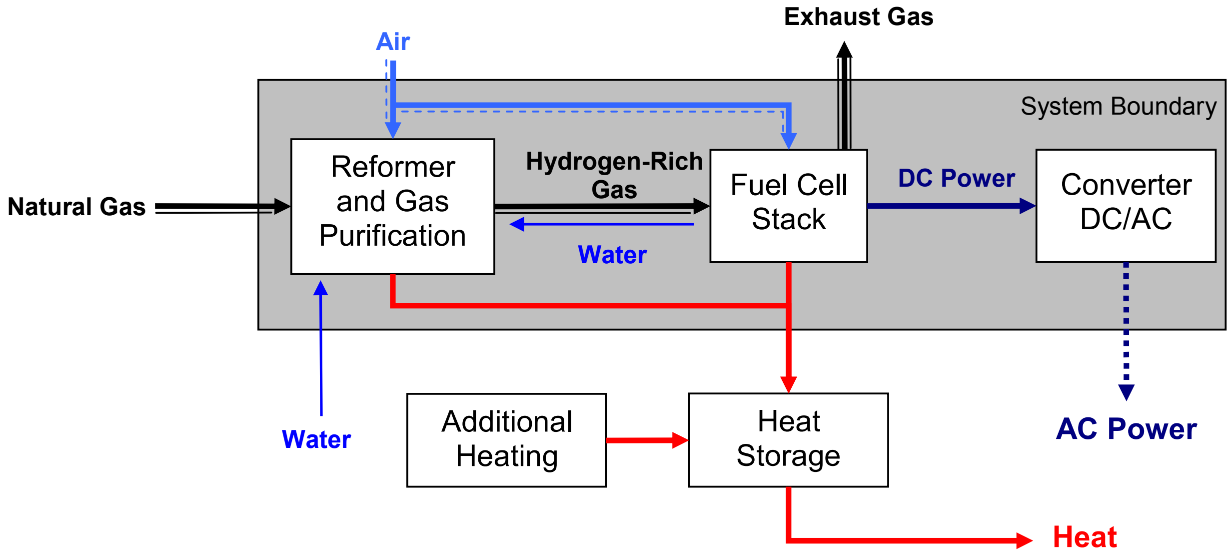
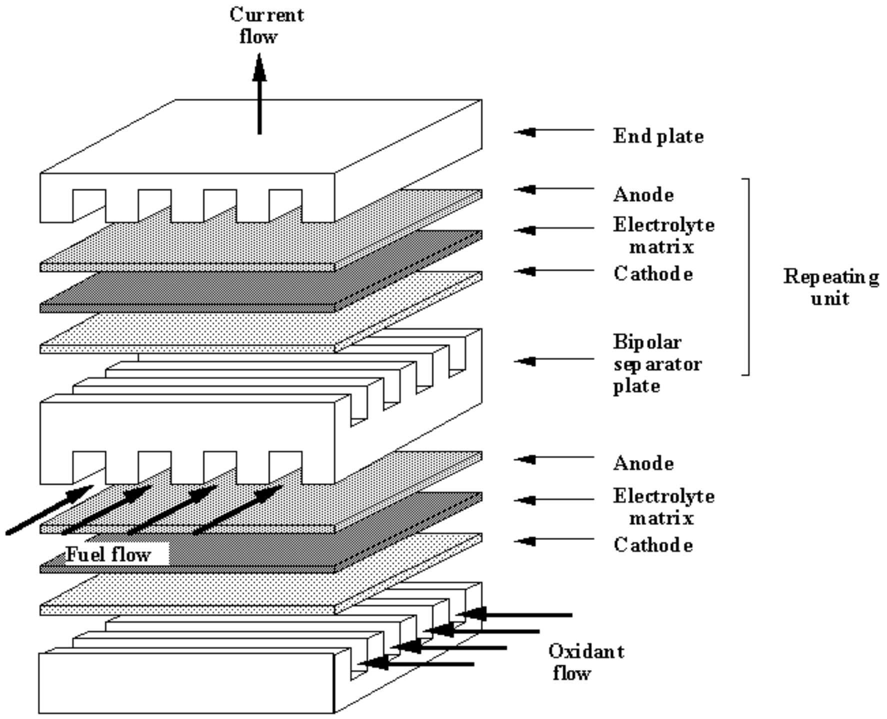


Figure III-5: Stationary Natural Gas supplied Fuel Cell CHP System

Stack

As the maximum voltage for a single cell is about 1 V (see Table III-1) several cells has to be linked in a series to form a so called stack. This technique allows the voltage of a fuel cell system to be adapted to a wide range of applications. An example of a stack is shown in Figure III-6. The single cells in this planar architecture are separated by bipolar plates. These plates take the role of electrical isolation between the cells and provide a system of fine fuel and air supply channels.



Source: [Kinoshita, 2001]

Figure III-6: Assembling of Several Cells to a Stack

Reformer and Gas Purification

The preferred fuel for fuel cells is hydrogen. Exceptions are the high temperature fuel cells (SOFC, MCFC), which allow a cell-internal reformation, and the Direct Methanol Fuel Cell which is fuelled with methanol. As the area-wide supply of hydrogen is not realised because of economical and technical reasons, carbonaceous fuels are used. They have to be reformed to hydrogen. Around 90% of the dealt hydrogen is actually produced from natural gas.

The three most commercially developed and popular possibilities for the reformation of gas to hydrogen are shown in Figure III-7.

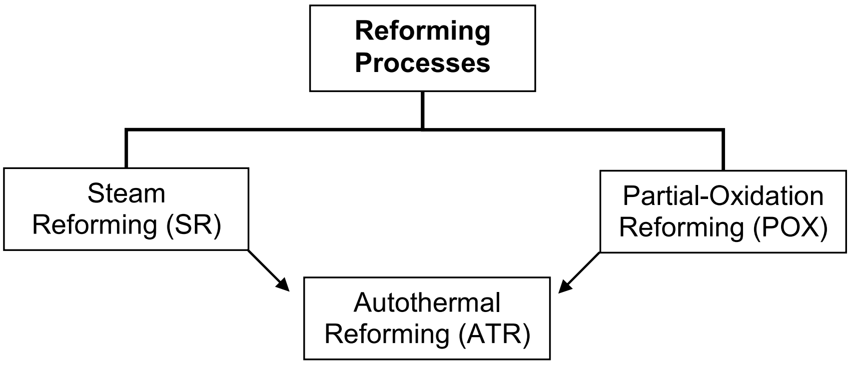


Figure III-7: Natural Gas Reforming Processes

Steam Reforming (SR) converts light hydrocarbons with the help of catalysts, steam and heat into hydrogen according to the formula III-15. It is the variant with the highest hydrogen production rate because of the supplemental hydrogen produced from the steam.

$$C_xH_yO_z + (x-z)H_2O \leftrightarrow xCO + (x+\frac{y}{2}-z)H_2 \qquad (\Delta H_R > 0\ \text{kJ/mol}) \qquad \text{III-15}$$

e.g.: $CH_4 + H_2O \leftrightarrow CO + 3H_2$ (ΔH_R=206 kJ/mol)

The **Partial Oxidation Reforming** (POX or CPOX) process partially combusts the fuel in a sub-stoichiometric atmosphere. Because of the lack of oxygen, only a small part of the hydrocarbons are converted into carbon dioxide and water. The rest is reformed into carbon monoxide and hydrogen (see formula III-16).This reaction is exothermic. The literature distinguishes between the catalytic (CPOX) and the non-catalytic partial oxidation (POX). The CPOX operates at lower temperatures but is more sensitive to contaminants especially sulphur which makes gas purification necessary.

$$C_xH_yO_z + \frac{(x-z)}{2}O_2 \leftrightarrow xCO + \frac{y}{2}H_2 \qquad (\Delta H_R < 0\ \text{kJ/mol}) \qquad \text{III-16}$$

e.g.: $CH_4 + \frac{1}{2}O_2 \leftrightarrow CO + 2H_2$ (ΔH_R= -35.9 kJ/mol)

Autothermal Reforming (ATR) is the combination of both processes. The heat needed for the endothermic steam reforming process is produced by the exothermic partial-oxidation. It is called autothermal because no heat has to be feed to or dissipated from the process.

Fuel cell types are quite sensitive to contaminants such as carbon monoxide or sulphur in the fuel gas or others and the purity specifications are higher as lower the operation temperature of the fuel cell is., Sulfer components, halogenated and condensable hydrocarbons as well as dust have to be reduced to less ppm.. **Gas purification** is therefore necessary. Common techniques for the purification are pressure swing adsorption, membrane processes, selective methanisation or selective oxidation [Heinzel et al., 2006].

III.2.3 Fuel Cell Types

PEMFC

Polymer electrolyte membrane fuel cells (PEMFC) are at the moment the most common technique for fuel cell micro CHP systems (see Figure V-2). The characteristics of PEMFC are the relatively low operation temperature and the electrolyte, which is made of a solid phase polymer membrane. To ensure the ion conductivity of the electrolyte and the removal of the generated water, an extensive water management is required. As PEMFC's are very sensitive to carbon monoxide contamination in the fuel supply, gas purification is necessary. Because of the low operation temperature, the dynamics of PEMFC are very good and the thermal, chemical and mechanical stresses are low.

SOFC

Another important technology for micro CHP systems is the solid oxide fuel cell (SOFC). SOFCs have an electrolyte that is a solid, non-porous metal oxide, usually yttrium stabilized zircon dioxide (ZrO_2/Y_2O_3). The cell operates at high temperatures, which makes internal reformation possible. The requirements for gas purity are relatively low in comparison to those required for other types of fuel cell. Because of the high temperature level, there is a wide range of possibilities to use the released heat but long start-up and shutdown processes, complex sealing and higher thermal and mechanical stresses make this difficult.

AFC

The Alkaline Fuel Cell (AFC) was one of the first modern fuel cells. It was used to provide the on-board electric power for the Apollo space shuttle. As electrolyte aqueous potash lye (KOH) is used, AFCs need industrial grade hydrogen and oxygen and are very sensitive to impurities like carbon monoxide and carbon dioxide even at the levels of CO_2 found in air. Economic advantages of the AFC are low specific cost because of a simple design and the ability to incorporate non-noble metal catalyst. The technical advantage is the high electrical efficiency (50 – 60 %) for the generation of electricity from hydrogen.

Some figures for the three described technologies just described are arranged in Table III-1. For the main electrochemical reactions for the AFC, the PEMFC and the SOFC see Figure III-2.

Type	Electrolyte	Operating Temperature	Fuel	Sensitivity to
PEMFC	Proton Conducting Membrane	~ 70°C	Hydrogen, Natural Gas, Methanol	CO_2, S
SOFC	Yttrium Stabilized Zircon Dioxide	900-1000°C	Hydrogen, Natural Gas	S
AFC	Aqueous Potash lye (KOH)	60-120°C	Pure Hydrogen	CO, CO_2, S

Source: [DOE, 2004]

Table III-2: Operation figures for the described fuel cell types

High Temperature – PEMFC

As a future option the high temperature PEMFC (HT-PEMFC) is under research and development. It uses new electrolytes which are doped with phosphoric acid and which need not be humidified, so that higher operation temperatures are enabled. The higher temperature gives the possibility for future combinations with heat driven cooling systems and also simplifies the heat recovery for CHP-systems as the heat exchangers can be made smaller. Another very important aspect is the higher tolerance to carbon monoxide. However the technology it is not yet realised because there are factors to improve such as the power density and the system dynamics, which currently do not allow frequent load changes.

The Vaillant company is participating in a transatlantic consortium to intensify the R&D efforts for HT-PEMFC and to develop and test a 5 kW CHP-prototype. Partners in this cooperation are amongst others Plug Power (stack development) and PEMEAS (now BASF) which is developing the new electrolyte based on polybenzimidizole (PBI) with a phosphoric acid gel film. The temperature level of the cell is expected to reach up to 180°C [Badenhop, 2007].

IV Capacity range of energy supply systems by sector

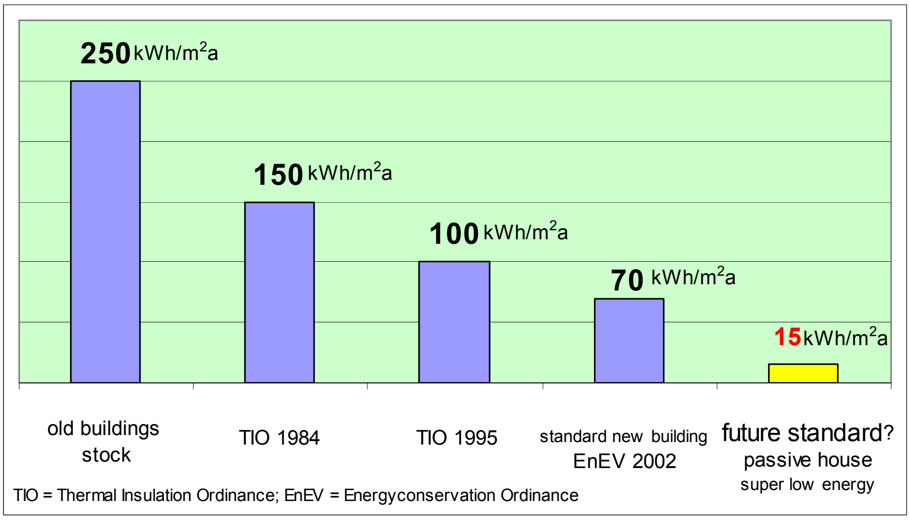
At the beginning of chapter III it was mentioned that a structural change of the energy supply system is likely to be initiated. The transition from the today's centralised supply system towards a decentralised structure makes the implementation of combined heat and power systems in the final energy consumption sectors like household, commercial and industry possible. The conditions within these sectors differ clearly and influence the applicable technologies as well as their capacities and operation modes.

The requirements and characteristics in the three sectors are analysed and the following chapter points out competitive conditions and the possibilities for fuel cells to come into the market.

IV.1 Residential sector

The sector household has been divided into two building categories: Single family houses, two family houses and row houses belong to the first while multifamily houses with up to some ten or more flats belong to the second.

The typical energy supply system for the first category is a heating boiler at each house with a capacity which corresponds to the heat demand. In new houses, which fulfil the today's insulation requirements, the installed heating systems have a capacity of around 5 to 12 kW_{th}. Older houses have insufficient or nearly no insulation, so that they need higher heating capacities up to a range of 20 to 30 kW_{th}. The statistics for Germany show that systems with a capacity of more than 30 kW_{th} are very rare. The development of the specific heat demand for the new buildings is shown for Germany in Figure IV-1.



Source:[EnEV, 2004], IEF-STE

Figure IV-1: Development of the specific domestic heat demand

There is no doubt, that the future standards are moving in the direction of 15 kWh_{th}/m^2a, however it will take many years (probably decades) to change the building stock as the lifetime of residential houses is currently around 100 years.

Typical within the second building category in the residential sector, i.e. multifamily houses, is the central heating system. Gas boilers of lower capacity supplying just one floor or flat are certainly an exception in Germany and probably elsewhere too. Normally such multi-unit dwellings have central heating systems with a capacity of twenty to thirty kW_{th} or more, depending on the number of supplied flats. As a rule heating oil systems have a higher rated capacity than gas systems, when used in similar circumstances.

Because of rising energy prices and directives for energy saving, new buildings today fulfil high insulation standards and have a very low heat demand, while old buildings are being retrofitted with energy saving installations, so that the specific heat demand is declining as shown with Figure IV-1. The reduced demand enables the installation of heating systems with lower capacities. It can be assumed, that this development will continue so that old heating systems with capacities of more than 15 to 20 kW_{th} (category single houses) will be substituted by new smaller ones within the next few decades.

And that can be expected also for many other OECD countries. The OECD assumes that the energy consumption in buildings in Europe and North America can be reduced with 50% by using measures that are feasible already today. Most OECD countries have norms for energy efficiency in the regulations for new buildings. The member states of the European Union have to incorporate the requirements of the European Energy Performance of Buildings Directive (EPBD) in national legislation by January 2006 and house insulation is one of the measurements to reduce the residential energy consumption. Several states of the United States of America have restrictive requirements like California. While Japan has not yet a comparable directive, Australia did introduce Energy Efficiency Provisions for Housing first in 2003 and did enhance them in 2006 [Lausten 2006] [Lausten 2008].

Fuel cell systems for home energy supply

When considering new heating systems, which fulfil the requirements of the users and the requirements of a sustainable and environmentally friendly energy supply, fuel cell technology has come into play. It has a relatively high electrical efficiency, based on electrochemical reactions. In spite of that characteristic, manufacturers like Baxi-Innotec, Acumentrics, Vaillant and others see the generated electricity only as by-product, the main purpose of the fuel cell home energy supply system is house heating. "*Combined heat and power generation plants will always be a viable solution when both electricity and heat are required - for example in domestic installations.*

Apart from the electrical efficiency, heat usage largely determines the operational life and hence the cost-effectiveness of a CHP system. This should be approximately 5,000 hours per year – the normal usage for an average detached house. Fuel cell heating systems represent typical CHP plants. A fuel cell process providing an output of 1.5 kWel and 3.0 kWth usually covers the basic heat requirements for the building. Sustainable and environmentally-friendly, it covers up to 75% of the electricity and 65% of the electricity and heat demand, respectively. The remaining heat - or so-called peak requirement - is generated by an integrated auxiliary burner (up to 100%)." /Baxi-Innotech/

The electrochemical principle of the fuel cell guarantees a very low emission level. Only auxiliary systems like reformer or after burner produce emission like CO_2, CO, NO_X or others. A further advantage is the fact, that fuel cells are constructed as modules (cells and stacks) which opens the possibility to vary the capacity by combining less or more modules corresponding to the demand.

An overview of the units which have been designed, are under development or have been tested for the use in the residential sector is given in Table IV-1 and Table IV-2.

The first one is the Intensys alkaline fuel cell system which started operation in January 2007 near Brussels in Belgium. That micro-CHP fuel cell system was designed in cooperation with the Russian system integrator Independent Power Technologies. The special features of this system are the high electrical efficiency of 45% and the power to heat capacity ratio, 6 kW_{el} respectively 5.2 kW_{th}.

Proton exchange membrane fuel cell systems for the residential sector are far into development and several companies are engaged in that field.

Five 4 kW_{el} demonstration units of the German Inhouse Consortium are being analysed in field tests and a 5 kW_{el} unit was presented in spring 2007 as a new system for the growing market of decentralised cogeneration systems.

The German company Baxi Innotech (former European Fuel Cell) is operating ~12 units in field tests. The BETA 1.5 unit has an electrical capacity of 1.5 kW_{el} and a thermal capacity of nominal 3 kW_{th}. It was developed for the residential market to serve the base heat demand of the house, while the peak load is supplied by an integrated boiler. The company expects to start with a batch production in 2010.

The German company Vaillant did manufacture and test together with the US company Plug Power a large number of fuel cell heating systems for the residential market, and thus they have very good experiences in that field. The results of the field tests were very good, but the perspectives for reducing manufacturing cost, volume etc. were not promising. So they stopped their activities with the "low temperature PEM Fuel Cell heating system" EURO I as well as EURO II, to start new

		Alkaline fuel cell	Proton exchange membrane fuel cell systems						
company		**Intensys**	**Inhouse Consortium**	**Baxi Innotech** (former EFC)	**Viessmann**	**Vaillant/ PlugPower**	**EBARA/Ballard**	**Matsushita Electric Industrial Co**	**Toyota/Aisin**
type		PULSAR-6	inhouse 4000	Beta 1.5	HEVA II				
		complete system	complete system	complete system	complete system	complete system			
principle		alcaline fuel cell	low temp PEM FuelCell	low temp PEM FuelCell	low temp PEM FuelCell	high temp PEM FuelCell	low temp PEM FuelCell	low temp PEM FuelCell	low temp PEM FuelCell
fuel		hydrogen (industrial grade)	natural gas	natural gas			city gas	city gas	city gas
electrical capacity	kW_{el}	6	4	1.5	2	5	1.0	1.0	1.0
thermal capacity	kW_{th}	5.2	3 - 10	3	5		~1.3$^{4)}$	~1.3$^{4)}$	~1.3$^{4)}$
additional peak boiler	%			3.5 - 15	24				
electrical efficiency	%	45	average 20.6 max. 27.3 $^{1)}$	up to 30	32	target: 35	31 (HHV)	33 (HHV)	33 (HHV)
thermal utility degree	%	43	average 57 max. 54.5 $^{1)}$	48 (target 50)			40 (HHV)	44 (HHV)	
overall efficiency	%	87		~ 78	> 87	target: 85			79 (HHV)
CHP coefficient			average 0.36 max. 0.47						
heating circuit temperature			40 / 60 °C						
natural gas consumption	m^3 / h		0.5 - 1.5						
water consumption	dm^3 / h		< 10						
actual specific price	Euro / kW_{el}		~ ten thousand						
targets specific cost/price	Euro / kW_{el}		4.000 $^{2)}$	~ 10.000	~ 6.000	750 $^{3)}$			
status		in field test	in field test	in field test			in field tests	in field tests	in field tests
number of units in field trials		1	5	12	1 unit starts summer 2007	-	183	88	24
									

$^{1)}$ results from test runs August 2005 - Dezember 2006, $^{2)}$ goal @ 200 units, $^{3)}$ total system cost @ production volumes, $^{4)}$ calculated

Source: IEF-STE, companies information

Table IV-1: Some alkaline and proton exchange membrane fuel cell systems

activities in developing a high temperature Polymer Electrolyte Membrane Fuel Cell system, which has better prospects.

Nearly 800 PEMFC-systems have been installed in 2006 in Japanese households. The units have an electrical capacity of 1 kW_{el} in each case and are combined with hot water storage tanks of some hundred litres. As the electricity demand of a household is too high and too fluctuating to be supplied by a fuel cell alone, the consumer is connected to the public grid. However the fuel cell can contribute to the base load until the hot water storage is fully loaded, then the system is shut down. Sanyo Electric Cooperation operates the largest number of units (266) followed by Toshiba FCP with 216 units and Ebara, which is testing 183 units. Panasonic and Toyota also participate in the Japanese residential fuel cell demonstration program with some ten units each.

Table IV-2 shows three solid oxide fuel cell types. All have a nominal electrical capacity of 1 kW_{el} and are developed for application in individual houses.

Characteristic of the $NetGen^{Plus}$ fuel cell module of Ceramic Fuel Cell Limited is the high power to heat ratio of about 1.5. Because of that feature it is expected to be economic in operation, as much electricity as possible would be generated and sold. It is planned to integrate the module into a condensing boiler platform to ensure the heat supply. Four units are currently being operated in field tests in Germany.

		Solid oxide fuel cells			
company		**Ceramic Fuel Cell Limited**	**Hexis**	**Acumentrics**	**MTS / Elco / Acumentrics**
type		$NetGen^{Plus}$ fuel cell module[1)]	Galileo 1000 N	AHEAD	
		Stack module	complete system	complete system	complete system
principle		SOFC planar	SOFC planar	SOFC tubular	SOFC tubular
fuel		natural gas	natural gas	natural gass	natural gas
electrical capacity	kW_{el}	1	1	1 (2.5 peak)	1
thermal capacity	kW_{th}	~ 0.65 offgas cooled @ 20°C	2.5	1 - 24	2
additional peak boiler	kW_{th}		20		22
electrical efficiency	%	> 50	25 - 30 (target > 30)	30	25 - 30
overall efficiency	%	60 - 85	> 90	90	~85
status		available	under development	pre-commercial stage	under development
number of units in field trials		4	4	min 30	zero
[1)] ready for integration into appliances					

Source: IEF-STE, company's information

Table IV-2: Solid Oxide Fuel Cell systems for the residential market

The Galileo system of the Swiss company Hexis AG can be seen as the further advancement of the former Sulzer-Hexis system HXS 1000 which did not lend itself to a successful future with regard to material, volume and cost reduction, improvement of performance, maintenance reduction etc.. Nearly 110 units of the type HXS 1000 were operated with success in demonstration and field tests. The concept of the new type Galileo 1000 N was based on this experience and is more compact and light because functions and components could be combined and simplified. The employment of standard components from conventional heating systems makes the device simpler, facilitates serial production and simplifies the maintenance. The Galileo is still in the design stage and the current work is concentrating on the improvement of the stack efficiency and lifetime. The developers are confident of reaching their targets and becoming competitive in the near future.

The third one is the 1 kW_{el} Acumentrics' Home Energy Alternative Device (AHEAD) which uses the tubular cell concept. The US company Acumentrics announces that the development has reached a pre-commercial stage and that units are being tested at qualified customers. The company has a joint venture with the Italian MTS Group (Merloni Termo Sanitari) on developing a fuel cell heating system for the European market. MTS is developing, together with its German part Elco, a 1 kW_{el} wall mounted fuel cell house heating system, which has an additional heating boiler to supply the peak load, see example 4 in the Table IV-2. It is planned to start installing a couple of test units around the end of 2007 in European countries.

Fuel cell micro CHP units up to the power of nearly 5 kW_{el} usually are equipped with a one phase feeding into the grid; for higher power inputs 2 and 3 phase systems are used.

From the forward looking statements of the enterprises it does not become clear, with which capacity sizes the house heating systems shall go into the market. However the impression strengthens that single family houses are an important market which can be reached with small units and there are companies which are developing wall mountable systems. It cannot be excluded, that the Japanese example stands for it godfather, where already some thousand 1 kW systems are in extensive field tests

Competitors for the fuel cell systems will be bio-mass based heating systems or condensing boilers, heat pumps or advanced combined heat and power generating systems with reciprocating engines, steam expansion engines or Stirling engines.

Wood pellet heating boilers can be seen as representatives of the category bio-mass based heating systems for the sector household. They have a capacity range of ~5 to 30 kW_{th} and more so that they can be used in single family houses as well as in multi family houses. The boiler efficiency is indicated to be ~90% by different manufacturers.

The capacity range of **condensing boilers** starts at ~3 kW_{th} and reaches up to more than 100 kW_{th}. Because of their variability they can be used in flats, single houses and in multifamily houses too. Table IV-3 shows example data for condensing boiler systems which can be seen as typical for installations in the market segment single houses. Except for the wood fired Logano boiler of Buderus, all can be mounted on the wall. These systems need little space, so that they can be placed either in the cellar, the bath room or the loft with the advantage then of using a short and cheap flue pipe instead a conventional chimney. The thermal utility degree of more than 100 % in the table can be explained by the fact, that the condensing of hot gases can turn the latent energy contained in water vapour into useful heat since the basis for the measurement is the Lower Heating Value (LHV).

		Condensing boiler			
		Vaillant	Viessmann	Buderus	Junkers
		ecoTEC	vitoladens 300-W	Logano SP 131	cerapur
fuel		**natural gas**	**heating oil**	**wood**	**natural gas**
electrical capacity	kW_{el}	-	-		
thermal capacity	kW_{th}	3/13, 4/20 etc	13/19, 16/23	14,9 / 22	3/16, 7/22
additional peak boiler	%				
electrical efficiency	%	-	-		
thermal utility degree	%	109 [1)]	104 [1)]	90	109
fuel utilisation degree	%				
price (installation inclusive)	Euro	~ 3,000	~4,000	~ 12,000	~ 2100
[1)] DIN 4702					

Source: IEF-STE, companies publication

Table IV-3: Examples for condensing boilers

Except for the wood fired Logano boiler of Buderus, all can be mounted on the wall. These systems need little space, so that they can be placed either in the cellar, the bath room or the loft with the advantage then of using a short and cheap flue pipe instead a conventional chimney. The thermal utility degree of more than 100 % in the table can be explained by the fact, that the condensing of hot gases can turn the latent energy contained in water vapour into useful heat since the basis for the measurement is the Lower Heating Value (LHV).

Reciprocating engines convert the fuel energy into mechanical energy and are well known from their use in the automobiles. In that application they are normally operated with benzene (motor spirit) or diesel, but they can be operated with gaseous fuels too. If the technology is used for a stationary application it drives an electric generator and the heat of the exhaust gas, the cooling water and the lubricant (oil) is regained by heat exchangers to supply a heating system. Table IV-4 gives a general view of the characteristics of diesel and spark ignition engines.

	Thermo dynamical cycle	Fuel used	Efficiencies		Power size range
			total	electrical	
Diesel engine	Diesel cycle	Gas, biogas, ELFO*), LFO **), HFO***), rape oil, RME ****)	65 - 90	35 - 45	5 kWel to 20 MWel
Spark ignition engine	Otto cycle	Gas, biogas, naphtha	70 - 92	25 - 43	3 kWel to > 6 MWel
Average cost investment in €/kW_{el} (Fuel oil engine)			340 - 2000		
Average cost investment in €/kW_{el} (spark ignition gas engine)			450 - 2500		
Operation and maintenance costs in €/kWhel			0,0075 - 0,015		

*) Extra Light Fuel Oil, **) Light Fuel Oil, ***) Heavy Fuel Oil, ****) rapeseed methyl ester

Source: Simader

Table IV-4: General characteristics of diesel and spark ignition engines

More detailed data for three reciprocating CHP units which are available on the market are given in Table IV-5.

The company SenerTec claims to be the European market leader in the category small CHP units. Since the start of production ~17,000 Dachs units have been sold and most are still in operation. Around 70% are sold to private users. The electrical efficiency of the diesel version of the Dachs is higher than that one of the gas-version engine. Further usable fuels are gaseous or liquid bio-fuels.

		Reciprocating engines		
company		Senertec (BaxiGroup)	PowerPlus Technologies (Vaillant Group)	Honda
type		DachsSEplus	Ecopower	GE160V
fuel		Gas, Oil, RME	Gas	Gas
electrical capacity	kW_{el}	5.0 - 5.5	1.3 - 4.7	1
thermal capacity	kW_{th}	12.5 - 20.5	4 - 12.5	3.25
electrical efficiency	%	~ 27 @ gas ~ 30 @ oil	25	20
thermal efficiency	%	~ 60	65	65
total efficiency	%		90	85
price	Euro	~ 20,000 1)	~ 16,000	~ 6,200 2)
1) 2007 2) 2005-exchange rate from Yen to Euro				

Source: IEF-STE, companies publication

Table IV-5: Examples for reciprocating engines

The Ecopower CHP unit is integrated into the building services in parallel with a peak boiler. In that combination the CHP unit covers the base and medium heat load, while the peak load is supplied by the boiler. It has a continuously variable engine speed so that it always operates at optimal efficiency and offers long operating periods. It has an output control which enables optimisation of the electricity production.

The Honda system is designed for family house use. The information available on the system is promising. It is only sold in Japan and is not yet available in other countries. The price of 6,200 Euro for the GE160V results from converting the 2005 Yen-price to Euro.

Stirling engines are external combustion devices and differ substantially from conventional combustion engines where the fuel burns inside the machine. Heat is supplied to the Stirling engine by an external source, such as fuel burner. This makes a working fluid, e.g. helium, expand and cause one of the two pistons to move inside a cylinder. The Stirling engine has fewer moving parts than conventional engines, and no valves, tappets, fuel injectors or spark ignition systems. It is therefore quieter than normal engines and requires little maintenance [Irish CHP Association]. Characteristic data for three representative systems are given in Table IV-6.

		Stirling engine			
		WhisperGen (Mk5)		Solo Stirling 161	*Sunmachine* 4)
fuel		**natural gas**		**natural gas**	*wood pellet*
electrical capacity	kW$_{el}$	1.0 1)	1.0 2)	2 - 9,5	*1.3 - 3*
thermal capacity	kW$_{th}$	9 1)	7.5 - 12.0 2)	8 - 23	*4.5 - 10.5*
additional peak boiler	%	5.5 1)			
electrical efficiency	%	10 - 20	9 2)	22 - 24.5 3)	*20 - 25*
thermal utility degree (related to LHV)	%		83 2)	65 - 75 3)	
fuel utilisation degree	%	90			*90*
price (installation inclusive)	Euro	~ 4,500 (UK price)		~30,000	*target: ~27,000*
1) Company broschure 2) DBI GUT test results & VSE AG calculations 3) related to cooling water income temperature 50°C 4) under development					

Source: IEF-STE, companies publication, lab-test results

Table IV-6: Technical data for Stirling engine based small CHP units

The WhisperGen^{TM} micro combined heat and power system of the New Zealand Company WhisperGen Limited was developed from a DC system for marine and remote application. It is being tested in UK and Germany, whereby some thousands of units are installed under special contract in the UK residential market. Though the appliance is available, it is still under development, as the practical test results do not yet reach the targets or the company’s lab-results. There are still remarkable differences with regard to the electrical efficiency, the thermal efficiency and the total efficiency. Satisfactory results could be measured in continuous operation, but performance decreases in real operating situations.

The electric power output of the SOLO Stirling cogeneration unit can be modulated between 2 and 9.5 kW$_{el}$ and the thermal energy output between 8 and 23 kW$_{th}$. This feature makes it suitable for medium to large living areas and for the commercial sector as well as for industrial application. This product has been on the market for

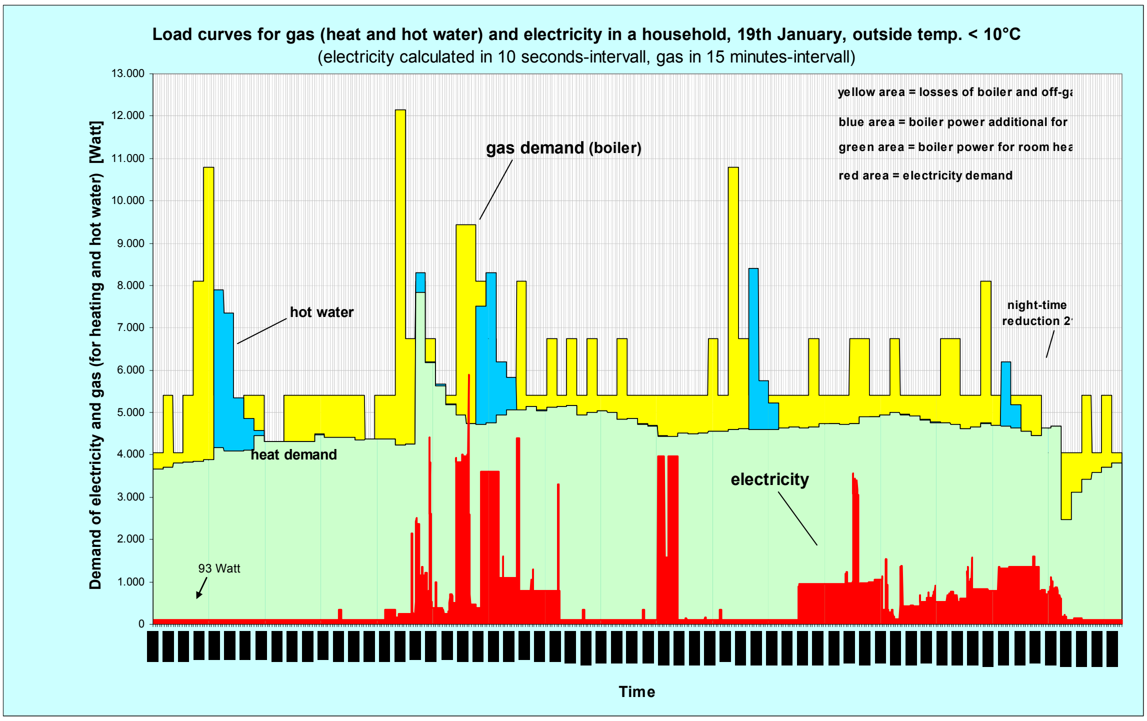
~3 – 4 years. The company informs that up to now ~ 150 units have been sold and are in operation. (Because of financial liquidity problems, SOLO Stirling was taken over by a Swiss company, Stirling Systems AG, in late spring 2007 and it is reported, that the production of that system will continue.)

The wood pellet fired Sunmachine CHP unit can be looked upon as a special case. It is a derivative of a gas fired Stirling system with the advantage that it is fired with a renewable energy carrier. The field tests are not yet finished, but the company is confident that it will be able to solve remaining technical deficiencies so that a commercial version can be presented in 2008.

IV.2 Requirements of energy supply systems in the residential sector

The mainly required energy service in the residential sector is space heating. In Germany it has a share of 75% of the final energy consumption, followed by 16% for process heat for hot water preparation and cooking. That demand influences strongly the load curve for heat and electricity in households.

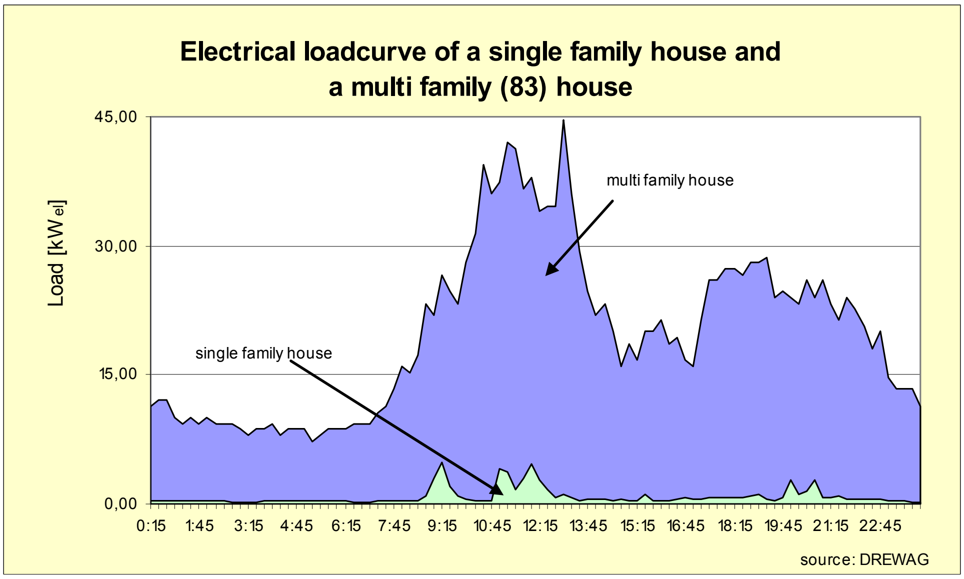
Figure IV-2 points out the load curve of electricity and heat of a free standing one-family house, which is inhabited by 4 persons, two adults and two children. The electricity load curve is determined in 10 second intervals, while the heat/gas curve was calculated in 20 minute intervals. The gas boiler has several starts per day, which is mostly caused by the hot water demand.



Source: IEF-STE

Figure IV-2: Load curve electricity and heat (via gas boiler) of a single family house

The load curve of the calculated heat demand is relatively constant, as the house has good heat storage characteristics because of its heavy steel, concrete and lime sand brick construction. The electricity load curve of this highly electrified house is characterised by sudden load variations, from less than a hundred Watts to some thousands of Watts and back. Because of the consumer's habits, there is a high electricity demand in the morning, a peak around noon and a moderate demand without extreme peaks from the late afternoon until the evening. The base load of the house is in the range of around 100 Watt and it is caused by the stand-by demand of appliances like doorbell, cordless telephone, clock radios, heating boiler control, refrigerator, freezer, house alarm system and other permanently powered control systems.



Source: IEF-STE, DREWAG

Figure IV-3: Example for the load curves of a single and a multi family house

Figure IV-3 shows the different electrical load curves for one single household and for a multi-storey building with 83 flats. The minimum value of the electrical load is near 10 kW along the whole day, so that a system with higher electrical capacity than for a single family house can be operated. If the heat demand is suitable, a CHP plant can find optimal operating conditions in those buildings.

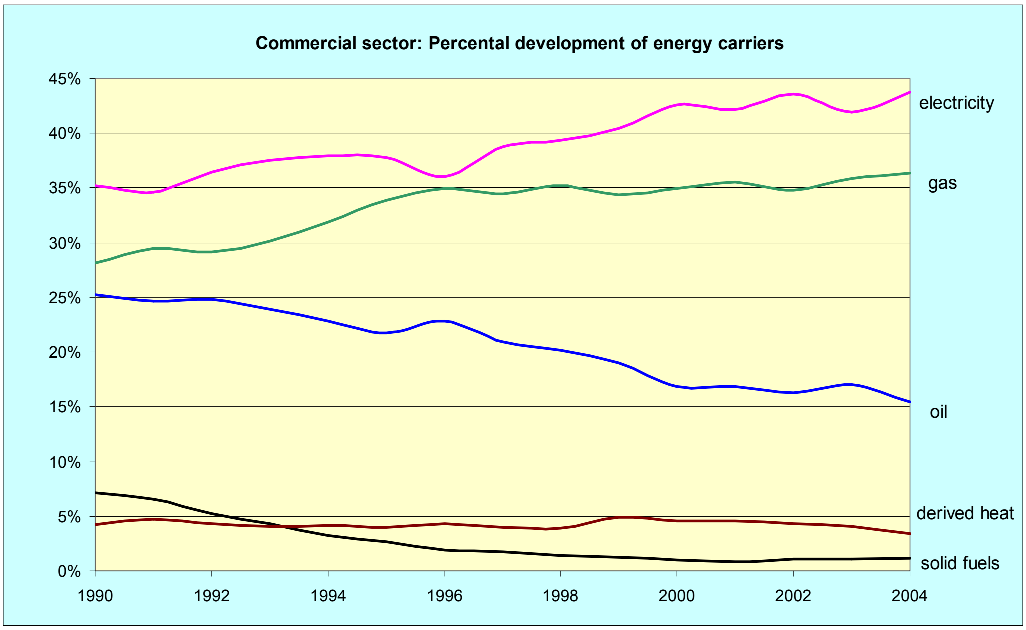
In general the difference between the single and multi family house demand of heat and electricity is the higher base load for the later one. There is a smoothing of heat and electricity peaks in the multifamily house because of the coincidence factor of electricity and heat demand. The demand profiles depend strongly on the behaviour of the inhabitants. Different ways of life in apartment buildings leads to higher electricity and heat base load.

IV.3 Commercial sector

The commercial sector consists of quasi non-manufacturing business branches. Included are building/construction trade, financial institutions, publishing houses, retail trade, shopping centres (mall), restaurants, bakeries, laundries, airports, greenhouses, federal, state and local governments as well as health, social and educational institutions etc.

Although the purposes of the energy use vary widely for such a heterogeneous collection, the use of energy carrier for room heating clearly dominates the energy demand (45% of the energy carrier consumption in the commercial sector in Germany). Process-heat preparation (hot water preparation included) is the second most important purpose (26% in Germany), followed by mechanical energy (19% in Germany in 2006). Although lighting is an essential part of energy utilisation in many divisions of the commercial sector, similarly in restaurants, offices, malls or airports, it plays in total only a secondary role, air conditioning is much more energy intensive for example.

Figure IV-4 shows that the demand for gas and electricity in the EU25 rose since 1990, while derived heat remained at a low level. Solid fuels now have only a 3 % portion and oil lost 10 percentage points. One of the reasons for this development is the change from oil fuelled to gas fuelled systems, caused by reasons of convenience, economy and probably also for environmental reasons. The increase of the electricity demand can be explained by more electrical appliances in all ranges, i.e. offices, hospitals and even in bakeries, which use more and more electrical ovens to bake industrially prepared products.



Source: IEF-STE, [Eurostat, 2007b]

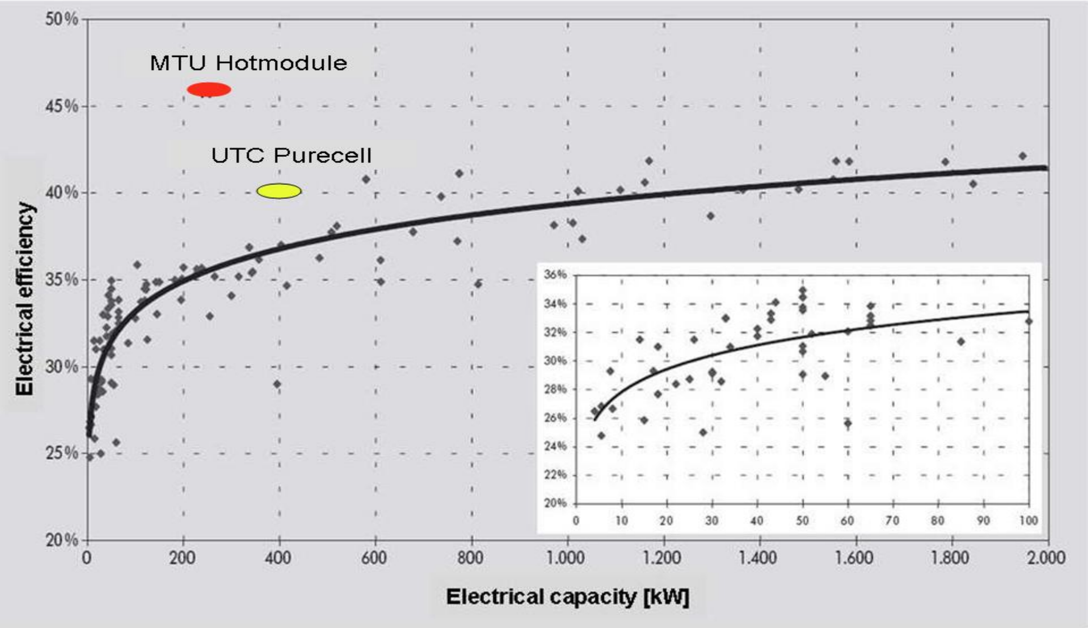
Figure IV-4: Development of fuels in the commercial sector, EU25

The capacity range of the energy generation units in the commercial sector varies over a wide range. It starts with some kW as used in restaurants or small hotels and ends at some MW which is needed in a mall or in hospital centres.

The majority of the buildings are equipped with conventional gas and oil boilers. For many years CHP units have been available and are installed when sufficient economic incentives exist. This is mainly influenced by having a continuous and simultaneous demand for heat and electricity and having a heat demand which enables around 5,000 and more yearly operation hours. In general the CHP units supply the base load while an additional boiler is used for the peak demand.

As mentioned before, the capacity range of the units corresponds to the demand of the object and is very wide, starting with a few kW_{el} respectively kW_{th} and ending in the MW-region. The Dachs and the Ecopower reciprocating engines from Table IV-5 are predestined for small objects and their capacity can be multiplied by combining several modules.

The department “Energiereferat” of the municipality of the city Frankfurt in Germany published in 2005 an analysis on European CHP units for commercial application. 20 European manufacturers delivered data for 277 modules which are optimised for the heat supply. The data of 127 gas fuelled CHP modules with a capacity range of 4 – 6,790 kW_{el} were analysed, of 86 bio-/sewage gas modules (14 – 6,790 kW_{el}/ 16 – 800 kW_{el}), of 20 heating oil modules (3 – 5,105 kW_{el}) and of 16 rape oil modules (5.5 – 4,300 kW_{el}).



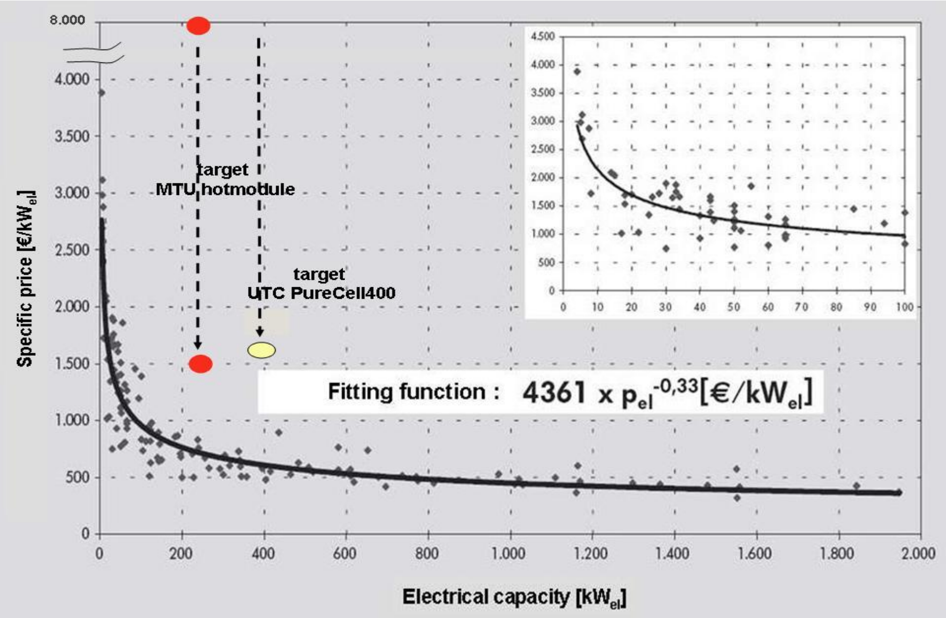
Source: [ASUE, 2005]

Figure IV-5: Gas fuelled CHP modules, correlation of electrical efficiency and electrical capacity

The efficiency depends directly on the size of the module and as a rule larger units are more efficient. Figure IV-5 shows the range of electrical efficiency of the gas fuelled modules. The white sheet at the right corner is an enlargement of the curve for smaller units. It can be seen that the efficiency of these varies between 25% and 34% and is clearly lower than for units which have a higher capacity. The best value of 46% is reached by the MCFC type of MTU, followed by the 40% efficiency of the Purecell types (PAFC) of UTC.

The "Energiereferat"-study analysed also the cost structure of the CHP units and found out, that the engine itself normally has a cost-share of nearly 55 to 60%, dropping back to less than 50% for units which are larger than 2 MW. The other costs are attributed to balance of plant, for example the electrical control cabinet (14 to 10%), noise insulation, catalyst, lubricant management, ventilation and installation.

Specific unit prices (€/kW$_{el}$), calculated from the list prices, are shown in Figure IV-6 . The evaluation demonstrates that the prices for small units are much higher than for larger units. Over the range of 5 to 200 kW$_{el}$ extreme price reductions are evident. They goes down from 2,000 €/kW to 500 €/kW. But the range of 1,500 to 2,000 €/kW is the target value for those two fuel cell types which are far developed and in a market entrance phase.



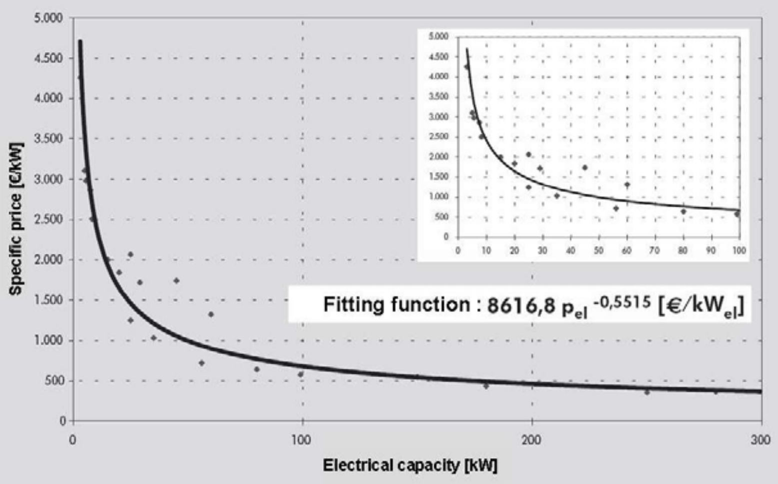
Source: [ASUE, 2005]

Figure IV-6: Specific prices for gas CHP units, installation included, without remote control

A further result of the evaluation is the expected costs for additional remote control systems, for which the manufacturer calculate around 1,700 Euro. That information will be of interest for future virtual power plant concepts, which make such systems necessary to enable a coordinated operation of many decentralised generation appliances.

The authors of the study collected also data for 86 biogas units. In general there are no technical difficulties to operate the gas engines with biogas. Only minor modification is necessary and the efficiencies are comparable to those of the gas units. The lower heating value of the biogas causes the biogas systems to have a lower electrical output than natural gas fired engines. The prices are marginally higher as fuel clean up must be installed.

Only 20 heating oil CHP units fulfilled the strict emission thresholds, so that the database has a limited validity, see Figure IV-7. As diesel engines give quite good efficiencies, the electrical efficiency of the heating oil CHP units is a little bit better than of the gas units. Because of better thermodynamic conditions of a diesel process, the electrical efficiency is a little bit higher than of a gas engine. But the heat recovery from the water and oil cooling systems is complex and costly so that it is not often used.



Source: [ASUE, 2005]

Figure IV-7: Specific prices for heating oil CHP units, installation included, without remote control

The evaluation of all the data resulted in an average electrical efficiency of 35% (max 46%), in an average thermal efficiency of 49% (max 60%) and in an average overall efficiency of 85% (max 91%). The curve in Figure IV-7 shows the same effect as for gas engines, the specific cost per kW_{el} of small units are clearly higher than those for large heating oil CHP modules.

The micro gas turbine is a new technology which extends the application of CHP technologies especially when a higher temperature level of the heat is required. At a capacity range of 30 kW_{el} to about 500 kW_{el} micro turbines can be applied in the commercial sector.

The basic technology of micro turbines is derived from aircraft auxiliary power systems, diesel engine turbochargers and automotive designs. Micro-turbines are notable for their reliability, small size and low weight. Presently, R&D efforts are dedicated to the construction of micro turbines with a power output of only a few kilowatts.

Micro turbines work in the same way as their large-scale counterparts, but their electrical efficiency is about 15%. However, this poor performance is normally improved by the installation of a recuperator (heat/heat exchanger), which preheats the air used during the combustion process by reusing exhaust gas heat. With that measure an electrical efficiency of 25% - 30% can be achieved, as shown by the examples in Table IV-7. Today's devices are characterised by lower NO_x- and CO-emission levels than internal combustion engines.

		Micro gasturbines				
manufacturer		Capstone Turbine Corporation, USA	Turbec S.p.A., Italy	Bowman, USA	Elliott Energy Systems, EBARA JP	Ingersoll Rand Industrial Technologies, USA
type		C30, C65	T100	TG80	TA-100 CHP	MT 70
fuel		Gas (biogas, diesel, kerosene, methanol, LPC)	Gas (biogas, diesel, kerosene, methanol, LPC)	Natural gas	Natural gas	gaseous fuels
electrical capacity	kW_{el}	28 - 65	100	80	100	68
thermal capacity	kW_{th}	70 - 135	155	133	172	105
electrical efficiency	%	~ 27 - ~ 30	30	27,8	29	26
thermal efficiency	%	~ 58				66
total efficiency	%	~ 85 - ~86	~76	72,8 [2]	>75	
specific price	Euro/kW	~ 1,700 - ~1,200[1]	~ 1,000[1]	~ 700	~1,100	~1,300
[1] without gas compressor, foundation and peripheral components [2] without boost compressor						

Source: [Müller, 2006], companies publication, IEF-STE

Table IV-7: Overview of micro-turbines

Ambitious targets for micro-turbine R&D activities are the enhancement of the electrical efficiency up to 40% and the reduction of the system cost down to ~400 €/kW_{el}.

The phosphoric acid fuel cell, the molten carbonate fuel cell and the solid oxide fuel cell technologies complete the list of fuel cell types which will compete with other technologies in the future commercial market.

Table IV-8 shows data of three phosphoric acid fuel cell units, manufactured in the United States of America and in Japan.

		Phosphoric-Acid Fuel Cell		
company		UTC Power, USA	Toshiba FC Power System	Fuji Electric Advanced Technology Co.,Ltd
type		PureCell^{TM}	PC25^{TM}C	FP 100 series
principle		PAFC	PAFC	PAFC
fuel		Natural gas or anaerobic digester gas	Natural gas (opt. LPG, ADG[1], Biogas, hydrogen)	Natural gas (opt. LPG, ADG, Biogas, hydrogen)
electrical capacity	kW$_{el}$	200	200	100
thermal capacity	kW$_{th}$	263		
electrical efficiency	%	~39	40	40
thermal utility degree	%			47
overall efficiency	%	~90		87
actual price	Euro / kW$_{el}$	~3,500 [2]		~3,500
targets cost/price	Euro / kW$_{el}$			~1,800 in 2009
status		commercial stage		
number of sold units		~260		
[1] Anaerobic digister gas = ADG [2] 4,200 $				

Source: IEF-STE, [JSME, 2006]

Table IV-8: Examples for Phosphoric-Acid Fuel Cell units suitable for the commercial sector

UTC Power, previously operating under the names ONSI and International Fuel Cell, has the best experience in manufacturing and operating PAFC systems. More than 250 units have been sold. UTC has cooperation with Toshiba FC Power System which is using the PC25 unit in Japan.

Fuji Electric is developing its own PAFC system and both companies have tested a few of the units in a variety of applications. Research is currently underway to lower the purchase and maintenance costs, to stimulate new demand.

Table IV-9 shows the molten carbonate fuel cell units of which the first three have reached the pre-commercial respectively the commercial stage without being directly competitive with conventional technologies. The manufacturing cost respectively the purchase prices are still too high, so that the most European projects are realised with governmental funding.

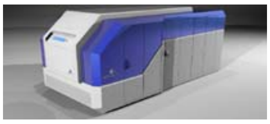
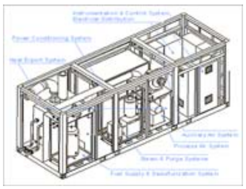
		Molten Carbonate Fuel Cell			
company		Fuel Cell Energy , USA	CFC Solution, Germany	Fuel Cell Japan (FCE, Marubeni)	AnsaldoFuelCells, Italy
type		DFC300 A	Hotmodule	DFC300 series	Series 500
fuel		Natural gas (opt. ADG, Biogas)	Natural gas (opt. ADG, Biogas)	Natural gas (opt. ADG[1], Biogas)	Natural gas (opt. ADG, Biogas)
electrical capacity	kW_{el}	300	245	250	500
thermal capacity	kW_{th}		180		500
electrical efficiency	%	46,6	47	47	
thermal utility degree	%				
overall efficiency	%		90		
actual price	Euro / kW_{el}	~4,000 [2]	~8,000	~4,200	
targets cost/price	Euro / kW_{el}		1,200 - 1,500		~ 3,500
status		commercial level	commercial level	pre-commercial level	
number of units in field trials		over 50	18	11	
[1] anaerobic digester gas [2] 4,800 $ January 2006					

Source: IEF-STE, companies information

Table IV-9: Examples for molten carbonate fuel cell units

FuelCell Energy Inc. has high competence in molten carbonate fuel cell technology, since it has been engaged in that area for more than 30 years. It has cooperation in the main regions of the world, in Europe with CFC Solution (a department of MTU Onsite Energy) and in Japan with Marubeni Corp. for the Asian market. Together with its partners Fuel Cell Energy services more than 50 power plant sites. The units are designed to provide base load power and process heat respectively district heat for a wide range of customers and applications.

With regard to larger SOFC-systems there are still two to three companies which are engaged in that field, whereby the finish company Wärtsilä seems to be most successful. They did install a 20 kW$_{el}$ system (WFC20) in summer 2008 at the Vaasa housing fair which was fuelled by biogas. Wärtsilä's intention is to develop modules up to 250 kW$_{el}$, which can be upscaled by doubling and used for a wide range of purposes like in telecom/data centers, hospitals, banks, hotels, malls, offices, industries and even for operation in short route ferries, car carriers or cruisers Table IV-10 shows some data of the Wärtsilä system but also of the Siemens idea and the Rolls-Royce planar SOFC project.

		Solid Oxid Fuel Cell		
company		Wärtislä	Rolls Royce	Siemens
type		**WFC20** (WFC50, WFC 250)	SOFC	SFC-200
fuel		Natural gas, methanol, bio gas	hydrocarbon based fuels	Natural gas (opt. other fuel gases)
electrical capacity	kW$_{el}$	**20** (50, 250)	250	125 (net AC)
thermal capacity	kW$_{th}$	14 to 17		100
electrical efficiency	%	~46	more efficient than nearest rival	44 - 47
thermal utility degree	%	~34	more efficient than nearest rival	33- 36
overall efficiency	%	~80	more efficient than nearest rival	~ 80
actual price	Euro / kW$_{el}$	24 - 17		
targets cost/price	Euro / kW$_{el}$	3,5 - 1		
status		under development, successful field test with WFC20 since 2008	Field trials commencing in 2008	pre-commercial level
				

Sources: Companies brochures

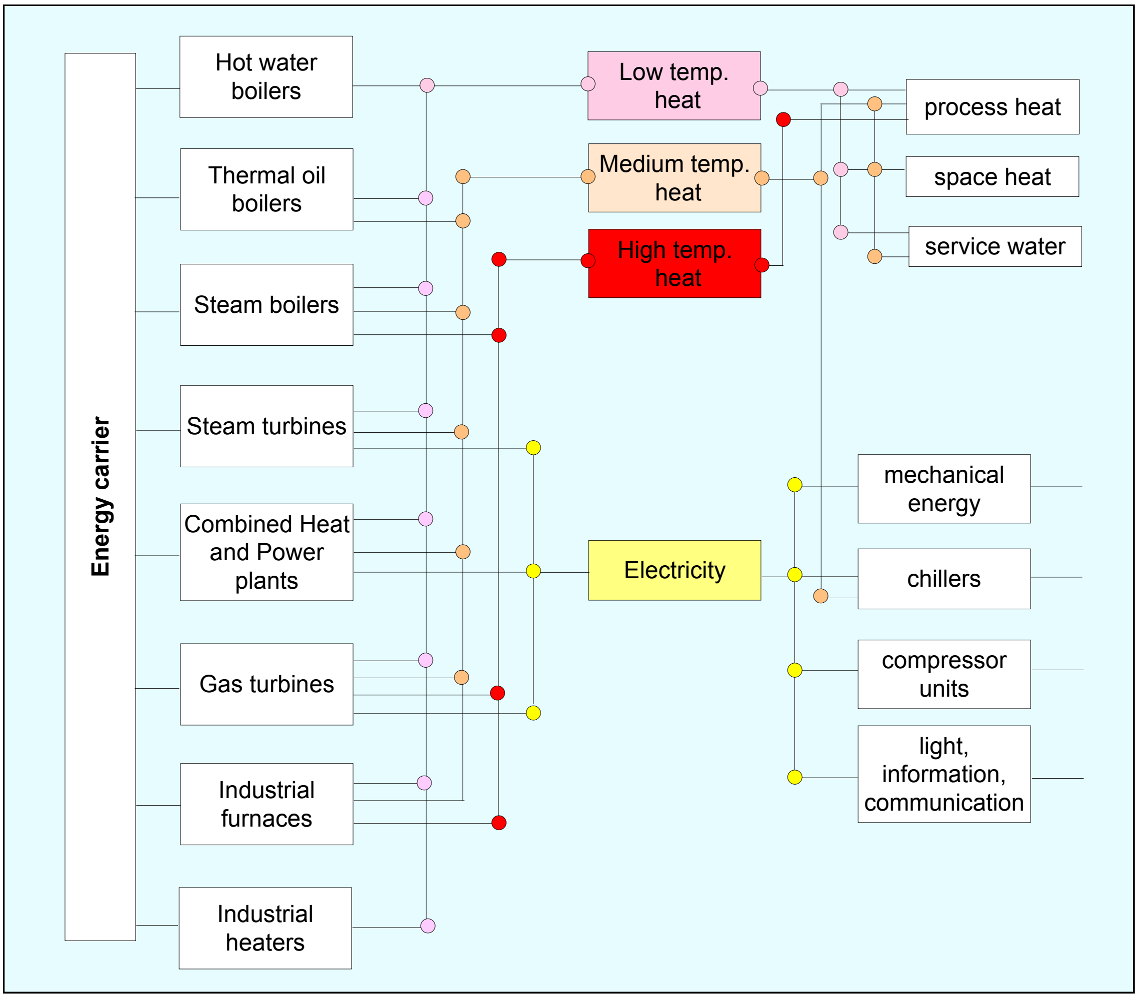
Table IV-10: Examples of larger SOFC CHP-units

Although there are a couple of fuel cell systems under successful demonstration or test operation, it is not clear, if all companies will continue their engagement as a long breath is necessary to reach the challenges for further development: "getting down the capital costs; lengthen the lifetime of FC stack, improving applicability and reliability of the FC systems." The 2008 report of FuelCellToday on large stationary fuel cells explains, that "Siemens are purported to be selling off their SOFC business".

IV.4 Industrial sector

In the EU25 industrial sector ~12.6 MJ of final energy carriers are consumed, which is a share of ~43% of the total final energy consumption, the transportation sector excluded. Though the requirements of branches like Iron & Steel and Food, Drink and Tobacco are very heterogeneous, In Germany around 68% of the final energy carrier are used for generating process heat [Tzscheutschler, 2007]. It can be expected, that there are less structural differences between the industrialised countries. Heat is used for sterilisation, drying, welding, smelting, galvanising and other processes. Because of the required high temperature levels, the use of waste heat from thermal or production processes is often not practicable, so that all the process heat is normally generated by burning fuels or by electricity in the case of arc furnaces, smelters, foundry stoves etc.

Figure IV-8 gives a schematic overview of industrial energy converting structures, with technologies at the left side, the products heat and electricity in the middle of the figure and the intended purpose at the right side. Together with Figure IV-9 it gives first hints if and where fuel cells can be introduced.

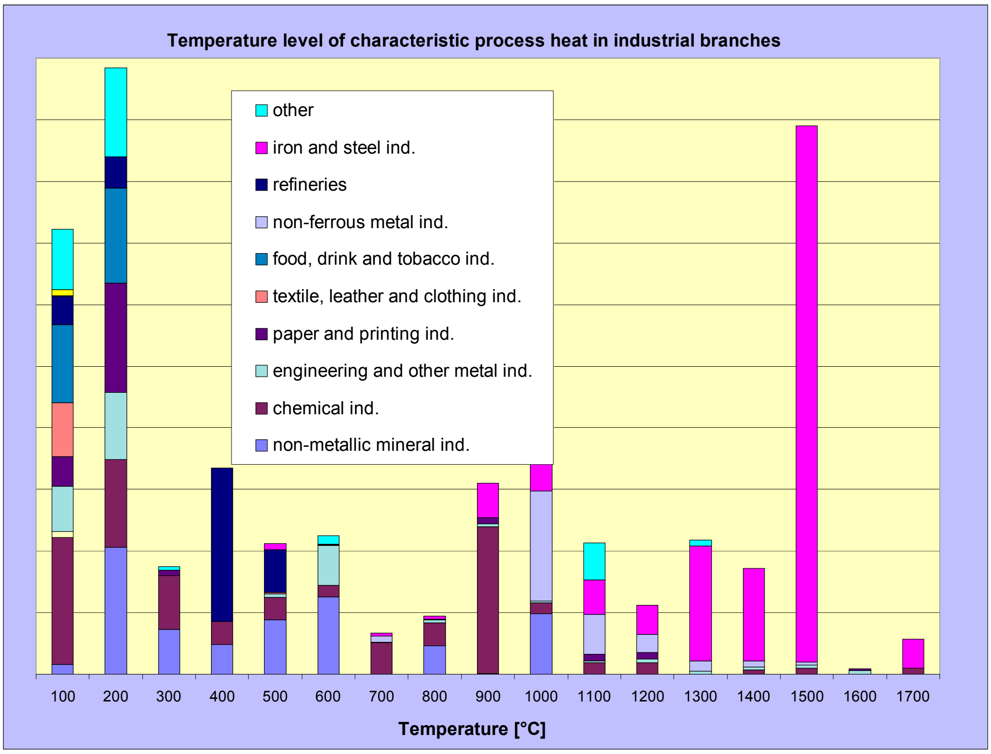


Source: [Temming, 2005], IEF-STE,

Figure IV-8: Structures of the industrial energy conversion steps

In Germany the room heating demand in the sector industry is in the range of 60 TWh, whose supply can be done by all fuel cell types and would not be reserved for high temperature fuel cells. They do have the potential to be used for generating process heat up to a temperature level of around 500 °C and Figure IV-9 shows, which branches do have process heat demand in that range. At the first view the food, drink and tobacco industry, paper and printing and the chemical industry catch someone’s eye, but a deeper analysis should show, if the general process and working cycles enable CHP operation in general and fuel cell operation in particular.

The reduction of the final energy demand in the industrial sector between 1990 and 2004, mentioned in chapter II.1, can be attributed to two main causes: One is the economic stagnation and the other successful efforts in energy conservation by more efficient processing, by combined heat and power technology and by heat recovery, which incidentally makes additional pumps, fans and control systems necessary, whereby electricity demand is increased.



Source: IEF-STE, [Hofer, 1994]

Figure IV-9: Process temperature level, typical for different branches, data for Germany

Typical energy generation/conversion technologies for industrial application are hot water boilers, steam boilers, steam turbines, gas turbines and direct fired furnaces. The capacity range of these technologies reaches from some 10 kW to some 10 MW, in individual cases even up to some 100 MW. The electrical efficiencies depend on the technology type and vary between 30% and 60%, whereby it should be said, that normally heat is the main product and electricity a by-product, which can be fed into the public grid. As mentioned before the temperature level of ~ 400°C is a barrier for heat recovery systems, so that direct fired furnaces are used for drying, calcining and other processes.

Because of favourable conditions and many operation hours with a simultaneous demand for useful heat and electricity, cogeneration technologies are very common in industrial branches. Essential conditions are sufficient heat demand and an appropriate temperature level for the heat application, which may not be higher than ca. 400 °C – 500°C, as that is the technical limit for conventional cogeneration application. The capacity range for typical industrial energy conversion respectively generating systems is shown in the following tables.

The three examples in Table IV-11 are representative of the types of boiler manufactured worldwide. They have a very wide capacity range, broadened by combination of multiple units, and are used to generate heat, process heat and steam. The temperature level is in a range which can be principally supplied by the high temperature fuel cell types as demonstrated for example with a 250 kW MCFC which was operated in parallel with conventional systems to generate 200°C hot process steam for tire production in the Michelin tire manufacture Karlsruhe (Germany).

	Hot Water Boiler	Thermal Oil Heaters	Steam Boiler
firing thermal capacity	0,6 - 18 MW_{th}	0,1 - 17 MW_{th}	0,1 - 17 MW_{th}
fuel	gas/oil	gas/oil	gas
Hot Water Temp	up to 205°C at 25 bar	> 200°C	
Steam capacity @ 102°C boiler feed water temperature			25 t/h
Boiler efficiency		86 - 92%	88%
NO_x mg/nm^3		<100 @gas <200@oil	
	Viessmann 	Babcock Wanson 	Viessmann 

Source: IEF-STE, company's information

Table IV-11: Three typical boiler types for industrial application

For higher temperature requirements steam- and gas turbine CHP systems are common well proven. Table IV-12 gives some examples for the use of steam- and gas turbines in a variety of CHP applications.

	Steam Turbines	Gasturbine SGT-100	Gasturbine SGT-800	Gasturbine FT8 Mech Pac	Gasturbine FT8-30 TwinPac
capacity range		4 - 5 MW_{el}	45 MW_{el}		
generator drive	1 - 180 MW				55 MW_{el}
mechanical drive				25,9 MW	
firing thermal capacity					
fuel		gas/oil	gas		gas
electrical efficiency $_{el}$		31,00%	37% at GT plant		38%
electrical efficiency $_{el}$			54% at Cogeneration		
thermal efficiency $_{th}$	48%			38,6	
		as CHP-plant thermal efficiency up to 95%			
NOx-emission (calc. at 15% O_2, dry)		below 25 resp. 50 vppmd at gaseous resp. fluid fuels	< 15 vppm		<120 mg/Nm^3
	Siemens	Siemens	Siemens	MAN Turbo	MAN Turbo
					
				natural gas compression	CHP inChemical Industry

Source: IEF-STE, company's information

Table IV-12: Examples of industrial turbines and application

They can be used as mechanical propulsion for compressors and other items of machinery, but also for electricity generation in industrial CHP units and for process steam generation. But up to now there is not seen, that high temperature fuel cells will substitute them, the described case was a single demonstration.

A large amount of the final energy demand in the industrial sector is consumed as process heat in industrial furnaces, of which five examples are shown in Table IV-13. They are used for processes in the primary, capital goods and consumer goods industry, where very high temperatures are required and which can only be done by direct firing.

	Bell furnaces	Directly heated rotary furnaces	Belt conveyor furnaces	Drum Dryers	Rotary Kilns
Mode of heating	electric or fuel-fired	electric or fuel-fired	electric or fuel-fired	fuel fired	fuel fired
Fuel	gas/oil	gas/oil	gas/oil	gas/oil	gas/oil/secondary fuels
Capacity range	MW_{th}	MW_{th}	MW_{th}	0,1 - 11 MW_{th}	MW_{th}
Temperature rang	**250 to 1.650°C**	**800 to 1.450 °C**	**250 to 1.150 °C**	**to 1500°C**	**to 2.000°C**
	Non-ferrous and light metal components, Chemical industry, Industrial glasses, Industrial ceramics, Brazing and Soldering, Powder metallurgy, Iron and Steel	Chemical industry, Recycling processes	Non-ferrous and light metal components, Chemical industry, Industrial glasses, Industrial ceramics, Brazing and Soldering, Powder metallurgy, Iron and Steel, Recycling processes	Nonmetallic Mineral Products Industry (Silica sand drying)	Nonmetallic Mineral Products Industry (cement industry)
Manufacturer	www.Riedhammer.de	www.Elino.de	www.Elino.de	http://www.allgaier.de/verfahrenstechnik/	www.pillard.de
					

Source: IEF-STE, companies information

Table IV-13: Examples of industrial furnaces for high temperature processing

These processes are very energy intensive and though the efficiency of the furnaces and the processes has been enhanced over the last few years, the average utilisation ratio is calculated at only ~60%. That opens up a general possibility of further efficiency enhancement. Today's available high-performance furnaces with modern burners attain efficiencies of 75% to 85%. Further contributions to the general efficiency enhancement can be achieved by optimised control and communication systems, increased use of waste heat and by improved insulation of the technical equipment, see Figure IV-10. [ISI, Bine 3/00] It cannot be seen, that fuel cells will be competitors in that field as their temperature level seems not to be high enough.

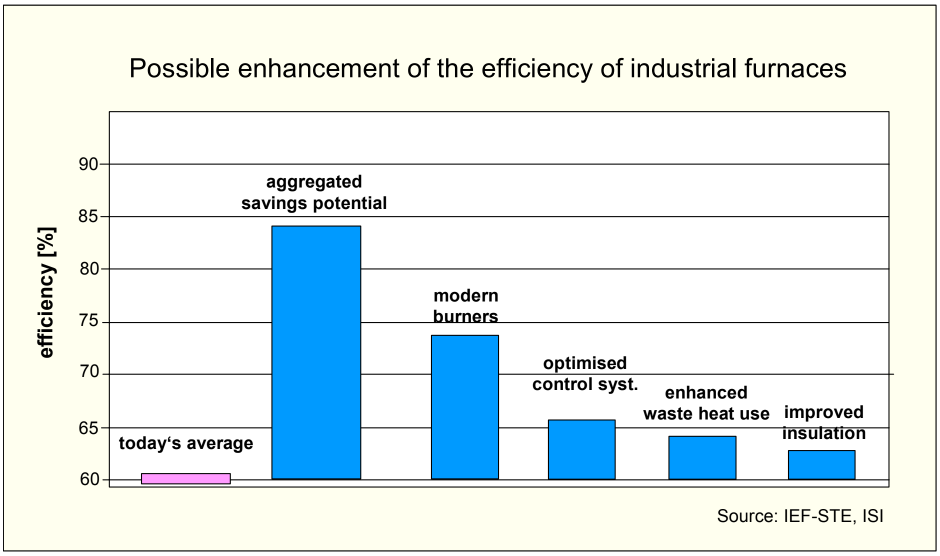


Figure IV-10: Possibilitoes to improve the efficiency of thermo-process appliances

V Market Survey of Micro CHP Fuel Cell Systems

This section presents the approach (sources and selection criteria) and the results of a more general market survey in addition to chapter IV. This survey is not exhaustive. Based on company's and other sources (complete list see annex) it starts the attempt to build up a comprehensive overview of worldwide activities in fuel cells and their associated systems.

V.1 Approach

V.1.1 Sources

To get an insight into the actual activities and trends in the fuel cell market several literature and Internet sources have been scanned and direct information from the manufacturer at official meetings and public fairs has been collected as well.

Internet

The online sources [FUEL CELLS 2000, 2007] and [fuelcelltoday, 2007] gives an interesting general overview of fuel cell projects, manufacturers and news out of the fuel cell community. The aim of both web sites is to promote the development and early commercialisation of fuel cells.

[FUEL CELLS 2000, 2007] is part of the Breakthrough Technologies Institute which is based in the USA. Its activities include a free searchable database which contains fuel cell projects all over the world.

[fuelcelltoday, 2007] is an internet portal which provides information for everyone interested in fuel cell technology. Organised in a database it is easy to find industrial, governmental or academic organisations, manufacturers or investors who are dealing with fuel cells. Another interesting activity of [fuelcelltoday, 2007] is the annual market survey for different fuel cell applications (e.g. [Adamson, 2006]).

A number of other online sources like the manufacturers' web sites and other general fuel cell information portals (e.g. [IBZ, 2007]) have been used for this survey.

Literature

Some studies covering the stage of and needs for development, market analyses and launches have been screened. E.g. [Brand et al., 2006] and [Blesl et al., 2006] give interesting insights and information on the fuel cell activities in certain countries and of certain manufacturers.

Other Sources

Some direct information could be collected on an IEA meeting in Jülich (Germany) in March 2007 where some international researchers and manufacturer representatives came together under the topic of fuel cell development.

On the Hannover Fair 2007 (Germany) many of the actual fuel cell manufacturers were present. In discussions with several representatives (e.g. Vaillant, Plug Power, Baxi INNOTECH, Viessmann) interesting information could be gathered.

V.1.2 Selection Criteria, Researched Aspects, Quality of Data

To restrict the amount of data collected for the study some preliminary criteria for the registered systems have been defined:

- period of information scan 2003 - 2007
- maximum electric power output $\geq 0{,}5\ kW_{el}$ and $\leq 6\ kW_{el}$
- stationary system
- hints on domestic, residential or CHP systems

The chosen systems were analysed for the main aspects:

- Fuel Cell Type
- Power Output (thermal/electric)
- Efficiency (thermal/electric/overall)
- Fuel
- State-of-the-art
- Price
- Year of Market Availability

To consider the quality of the collected data and the researched sources a quality evaluation system has been implemented. It is composed of the categories in Table V-1.

Category	Description
1	verified manufacturer’s data (e.g. measured data)
2	other manufacturer’s data (e.g. data sheets)
3	indirect information (e.g. studies and reports)
4	personal information (e.g. interviews, presentations, telephone calls)

Table V-1: Quality of Data Evolution System

V.2 Results

Countries

In the study forty six companies from thirteen different countries are analysed. Nearly 90% of the manufacturers comes from the three regions: North America, Japan and the EU-25 (Germany (5), UK (4), France and Italy (2), Estonia and Belgium (1)). Especially in Japan there are large-scale demonstration programs for stationary fuel cells [Hato, 2007]. Six companies are based in other countries like Switzerland (2), Korea (2), Russia (1) and Australia (1).

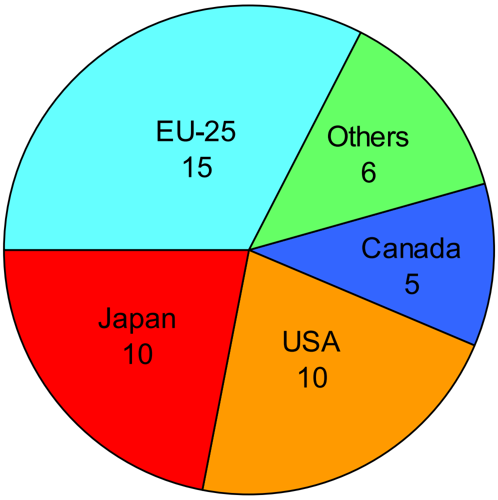


Figure V-1: Fuel Cell Companies by Region

Systems

Sixty nine systems, of which forty are CHP-systems, are registered in the database. Within these forty CHP-systems about 73% (29) are based on PEM systems and nearly one quarter on SOFC (9). The remaining 5% are AFC systems (see Figure V-2). This dominant role of the low temperature PEMFC may be due to the experiences in the automobile industry where this technology has been on test for many years.

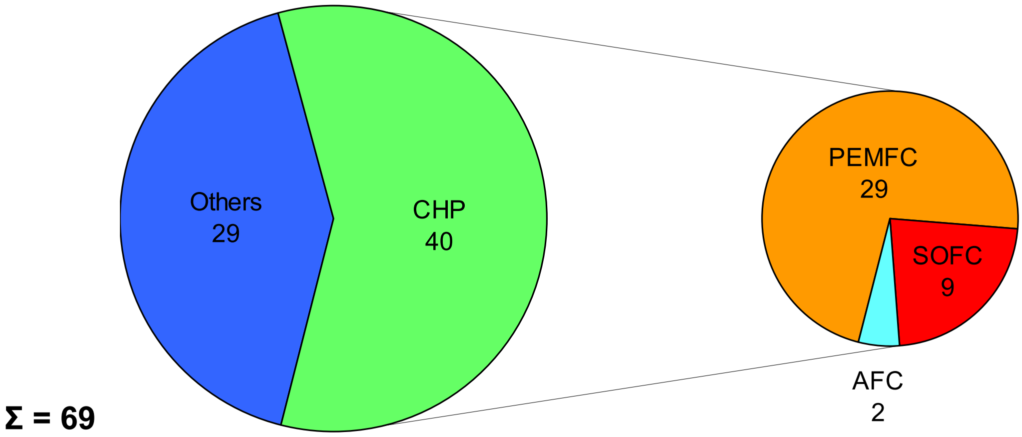


Figure V-2: Analysis of Fuel Cell Types for CHP systems

Fuel

Of these systems nearly three-quarters work on natural gas and pure Hydrogen is used in 12%.. Furthermore kerosene, LPG (Liquefied Petroleum Gas), town-gas and propane are used in some systems (15%)) (see Figure V-3).

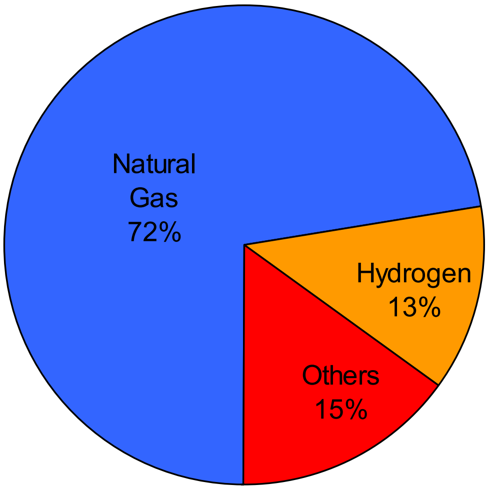


Figure V-3: Analysis of Fuels for Fuel Cell CHP Systems

Statistical Distribution of Electric and Thermal Power

The analyses of the statistical distribution of electric power rating shows clustering around 1 kW_e and 4.5 kW_e (see Figure V-4). The systems with an electric output of around 1 kW_e are designed for single family houses (e.g. HEXIS: Galileo, see Table IV-2) whereas an output of 4 to 6 kW_{el} is intended for multi family houses and small consumers (Vaillant/ PlugPower see Table IV-1).

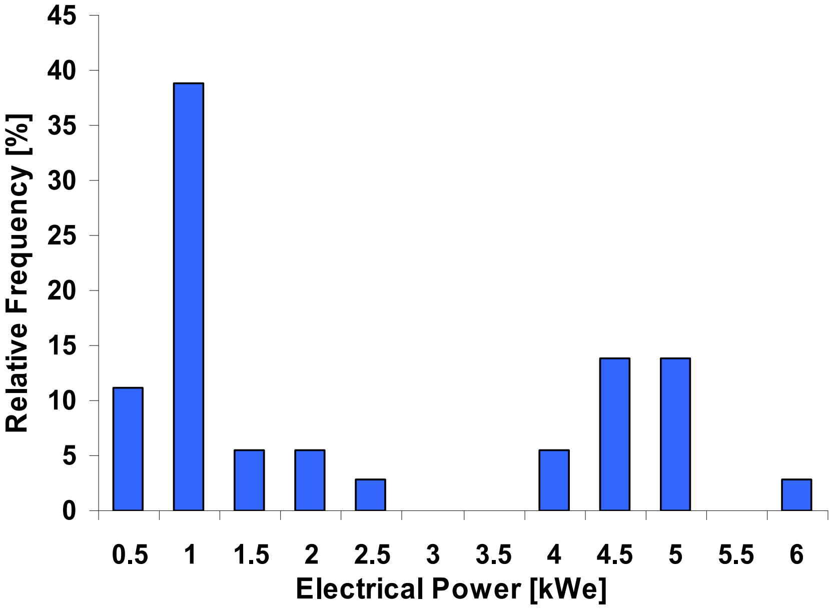


Figure V-4: Statistical Distribution of Electric Power

For the thermal output distribution there is no such clear clustering (see Figure V-5). The outputs range from 0.75 kW_{th} up to 9 kW_{th}. However inspection of the details shows that the higher outputs are mostly systems for multi-family and commerce, trade and services applications. The output for most of the systems for single houses (56%) is lower than or equal to $3kW_{th}$. Unfortunately this result is based on only a few systems (18) as for most of the systems no concrete data were available.

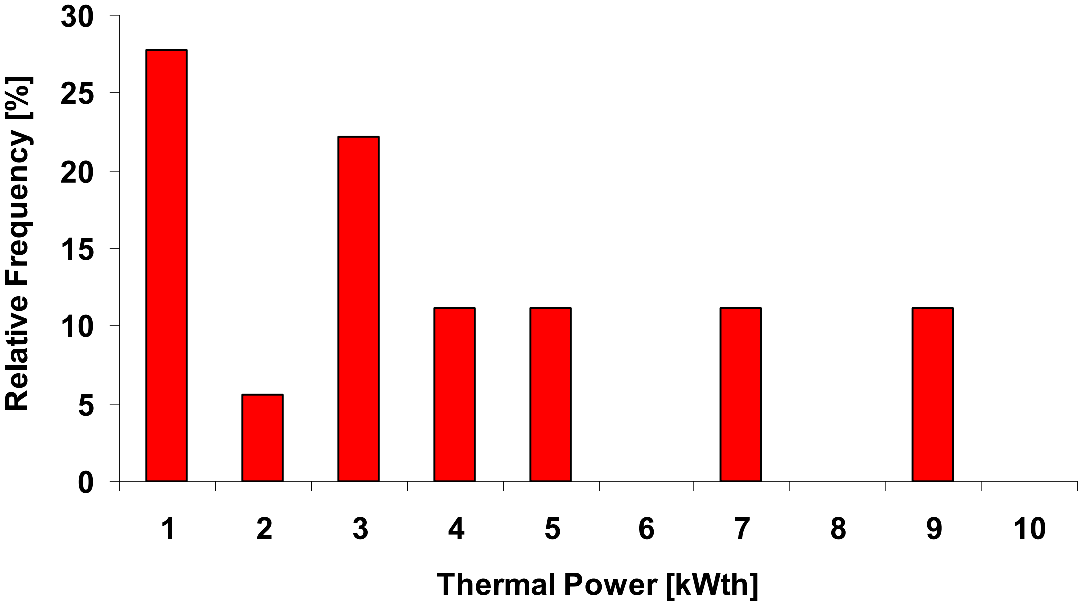


Figure V-5: Statistical Distribution of Thermal Power

Efficiency

From literature and companies announcements we took information on the efficiency for an ensemble of fuel cell systems to generate average values for the PEMFC or the SOFC systems, see Table V-2. For SOFCs the electrical efficiency is significantly (~5%) higher than for the PEMFCs whereas the thermal efficiency is of a comparable range. With regard to Table III-1 and the theoretical thermal efficiency of the basic cells, these results were not expected because of the higher thermal efficiency of PEMFC (93%) in comparison to SOFC (79%). These differences can be explained by the complex and energy consuming water management, which is needed for the PEMFC and by other aspects of the balance of plant under development for these systems.

It must be also mentioned that these values are not yet realised. But the manufacturers aspire to reach them in order to fulfil the economic preconditions for micro-CHP-units in the real marketplace. The targets of the European Hydrogen &

Average Efficiency [%]			
	electric	**thermal**	**overall**
SOFC	35.8	46.8	82.5
PEMFC	29.7	44.1	73.9

Table V-2: Average Efficiencies for PEMFC and SOFC Systems

Fuel Cell Technology Platform (HFPeurope) are more ambitious, 34 – 40 % electrical efficiency and 6,000 Euro/kW system cost for residential systems up to 2009 – 2012 and 50 % electrical efficiency and 1,500 – 5,000 Euro/system cost for larger systems for industrial or communal application. [HFP-Imp 2007]

Price Aims and Market Entry Date

It is very difficult to get cost data or a realistic timetable for market entry. The available data are often not comparable as the price is sometimes given for the whole unit, in case of Baxi even the peak burner is included, and otherwise per unit of electric power output. In addition these price specifications refer to different expected market entry dates. An overview of the costs and market entry dates discovered in the study is given inTable V-3. It must be mentioned that up to now no company has reached their price targets.

Company	Product	Type	Date	Price
Baxi INNOTECH	Beta 1.5 plus	PEMFC	2015	10,000 €/unit1)
Matsushita	1 kW system	PEMFC	2008	7,368 €/unit2)
Fuji Electric	1 kW system	PEMFC	2015	1,713 – 2,742€/kW$_{el}$3)
Inhouse	Inhouse4000	PEMFC	2010	4,000 €/kWel
Viessmann	HEVA II	PEMFC	2012	6,000 €/unit

1)peak burner included; 2) 1 Euro (EUR) = 162.862 Japanese Yen; 3) 1 Euro (EUR) = 1.45872 US Dollar, exchange rates at 02.01.2008

Source: [Adamson, 2006], [Brand et al., 2006], companies information

Table V-3: Costs and Market Entry Dates for several Fuel Cell Systems

VI Residential Load Curves for Heat

Cogeneration is only reasonable if the produced heat can be used. As mentioned earlier the unused electricity is fed into the public grid. This chapter therefore deals with the heat demand in the residential sector under different climatic conditions. Because the demand for hot water is concentrated within short time-frames, which can be covered by the additional heat storage, the heat provision for hot water is not included. For the scenario calculations the energy effort for preparing hot water will be included. Energy consumption for hot water is in the range of 10 – 15 % of the final energy consumption in the EU 15. The demand for space heating is the dominating part.

VI.1 Heat demand

The heat demand or better said the thermal heat demand is that energy amount, which is necessary to hold the favoured room temperature, whose change is affected in negative or positive direction by transmission as well as ventilation losses at one hand and solar as well as internal gains at the other hand. So far the heat demand, which can be addressed as temperature difference between indoor and outdoor temperature, depends from the insulating properties of the walls, roofs or windows, from the leak tightness of the windows, the ventilation behaviour of the inhabitants and other factors. And that temperature difference can be roughly calculated by the so called heating degree days for each climatic zone. To establish an equation for the relationship between the heat demand and the temperature difference, two quasi stationary[6] models have been built up.

Heating Degree Days

The data used for heating degree days (HDD) of the statistical office of the European Union (Eurostat) is calculated by the following method:

$$HDD = \sum_{i=1}^{n} X_i \qquad \text{VI-1}$$

$X_i = (18°C - T_o)_i$ if T_o is lower than or equal to 15°C (heating threshold)

$X_i = 0$ if T_o is greater than 15°C

---

[6] The calculations refer to a monthly average temperature, short-term temperature fluctuations are not considered.

HDD : Heating Degree Days

T_0 : Mean Outdoor Temperature over a period of one Day: $T_0 = (T_{min}+T_{max}) / 2$

i : Number of the Respective Day

n : Total Number of Days of the Respective Month

Figure VI-1 illustrates the heating degree calculation method. The hatched area corresponds to the amount of heating degree days.

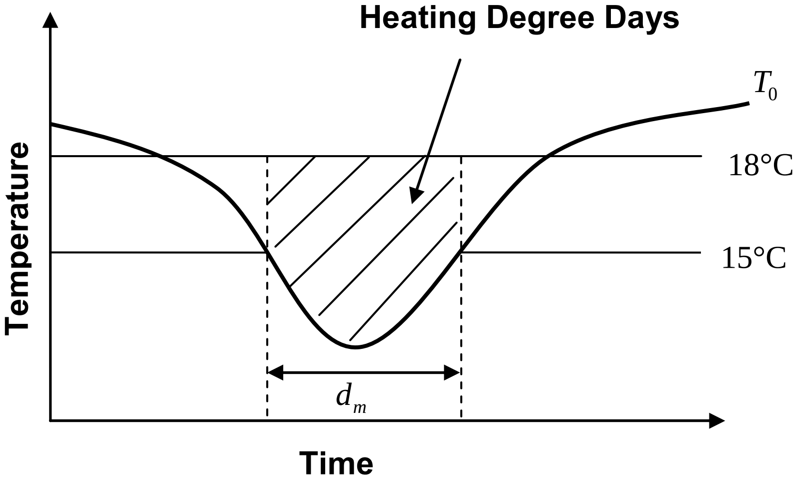


Figure VI-1: Heating Degree Days

For each administrative region on the level of NUTS 2[7] in the European Union this data has been collected and thus the national heating degree days for each country can be aggregated from this. In this study the three climatic zones are related to the typical countries in Table VI-1. The data for the heating degree days refer to 2004.

Zone	typical Country	HDD p.a. (2004)
Cold	Finland	5,536
Moderate	Germany	3,185
Warm	Greece	1,567

Source: [Eurostat et al., 2005]

Table VI-1: Correlation between Zone and Country

To calculate the monthly average temperature difference (ΔT_m) the number of heating days for the corresponding (d_m) month is needed. “Heating day” does not

---

[7] NUTS - Nomenclature des unités territoriales statistiques, NUTS 2 corresponds to regions with 800.000 to 3 million people

necessary mean that heating is required but that the mean outdoor temperature T_0 is lower than 15°C for this day.

$$\Delta T_m = \frac{HDD}{d_m} \qquad \text{VI-2}$$

ΔT_m : Monthly Average Temperature Difference

d_m : Number of Heating Days (when T_o < 15°C) for the Corresponding Month

On the basis of ΔT_m the heat demand can be calculated according to the following very simplified formula:

$$\dot{Q} = \Phi_B \cdot \Delta T_m \qquad \text{VI-3}$$

$\dot{Q}$: Heat Demand

Φ_B : Constant of Proportionality

"Φ" is a constant[8] of proportionality which represents the isolation standard for different climatic zones. Two evaluation methods of this factor are shown in the following paragraphs.

VI.1.1 Bottom-Up

Bottom-up analysis means the creation of a model building with defined U-Values[9] and surfaces for the main parts of the outer shell. The four main parts are the facade, the windows, the roof and the floor. This model neither considers other sources and sinks for heat nor does it take into account any kind of storage effect of the building stock[10]. Typical heat sources and sinks in residential buildings are internal loads from the inhabitants or electrical devices, solar radiant heat, ventilation losses and various others. To point out the ratio of transmission and ventilation losses Figure VI-2 shows an evaluation for the Austrian building stock in comparison to different standard of energetic renovated buildings. For all building types the main part of heat loss is the transmission through buildings parts like wall and roof. Therefore the analysis of heat demands in different climatic zones focuses on transmission heat losses.

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[8] Simplification: for this small range of temperature "Φ" is seen as constant.

[9] Thermal transmittance incorporates the thermal conductance of a structure along with heat transfer due to convection and radiation.

[10] Especially in the summer months this effect supersedes supplemental heating e.g. at night.

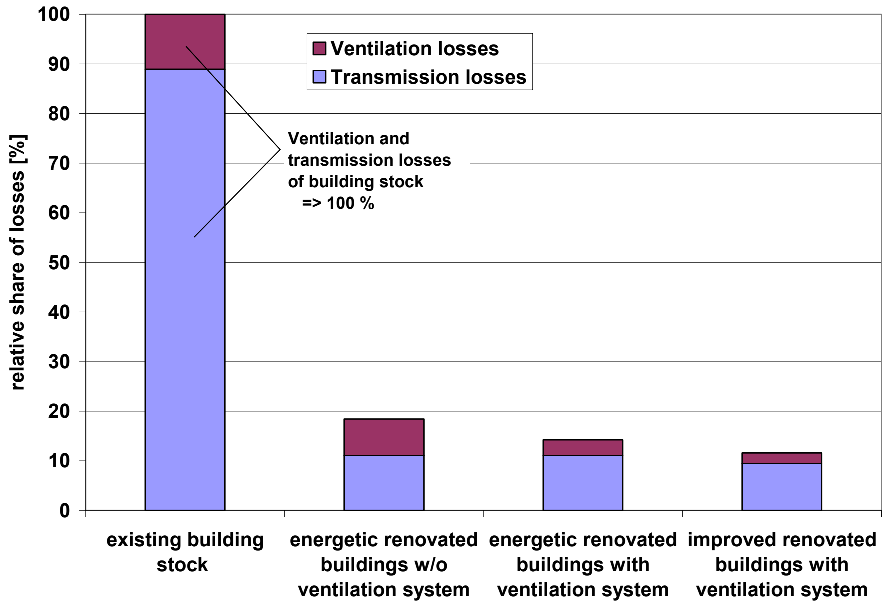

Figure VI-2: Example of ventialation and transmission losses in Austria [Lang 2008]

U-Values

For the model, building isolation standards for houses which were built in the period from 1991 until 2002 are chosen. According to three different climatic zones (cold, moderate, warm) Table VI-2 shows the U-Values which were applied.

U-Values [W/(m^2*K)]				
Zone	**Roof**	**Facade**	**Floor**	**Windows**
cold	0.15	0.2	0.18	1.6
moderate	0.4	0.5	0.5	2
warm	0.5	0.6	0.55	3.5

Source: [Petersdorff et al., 2004]

Table VI-2: U-Values for different Climatic Zones

Surfaces

As reference building is chosen a single house model in [Kraft, 2002]. It is a standard one-family house which is built between 1984 and 1994. The current surfaces are shown in Table VI-3.

Surfaces [m^2]			
Roof	**Facade**	**Floor**	**Windows**
123	213	75.33	29.67

Source: [Kraft, 2002]

Table VI-3: Surfaces of the Model Building EFH-H

With these two values the constant of proportionality for each climatic zone can be calculated.

$$\Phi_B = \sum_{j=1}^{4} A_j \cdot U_j \qquad \text{VI-4}$$

A : Surface
U : U-Value
j : Part of the House (1 Roof, 2 Facade, 3 Floor, 4 Windows)

Between the constant for the cold, moderate and warm zone there is a factor of nearly two respectively three (see Table VI-4). This broad range of values indicates the very different isolation standards in the three zones.

Zone	Φ_B [kW/K]
cold	0.122
moderate	0.253
warm	0.335

Table VI-4: Constant of Proportionality for the three Climatic Zones

By taking these constants, the heating degree days and the number of heating days for each month in 2004 (see Annex) the heat demand can be calculated by formula VI-3. The results are shown in Figure VI-3.

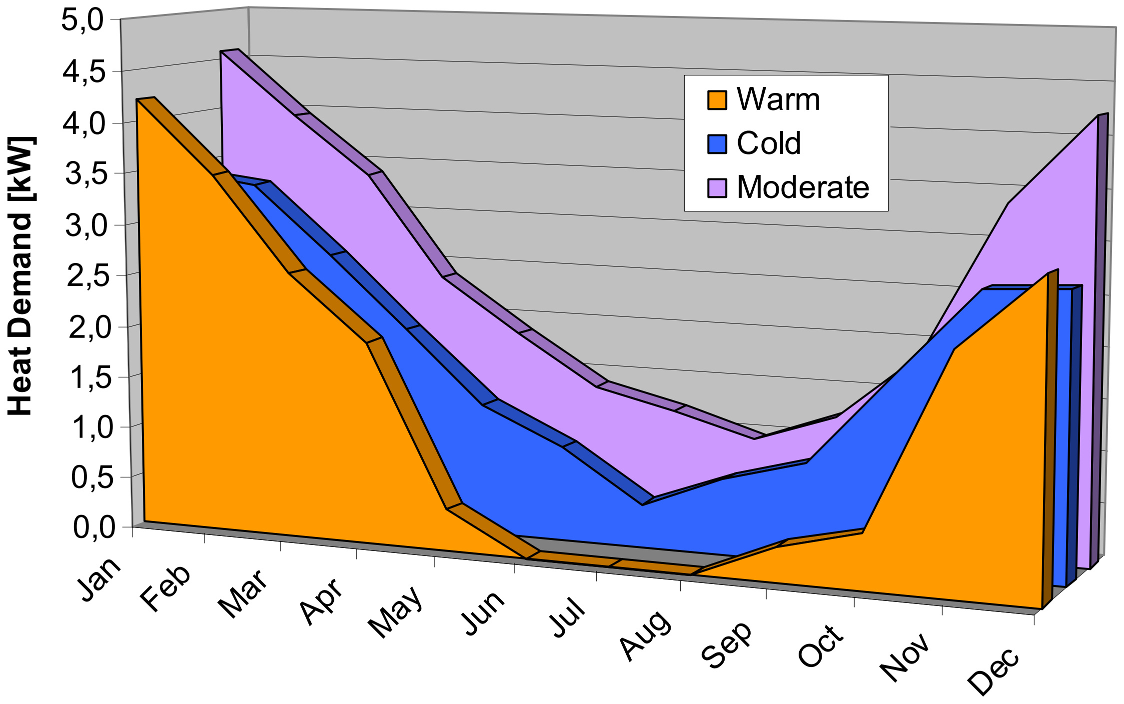

Figure VI-3: Heat Demand for the three Climatic Zones, 2004

Sorting the heat demand by size gives the annual load duration curve. It gives an overview of the time in which a specific heat load is needed (see Figure VI-4).

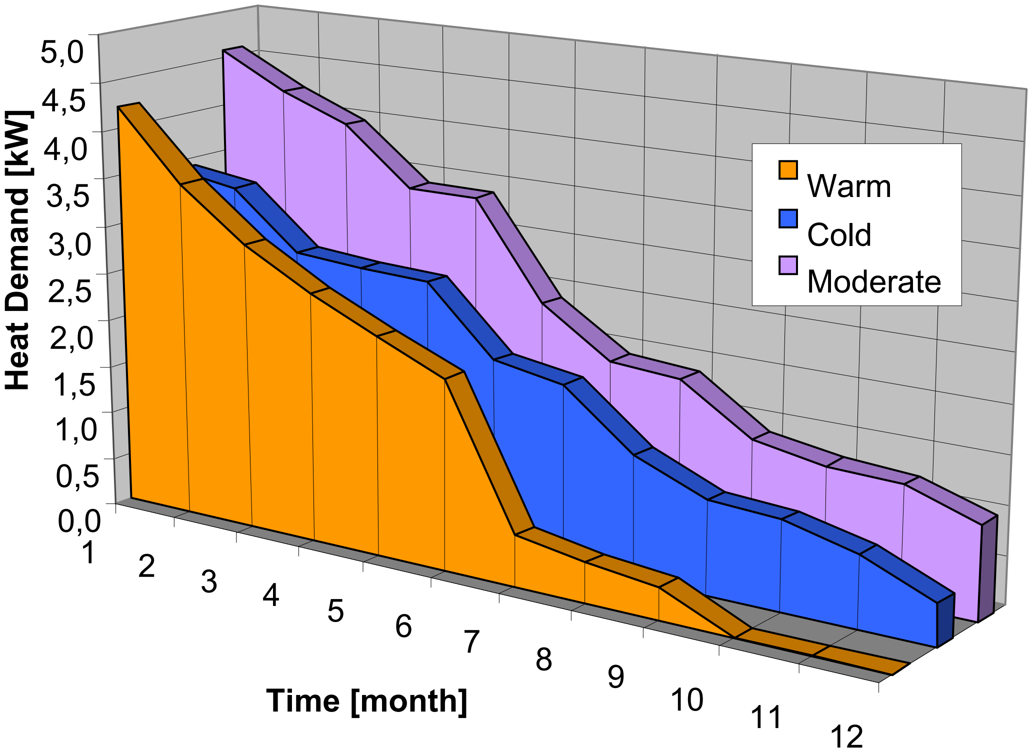

Figure VI-4: Annual Load Duration Curves for the three Climatic Zones, 2004

VI.1.2 Top-Down

To verify the dimension of the Bottom-Up analysis a Top – Down approach is done. It considers the total final energy consumption of households for space heat (FEC_{HH}), the number of households (n_{hh}), the ratio between single and multi family houses (k_{HH}), the heating degree days (HDD_y) in the respective region for a specific year (here 2004) and furthermore the efficiency for the transformation into heat (η_h). With these values a new estimate for the constant of proportionality "Φ_T" can be established.

$$\overline{\dot{Q}}_y = \Phi_T \cdot \Delta\overline{T}_y = \frac{FEC_{HH}}{n_{hh} \cdot k_{HH} \cdot d_y} \cdot \eta_h \qquad \text{VI-5}$$

$$\Rightarrow \Phi_T = \frac{FEC_{HH} \cdot \eta_h}{n_{hh} \cdot k_{HH} \cdot d_y \cdot \Delta\overline{T}_y} \qquad \text{VI-6}$$

with $HDD_y = d_y \cdot \Delta\overline{T}_y$

$$\Phi_T = \frac{FEC_{HH} \cdot \eta_h}{n_{hh} \cdot k_{HH} \cdot HDD_y} \qquad \text{VI-7}$$

$\overline{\dot{Q}}_y$: Average Annual Heat Demand

$\Delta\overline{T}_y$: Average Annual Temperature Difference

FEC_{HH} : Final Energy Consumption of Households for Space Heat

n_{hh} : Number of Households

k_{HH} : Ratio between Single and Multi Family Houses

d_y : Number of Heating Days p.a.

η_h : Heat Transformation Efficiency

HDD_y : Annual Heating Degree Days

Obviously this is a very rough calculation but it gives a feeling for the dimensions of the heat demand. This model neither considers any structural boundary conditions as for example the structure of the housing stock (age, size, isolation standard etc.) nor does it takes into account any user behaviour. The number of households per building represents an important factor. In buildings with more than one single household the relative outside surface to household ratio is lower (e.g. only one roof and floor per building) consequentially the heat demand should be lower for those buildings. This aspect is considered in the k_{HH}-factor. It is conservatively estimated by available data for Germany (for total calculation see annex). Table VI-5 shows the data used for the calculation and the results.

Zone	FEC_{HH} [TWh]	**HDD$_y$** [Kd]	**$n_{hh,2001}$**	k_{HH}	η_h [%]	Φ_T [kW/K]	Φ_B [kW/K]	$\Delta\Phi$ [%]
Finland	32.72	5,536.13	2,382,000	0.85	0.85	0.10	0.12	15
Germany	632.77	3,185.69	37,711,000	0.85	0.85	0.22	0.25	13
Greece	44.67	1,567.44	3,993,000	0.85	0.80	0.28	0.34	16

Sources: [Eurostat, 2007a], [Eurostat et al., 2005], own calculations

Table VI-5: Data to calculate the Top-Down-Φ_T (2004)

There is a variation of about 13% to 16%, dependent on the zone, compared to the calculated value in the Bottom-Up analysis. The approximate equality of both evaluations suggests the plausibility of these models. The results for the calculation with the "Top-Down-Φ_T" in comparison to the "Bottom-Up-Φ_B" for every zone are shown in Figure VI-5 to Figure VI-7.

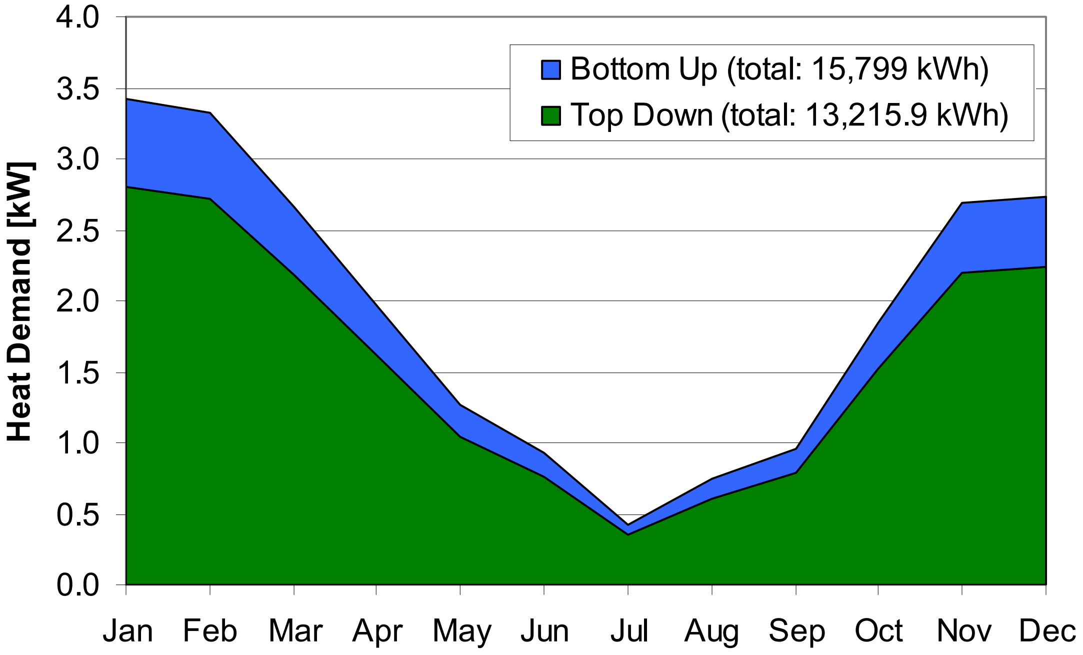

Figure VI-5: Comparison Top-Down and Bottom-Up Results Cold zone

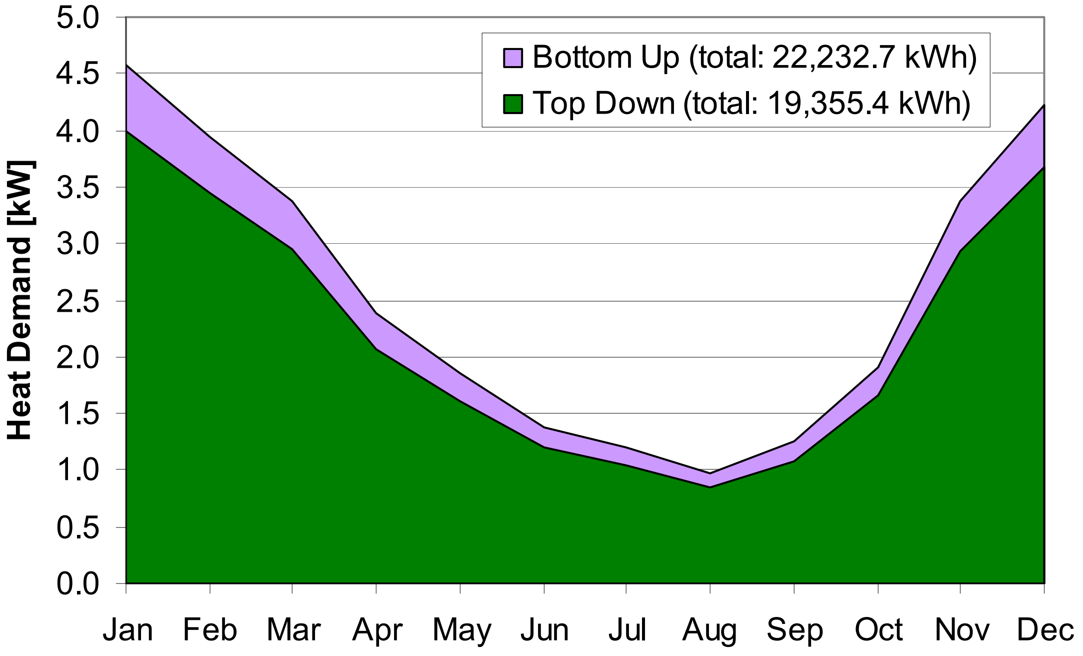

Figure VI-6: Comparison Top-Down and Bottom-Up Results Moderate Zone

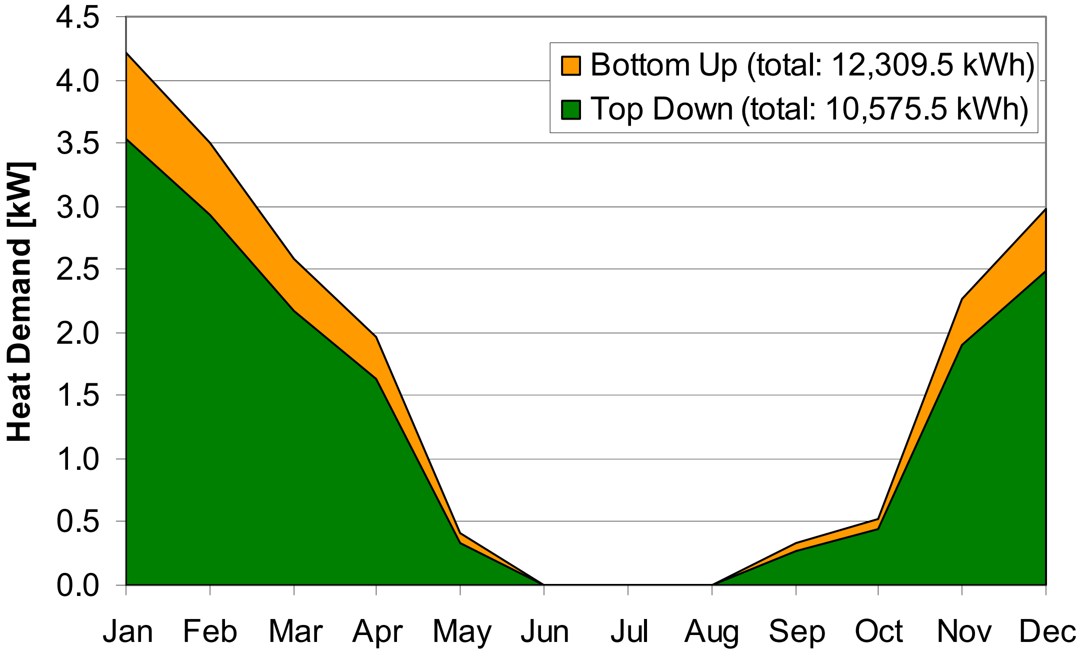

Figure VI-7: Comparison Top-Down and Bottom-Up Results Warm Zone

VI.1.3 Peak Load

As in the preceding calculations only average values are considered as information for the peak demand cannot be given directly. In Table VI-6 the peak demand for each zone with the estimated maximum temperature difference and the proportional constant of the Bottom-Up model for each zone is calculated.

Zone	**T_{min}** [°C]	**ΔT_{max}**[11] [°C]	**Peak Heat Demand** [kW]	
			Bottom-Up	**Top-Down**
Cold	- 20	38	4.6	3.8
Moderate	-10	28	7.1	6.2
Warm	0	18	6	5

Table VI-6: Peak Heat Demand for the Different Zones

The peak heat demand in the moderate and warm zone is higher in comparison to the cold zone due to the inefficient insulation and resulting high thermal conductance keeping in mind the lower average temperatures per month in the cold zone.

VI.2 Conclusions

The analysis of residential load curves for heat suggests some consequences for fuel cell heating appliance systems as well as for other CHP-systems.

For the cold and moderate zones there is a nearly steady base load for heat at about 1 kW_{th}. For seven (cold zone), respectively eight months (moderate zone), there is a demand higher than 2 kW_{th}. It seems obvious that the heat output for buildings comparable to the model house should be equal or not much higher than 2 or 3 kW_{th}. A supplemental peak burner is needed in either case to cover the peak demand.

The heat demand in the warm zone is only for at most six months on a level that heating is necessary (>1 kW_{th}). If the heat cannot be used differently in the summer month (e.g. for heat driven cooling devices) the cost effectiveness of those expensive systems is very questionable.

As already mentioned the disproportionately high heating peaks for the hot water demand can be covered by additional heat storage.

As fuel cell heating appliances only cover a base load additional peak burners are also needed. Referring to Table VI-6 the peak thermal output should be about 5 (cold zone) to 8kW_{th} (moderate zone). In case of dysfunction of the fuel cell the peak burner can supply the house alone.

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[11] $\Delta T_{max} = (18°C - T_{min})$

VII Scenario calculations

The goal of this chapter is to estimate environmental and economic effects of a large market launch for micro CHP in OECD countries. Therefore cost and scenario calculations are done. This results in estimation of CO_2 reduction potentials and estimated CO_2 avoidance costs.

The scenario calculations are split into two parts: The first part is the so called single technology analysis which focuses on the micro CHP technology itself. The second part of the scenario analysis is concentrated on the operating conditions in different climatic zones and the averaging process for the OECD. In this way results from chapter VI are used to come to an average CO_2 reduction potential for OECD countries..

With regard to international R&D activities in fuel cell systems, it can be said, that a strong focus is the application in the residential sector, i.e. single family houses. In the Annex I countries of the United Nations Framework Convention on Climate Change (UNFCCC) room heating and hot water preparation are main sources for carbon dioxide emissions (~8% of the world carbon dioxide emission [UNFCC, 2008]) and it is essential to introduce highly efficient systems which can contribute noticeably to CO_2 emission reduction.

Fuel cells are seen as such efficient conversion systems and worldwide many companies are developing small fuel cell house heating systems. So far this part of the analysis concerns the application of fuel cell systems as house energy generation units. A typical capacity range for house heating fuel cells is 1-3 kW_{el} / 4-8 kW_{th}. The system is completed by an integrated condensing gas burner which ensures the supply of the household heat demand at peak load.

The scenarios are not created for prediction of future market shares of micro CHP. The intention is to point out the effects on such items as CO_2 reduction potential or CO_2 avoidance costs of a set of assumptions.

VII.1 Facts and assumptions for scenario calculations

With regard to international activities in research and developing fuel cell systems, it can be said, that one focus is the application in the residential sector which is responsible for nearly 8% of the today’s worlds carbon dioxide emissions. (UNFCCC Annex I plus Non-Annex I parties: 2,073 million t_{CO2} in 2005 for the residential sector and 27.335 million t_{CO2} in total) [UNFCC, 2008].

In the Annex I parties of the United Nations Framework Convention on Climate Change (UNFCCC) room heating and useful water preparation are the main sources for carbon dioxide emissions and it is seen as essential to introduce sustainable high efficient heating systems which can deliver a noticeable contribution to carbon dioxide emission reduction.

Fuel cells are seen as such energy conversion systems and there are many companies reporting on their activities, tests and successes in the field of small fuel cell house heating systems. So far this part of the analysis acts with the application of fuel cell systems as house energy generation units. A typical capacity range for house heating fuel cells is 1-3 kW_{el} and 4-8 kW_{th}. The system is completed by an integrated condensing gas burner which shall ensure the supply of the household heat demand at peak load.

First it was tried to gather data on the stock of detached single family houses and the heating systems in the OECD countries, as that market segment seems to be predestined for such innovative technologies. But it was not possible to get realistic data on the number of detached single family houses and their heating systems. So we decided to use data on the sales of house heating systems from the market report of Bosch Thermotechnik GmbH (BBT 2006), in which also the future development of the market for heating systems is analysed.

The report numbers the 2006 world market volume of thermotechnical appliances as space heating systems, water heating systems and technologies using renewables with 24,4 $*10^9$ Euro, see figure I.1. The classic heating systems have a share of 49% of it. The share of the renewable systems such as heat pumps and others is not yet, significant but their growth is substantial.

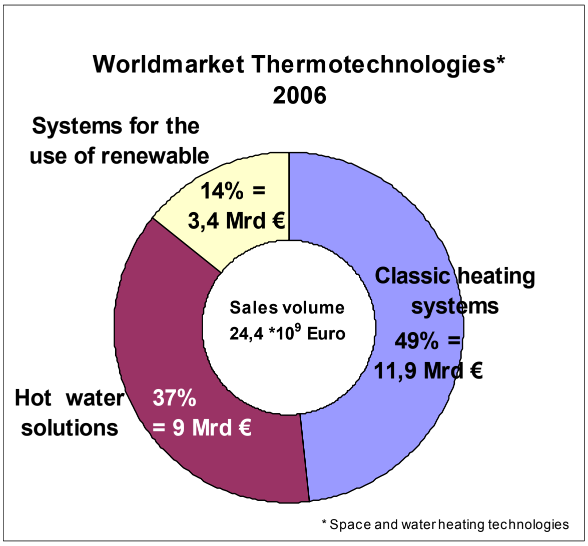


Figure VII-1: Volume of the 2006 world market for thermo technologies [BBT 2006]

At present these systems have double-digit growth rates, and a further increase is expected by the manufacturers.

Within the category “Classic Heating Systems”, the demand for house heating systems containing gas/oil fired boilers is still strongest world-wide, they have a volume of ~5 billion. Euro (= 43% at the total sales of 11.9 billion Euro), see Table VII-1.

Classic heating systems	**[Mrd. Euro]**
gas-/oil fired boiler	5,12
gas-/oil fired condensing boiler	2,68
air heating	2,19
electric heating	1,46
district heating	0,48

Table VII-1: Classic heating systems [BBT 2006]

Condensing boilers currently have double-digit growth rates partly triggered by governmental obligations (for example in Great Britain) and a continuation of this trend is expected. The main market for this technology is Europe where ~90% of the systems are sold.

Air heating systems have a share of ~18% in this segment and they are the dominant systems in the United States of America.

Electric heating systems have a strong market position in those countries which have low electricity costs and significant markets are France, United States and Scandinavian countries. District heating has a significant role in Denmark, Finland, Sweden or Iceland, see Figure VII-2, as well as in Eastern Europe and in Asia too [BBT 2006].

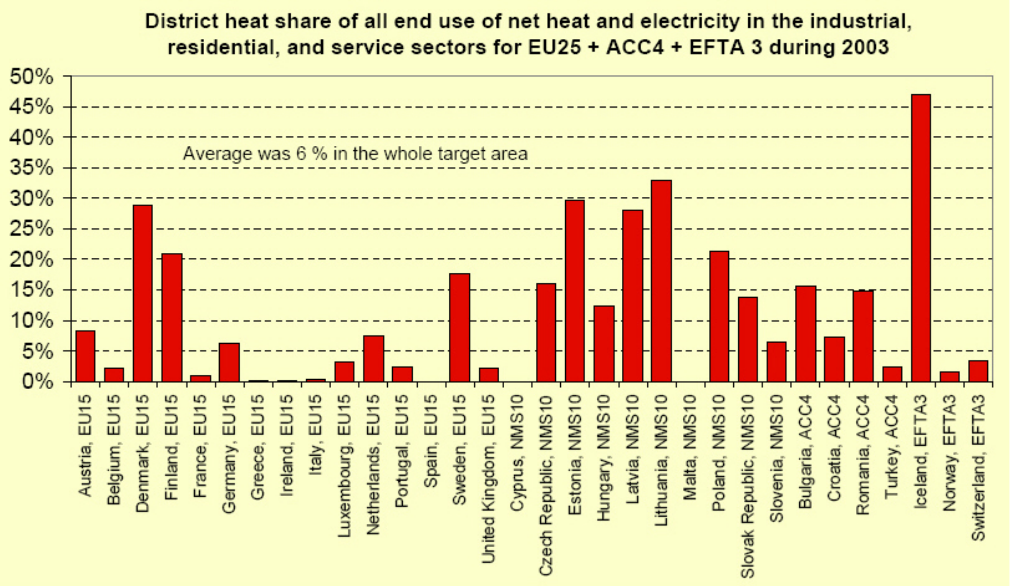


Figure VII-2: Market shares of district heating in Europe [Werner 2006]

The demand for systems which are using renewable energy for water (and space) heating has so much dynamic, that the sales volume increased by 20% in 2006.

Heat Pumps have a high share of the 2006 sales in this category, see table I.2, and Europe is currently the main market with 242.000 sold units in 2006. Around 23% of the world-wide sales are done in America and 19% in Asia principally in Japan.

Rising sales are also reported for solar collectors. In 2006 the newly installed collector area was 19,6 million square meters. The driver for simple collectors is China with the result that ~74% of the new collector area is built up in Asia. The share for Europe as the second most important market is only 18% but it is the main market for high-grade systems so that the share of the sales value is 37%. For Europe a rapid growth of collectors is expected, as new building regulations require these systems for new houses in Spain and Portugal.

The main region for the sales of solid fuel boilers with a share of 67% is Europe, mainly countries in Eastern Europe, where wood is still an important source of energy supply, but also Switzerland or France. Asia has a share of 19%, America 9% and Africa 5%.

Systems using renewables for water (and space) heating	**[Mrd. Euro]**
heat pump	1,46
solar collector	1,22
solid fuel boiler	0,70

Table VII-2: Heating systems using renewable [BBT 2006]

Figure VII-3 summarises the explanations once more and shows in a snapshot the volume and structure of the world market for thermo technical applications exemplarily at three global regions. Bosch differs three categories, systems for space heating, systems for hot water preparation and systems using renewable energy for both applications. The European market volume in 2006 was for the first time higher than 11 billion Euro with this development affected by the change towards condensing systems and systems which use renewable energy. The majority of the thermo technical appliances, 59%, are space heating systems.

The volume of the American market is half of the European and the structure of the American market for thermo technologies shows that 50% of the sales volume is done with space heating systems, whereby air heating is the dominant system. Though the sales of heat pumps, as an example for renewable systems, did increase in 2006, its share is still relatively small.

The entries for Asia Bosch data show that the Asian market for thermo technical appliances has nearly the same volume like the American market though much more people are living in that area. But their living conditions are completely different so that domestic thermo technical appliances are not yet widespread. The main products are systems for water heating. It is obvious that the renewable based systems have a clearly higher share as in the other regions. [BBT 2006]

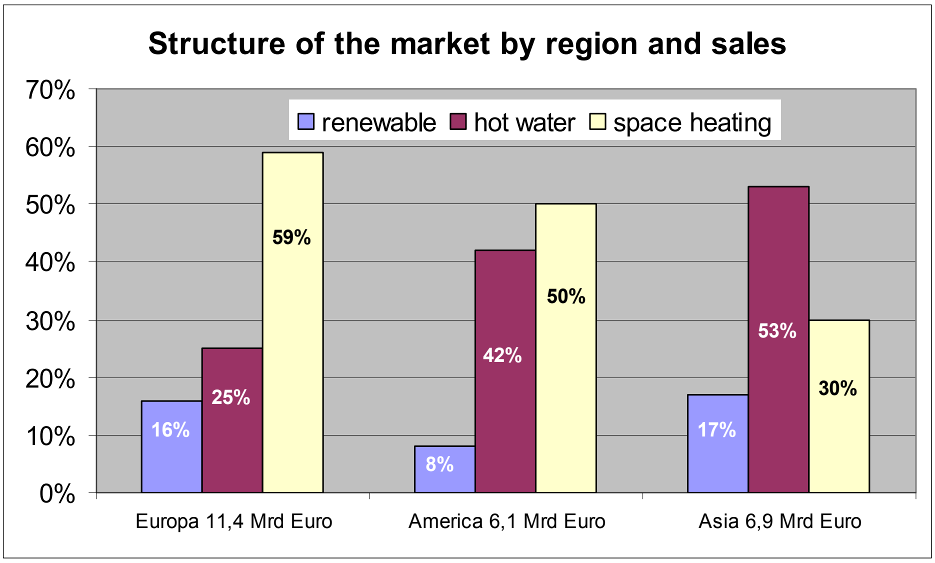
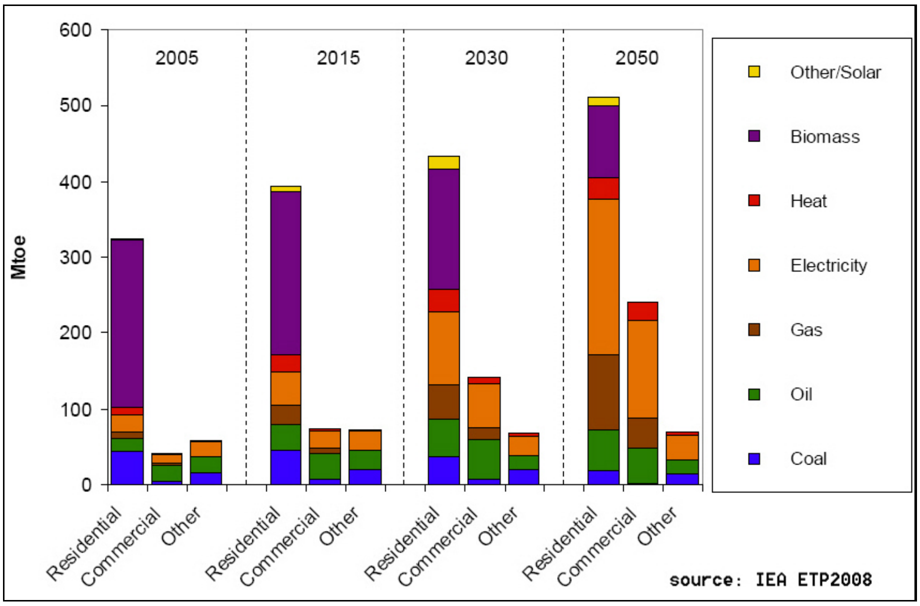


Figure VII-3: Structure of the market for thermo technologies by region [BBT, 2006]

The energy carrier availability in Asian countries and its distribution infrastructure differ from the European situation. That explains the strong market share of biomass as energy carrier in the building sector, exemplarily shown for China and India according to the ETP baseline scenario, see Figure VII-4 and Figure II-5.



source: IEA ETP2008

Figure VII-4: China buildings sector energy consumption by fuel [IEA 2006]

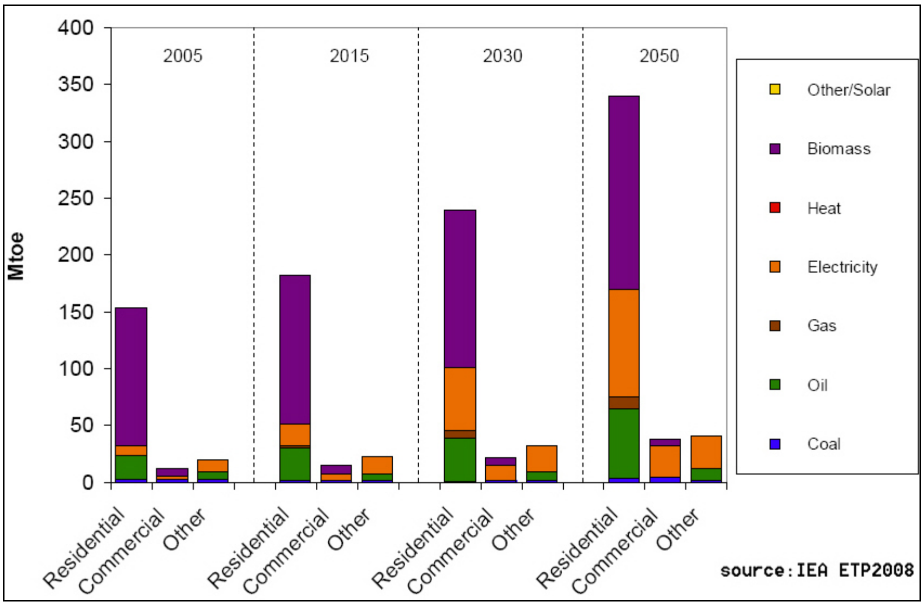


Figure VII-5: India buildings sector energy consumption by fuel [IEA 2006]

The development of the residential energy demand for these two countries mirrors the expectations of the manufacturers of thermo technical appliances, they expect a growing market in the next decades.

Before coming to the assumptions for our calculations, a more detailed look at the European data in the market report will be done.

Bosch reports the volume of the European market for heating systems as ~5.7 million systems for 2006. These 5.7 million units are partitioned into 2.65 million condensing oil/gas systems, for which Bosch expects an ongoing growth rate of 9% up to 2014. For the classical oil/gas heating boilers, of which ~3.1 million units were sold in 2006, the experts see reduced future sales with a decrease of 4%/year. An increase of 12% per annum starting from a low market level is seen for heat pumps and that development can be explained by the present trend to equip newly built low energy houses with renewable based energy supply systems. It must be remembered that European governments are promoting these technologies and even regulate their use by law (obligating the use, for example of condensing boilers in Great Britain). Promotion of solid fuel boilers is also done, noting in this case that solid fuel means wood and wood products like pellets or wood chips. In 2006 around 0.3 million units were installed in Europe. The experts of Bosch estimate a rising trend with growth rates of 4%..

In 2006 the Building Services Research and Information Association (BSRIA), UK, published the study “World Market for Heating (2005)” [BRISA, 2006]. BSRIA sees a rising volume for the world domestic boiler market, which had a volume of ~10 million units in 2005. For 2010 they expect nearly 12 million units will be sold. Non-condensing boilers still represent ~50% of the total market in volume, but a decline is expected in the future, just as predicted in the BBT-market report. Presently the sales of condensing boilers are growing at a rate of over 15% per year so that this technology is expected to reach a share of 27% by 2010.

VII.2 Fuel Cell market penetration

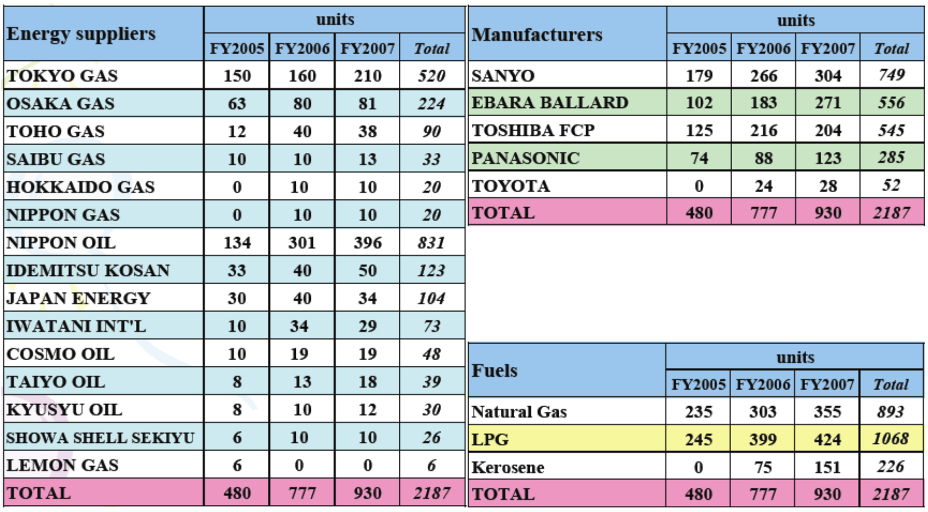
With our considerations for the introduction into the market and spreading of fuel cell heating systems we assumed a successful development of marketable and competitive systems within the next 6 to 7 years, which can be operated as reliably or better than existing offerings by everybody in their home. In order to find out, whether it is possible to contribute to the reduction of carbon dioxide emissions in the residential sector, we calculate based on an introduction in 2014. To support this approach we relied on different Japanese and European publications, which are listed in Table VII-3.

Fuel Cell systems are still under development and there are several obstacles to overcome for a mass market introduction: Currently fuel cell system costs are higher in comparison to other CHP applications. There are problems with availability and life time of the appliances, too. Technical problems that did occur during testing periods were partly caused by failure of peripherals. Future R&D work will focus for example on High Temperature PEMFC systems with the goal of simplification and higher system integration.

Country/Region	**Year of publication**	**Installation target for**	installed units per year	installed capacity **[MW$_{el}$/year]**	cumulated capacity **[MW$_{el}$]**	unit capacity	Source
Japan	**2006**	2015	500000	500		1 kW$_{el}$	"Overview of Fuel Cell R&D on NEDO", October 2006
		2020 ~ 2030	> 500000	> 500		1 kW$_{el}$	
Japan	**2006**	2005	480			1 kW$_{el}$	"Current Status of the Large-Scale Stationary Fuel Cell Demonstration Project in Japan", Shinji Nishikawa, New Energy Foundation, Nov. 2006
		2006	777			1 kW$_{el}$	
		2020			10000	1 kW$_{el}$	
		2030			12500	1 kW$_{el}$	
Japan	**2007**	2004		980		1 kW$_{el}$	"CHP in Japan present status and where it's heading", IEA CHP Program Kick-off Meeting, Paris, 02.03.2007
		2010		2200		1 kW$_{el}$	
Japan	**2007**	2009	1000 - 10000	1 - 10		1 kW$_{el}$	"R&D activities Japan", Japanese presentation at IEA Advanced FC Annex meeting march 2007, Juelich
		201?	100000	100		1 kW$_{el}$	
Japan	**2007**	2020			10000	1 kW$_{el}$	Current Status of the Largescale Stationary Fuel Cell Demonstration Project in Japan, Tomio Omata, NEW ENERGY FOUNDATION, San Antonio, Oct. 2007
		2030			12500	1 kW$_{el}$	
EU	**2005**	until 2020	100000 - 200000	2000 - 4000	8000 - 16000 (400000 - 800000 units)	< 100 kW$_{el}$	European Hydrogen & Fuel Cell Technology platform, Deployment Strategy, August 2005
EU	**2007**	until 2010			100		European Hydrogen & Fuel Cell Technology platform, Implementation Plan, January 2007
		until 2015	100000		1000		

Table VII-3: Start of market introduction and dissemination of small fuel cell house heating systems in the residential market

In Japan the application of small fuel cell systems for the residential sector is widely advanced and ~2,200 units are under operation. All these units are part of a large-scale demonstration project. It is initiated by METI as well as NEDO and is executed by a large number of gas suppliers and manufacturers, details are listed in Table VII-4.



Energy suppliers	units			
	FY2005	FY2006	FY2007	*Total*
TOKYO GAS	150	160	210	*520*
OSAKA GAS	63	80	81	*224*
TOHO GAS	12	40	38	*90*
SAIBU GAS	10	10	13	*33*
HOKKAIDO GAS	0	10	10	*20*
NIPPON GAS	0	10	10	*20*
NIPPON OIL	134	301	396	*831*
IDEMITSU KOSAN	33	40	50	*123*
JAPAN ENERGY	30	40	34	*104*
IWATANI INT'L	10	34	29	*73*
COSMO OIL	10	19	19	*48*
TAIYO OIL	8	13	18	*39*
KYUSYU OIL	8	10	12	*30*
SHOWA SHELL SEKIYU	6	10	10	*26*
LEMON GAS	6	0	0	*6*
TOTAL	480	777	930	*2187*

Manufacturers	units			
	FY2005	FY2006	FY2007	*Total*
SANYO	179	266	304	*749*
EBARA BALLARD	102	183	271	*556*
TOSHIBA FCP	125	216	204	*545*
PANASONIC	74	88	123	*285*
TOYOTA	0	24	28	*52*
TOTAL	480	777	930	*2187*

Fuels	units			
	FY2005	FY2006	FY2007	*Total*
Natural Gas	235	303	355	*893*
LPG	245	399	424	*1068*
Kerosene	0	75	151	*226*
TOTAL	480	777	930	*2187*

Table VII-4: Number of units installed in the Japanese Demonstration Project [Omata 2007]

The fuel cell house heating systems are of the PEFC type, have an electrical capacity of 1kW$_{el}$ and can be modulated to 30% load. They are installed at family houses and combined with a 200 litre water storage system to supply the useful water demand, see Figure VII-6 and Figure VII-7. For the first 175 units, installed in 2005, yearly operation hours of 5,454 hours per site could be realised, generating 3,172 kWh electricity.

Figure VII-6: Pictures of installation sites [Omata 2007]

Table VII-3 shows the expectations respectively targets of Japan and Europe with regard to the introduction and dissemination of stationary fuel cell systems. The Japanese specialists are expecting a cumulated installed capacity of 10 GW at ~2020, while HFPeurope expects with its Implementation Plan the installation of 2,000 to 4,000 MW$_{el}$/year fuel cell capacity respectively cumulated 8 – 16 GW$_{el}$ in 2020.

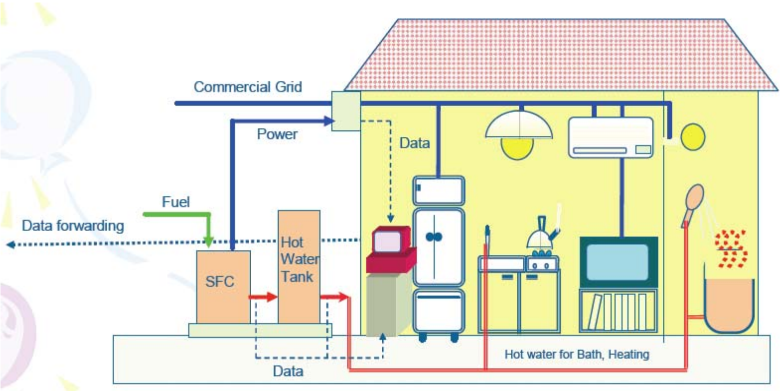


Figure VII-7: Stationary fuel cell demonstration project [Omata 2007]

Due to these expectations we decided to calculate the market adoption of the fuel cell house heating systems using a logistic function which describes the correlation between the market penetration of a product and the time until saturation. Two scenarios were developed, a low one in which the fuel cell systems will reach a market share of 5% and a high one in which the share reaches 20% of all house heating systems sales. In both scenarios the introduction starts in 2014 and reaches its saturation in 2030, whereby the sales will not remain at the 2030 values, they will increase further according to the total sales of house heating systems, see Figure VII-8. The upper (green) graph shows the sales development of the category “central house heating systems” and the graph is a continuation of annual sales data, as expected and published by BBT and BSRIA in 2007.

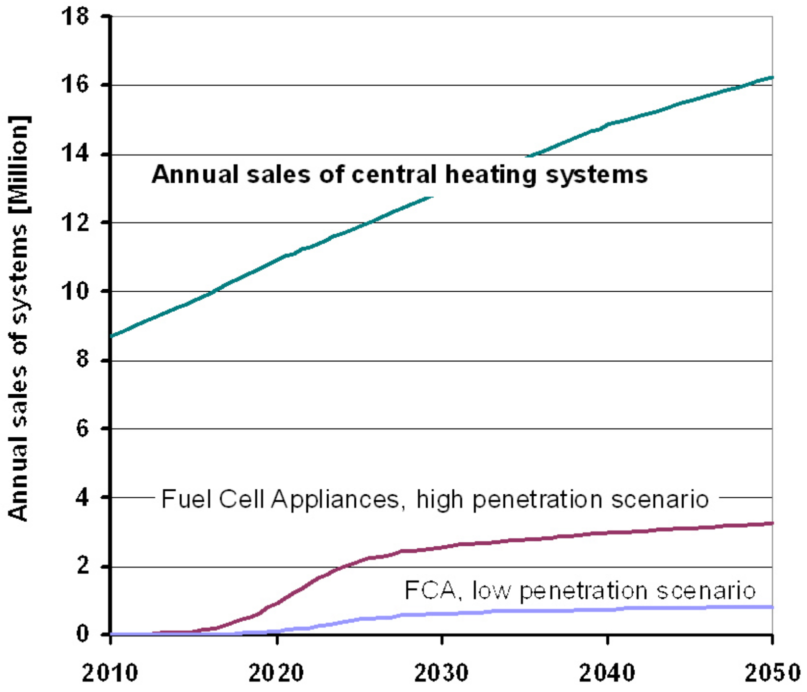


Figure VII-8: Market introduction and dissemination of fuel cell house heating systems

The total number of sold heating systems in 2050 is in the range of 16 million systems p.a. The two other graphs represent the development of the market penetration of fuel cell appliances, corresponding to the high respectively low penetration scenario.

The high scenario is characterised by a dynamic introduction into the mass market in 2014 with nearly 70,000 units. The sales graph achieves an exponential rise, which flattens itself however at around 2023, as the maximum market share is reached at 2030. In 2030 ~2.5 million units are sold and in 2050 around 3.2 million units, so that ca 80 million units will be in operation.

The low scenario starts restraint with 6,000 sold fuel cell systems, see the blue (lower) graph. The sales volume is moderate and comes up to 630,000 units in 2030 and ends with ca. 800,000 sold units per year in 2050.

In our market penetration scenarios the fuel cell house heating systems first displace the non-condensing boilers, of which still ~2 millions will be sold in 2014 according to the BBT market report [BBT 2006]. As the sales will decline with a rate of 4%/year, the fuel cells have to oust other technologies in the low penetration scenario from ~2020 onwards. In the high scenario, that possibility ends already in 2021. It is possible that this change in competition will have an influence on the further market penetration of the Fuel Cell. However for our scenario it is assumed, that the deployment of the fuel cell systems will not be reduced and that they will continue to gain market share up to 2030 in both high and low cases.

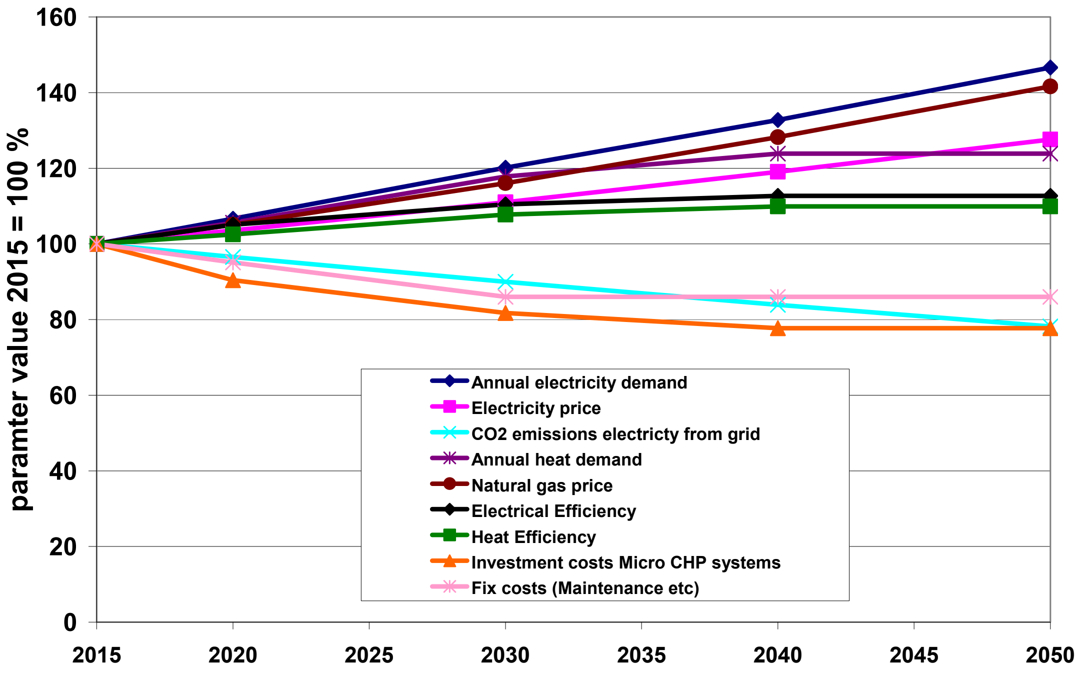


Figure VII-9: Assumed development of data for the scenario calculation for OECD region according to [IEA, 2007a], [IEA, 2007b], [IEA, 2007c], [IEA, 2006a]

For the scenario calculations other important numbers and assumptions about their development are required. Assumptions about the development of the key variables were made Figure VII-9 gives a survey of the important dates and possible development towards the year 2050. The basis of the assumptions was the “World Energy Outlook” and the report “Energy Technology Perspectives” of the IEA ([IEA, 2007c], [IEA, 2006a].

All scenarios expect rising primary energy prices and therefore rising electricity prices. For Micro CHP systems we assume a decrease in investment costs that represents learning effects for the production processes of these systems. Because of better system integration and higher performance of the fuel cells in future we also expect an increase of electrical and thermal efficiency for two decades. The specific CO_2 emissions for a produced kWh electricity out of the power plant sector decrease till 2050 by about 20%. This reflects the scenario calculations of the IEA with rising elements of nuclear and renewable electricity production and an increasing efficiency of power plant processes in the OECD region.

VII.3 In-depth Fuel Cell technology case analysis

To test out, if there will be essential differences between the results of a small solid oxide fuel cell type (SOFC) with a high electrical efficiency and a little bit larger polymer electrolyte fuel cell (PEFC), the supply of the house heat demand by these fuel cell devices is calculated.

The house data such as insulation standard and heat demand is taken from a calculation for a detached single family house in Germany, inhabited by 4 persons. In the case of a highly insulated house (EFHj), which fulfils today’s and future building regulations, the heat demand is 7,099 kWh/year for space heating and 1,506 kWh/year for hot water preparation. An un-insulated house (EFHE) represents the today’s housing stock and is the object of comparison. Its heat demand is 31,441 kWh per year [Kraft 2002]. For his calculations and simulations, Kraft did regard internal loads, house typical solar gains, transmission as well as ventilation losses but also absence of inhabitants because of holidays and others.

As the supply of room heating and water heating is the typical application of individual house energy supply systems, the fuel cell systems will be operated following the heat demand. With that operation strategy the generated electricity is a by-product, which can be used directly or is fed into the public grid as the feed-in compensation can be a strong incentive. For this reflection fuel cell electricity will substitute at any rate electricity from coal power plants, so that the carbon dioxide emission reduction potential is mainly caused by the differences between the emission of the coal power plants and that part of the fuel cell carbon dioxide emission which is allotted to its electricity generation. The latter is determined by the comparison of the emissions of the fuel cell appliance, peak burner included, with the emissions, which result from supplying the heat demand by a conventional gas boiler.

The fuel cell comparison should show if there are differences between the two fuel cell types, of which the SOFC has a high electrical efficiency of 45% and a thermal efficiency of 30%, while the PEFC has a thermal efficiency of 50% and an electrical efficiency of 30%. The results of the calculations did not show essential differences, whereby it was regarded for the operation of the SOFC, that its lifetime can be influenced negatively by too many starts and stops. The main restriction was the condition not to restart before some hours of downtime, so that in our simulation it had in the case of the un-insulated house (EFHE) 134 starts per year and 4,139 operating hours. In the high insulated house type case (EFHj), the SOFC had 49 starts per year and 5,117 operating hours.

Table VII-5 shows detailed results for the EFHE case and that there is only a marginal difference between the two fuel cell types with regard to a CO_2 emission reduction potential in the OECD residential sector. On the basis of 100,000 GWh electricity, generated by the fuel cell, the reduction by use of the small SOFC with a high electrical efficiency is 3.97% and of the PEFC 4.08%. The reference "CO_2-emission of the residential sector" of OECD countries is derived from Greenhouse Gas Inventory Data from United Nations Framework Convention on Climate Change [UNFCC 2008] and from the World Energy Outlook 2006 [IEA, 2007c].

low insulated house (EFHE) 2050	Capacity el/th	Stock units	Operation hours FC device/ a	Operation hours peak boiler/a	power generation FC	total gas consumption	CO_2 FCdevice	CO_2 of reference system (boiler & CoalPP)
	[Watt]	[mio units]	[h]	[h]	[GWhel/a]	[GWh]	[M t CO2]	[M t CO2]
Kyocera	700 / 467	83	4139	1632	238.972	3.182.413	638	781
Baxi	1500 / 2500	83	3676	1250	455.704	3.401.104	682	962

low insulated house (EFHE) 2050	CO_2 emission OECD residential sector	%reduction CO_2 emis / 100,000 GW_{el}	energy consumption reference system	% reduction energy consump/ 100,000 GW_{el}
	[Mt CO2/a]	[%]	GWh	[%]
Kyocera	1507	3,97%	3.466.983	3,63%
Baxi	1507	4,08%	3.977.934	3,18%

Table VII-5: Results for the fuel cell comparison in the low insulated house case (EFHE) high penetration

A similar result with 3.63% reduction for the SOFC-use respectively 3.18% for the PEMFC-use follows with regard to the energy consumption. The saved energy is calculated by the difference between the consumption of the reference system, gas for the gas heating boilers and coal for coal power, and the consumption of the fuel cell appliances, gas for its heat and power generation.

Less starts occur in the case of high insulated houses, see Table VII-6. As the continuous heat demand is lower than for EFHE house, the yearly operation time of the fuel cell house heating device is higher and thus the electricity generation too. And the “saved energy” is calculated by the difference between the consumption of the reference system - gas for the gas heating boilers and coal for coal power - and the consumption of the fuel cell appliances - gas for fuel cell heat and power generation.

The operation of the fuel cell appliances differs in the two house-type cases clearly as in the high insulation houses the peak boiler has much less operation hours. Fuel cell and storage seem to be tuned in a better way, so that the operation hours of the peak burner are reduced compared to the EFHE case, see Table VII-6. The number of starts for the SOFC type reaches only 50 and for the PEMFC type 3,317. It should be mentioned, that the peak boiler of the device for the high insulated houses has a thermal capacity of 10,000 Watt, while it has a capacity of 19,000 Watt in the low insulated houses, because otherwise a heat supply was not guaranteed. The smaller size of the peak boiler together with the heat capacity of the SOFC explains the higher number of yearly operation hours which is necessary, as the SOFC has a strong limitation for start-stop events. For the PEFC no restrictions are done with regard to the yearly number of starts, so that the fuel cell can supply most of the heat demand with the consequence of more than 3,000 starts per year but only 29 operation hours for the peak boiler.

high insulated house (EFHj) 2050	capacity el/th	stock	operation hours FC device	operation hours peak boiler	power generation FC	total gas consumption	CO_2 by FC device	CO2 of reference system (boiler & Coal PP)
	[Watt]	[mio units]	[h/a]	[h/a]	[GWhel/a]	[GWh Gas]	[Mt CO2/a]	[Mt CO2/a]
Kyocera	700 / 467	83	5.117	642	296.028	1.136.445	228	405
Baxi	1500 / 2500	83	3.406	29	422.278	1.261.996	253	512

high insulated house (EFHj) 2050	CO_2 emission OECD residential sector	%reduction CO_2 emis / 100,000 GWh_{el}	energy consumption reference system	% reduction energy consump/ 100,000 GWh_{el}
	Mt CO_2/a	[%]	[GWh]	[%]
Kyocera	1.507	3,97%	1.488.416	7,99%
Baxi	1.507	4,08%	1.418.276	5,65%

Table VII-6: Results for the fuel cell comparison in the low insulated house case (EFHj) high penetration

Both systems show less differences with regard to the specific CO_2 emission reduction, which is related to 100,000 produced GWh_{el}. A small difference becomes recognizable regarding the energy consumption reduction in the comparison to the reference system, which consists of gas-fired boiler and coal power station. The definition of coal power plant as the reference instead of the OECD power plant mix is intentionally, in order to show what the maximum effect would be. For the calculations in the next chapters the OECD power station mix and its corresponding CO_2 emission is the reference.

VII.4 CO_2 Avoidance Costs and reference systems

To provide a benchmark the CO_2 avoidance costs are calculated in comparison to conventional boiler systems for heat supply and a grid connected electricity supply (the reference system). Two supply situations are compared: a single family house with one household and 4 persons living their and a multifamily house with four households.

The CO_2 avoidance cost calculation is the result of a comparison between the so called reference system and the competing micro CHP system. In the scenario considerations of this study the reference system for supply of heat and electricity is the distributed heat production in condensing natural gas boiler systems and electricity supply from the public grid to a single and a multi-family house.

The electricity is generated by an OECD wide mix of natural gas, coal fired thermal and nuclear power plants. The values for CO_2 emissions from the power plant sectors follow closely the scenarios of the world energy outlook 2006 and the electricity information of the IEA ([IEA, 2007c]; [IEA, 2007a]).

The scenario considers only family houses with natural gas supply because nearly all current systems under development or in the market use natural gas as fuel. There are some systems that work also with heating oil or directly with hydrogen (see chapter V). For hydrogen we did not assume a widespread distribution grid for households so that we base the scenario on the supply of natural gas to households. Especially in the Asian/ Pacific region liquefied petrol gas is also a common fuel for household supply. The CHP systems have similar characteristics and costs to those of natural gas systems. For this reason no special LPG system is analysed. The cost data for the natural gas supply of households are taken out of [IEA, 2007c] and the report “Natural gas information 2007” of the IEA [IEA, 2007b].

Table VII-7 points out the data of the reference systems for the assumed market entry year 2015. For reasons of clarity only the values for 2015 are displayed. The development of all data till the year 2050 is shown in Figure VII-9.

	Reference system grid electricity & gas condensing boiler	
Type of housing	**Multi Family Home**	**Single Family Home**
number of households	4	1
Annual electricity demand [kWh]	14,000	3,500
Electricity price [€/kWh]	0.11	
Extra charges electricity [€/a]	60	
CO_2 emissions electricity from grid [kg/kWh]	0.470	
Natural gas price [€/kWh]	0.039	
Extra charges natural gas [€/a]	60	
Nominal heat Power [kW]	30	10
Heat Efficiency [% LHV]	95	95
Total investment cost system [€]	12,000	4.500
Installation costs [€]	1,000	500
Fix costs (Maintenance etc) [€/a]	250	150
Interest rate (%)	5	
economic life time (years)	10	

Table VII-7: Data for the reference heating system and electricity supply from the grid for the year 2015

The technical and cost data of the condensing boiler systems are average values of new installed systems (see chapter IV.1) for multi- and single family applications. The system consists out of a micro CHP system, peak boiler and heat storage. Therefore minute peaks for example hot water preparation will be buffered. CHP systems without any heat storage option (including hot water storages) have to be operated very dynamically. Due to natural gas reformers most of the Fuel Cell systems can not be operated in this mode. Especially SOFC systems have stand by operation modes. These modes cause additional losses.

The economic life time of the systems is the pay back time for private investments in the heating appliance sector. The technical life time is higher and reaches an average value of over 20 years for heating appliances for private use. All cost data are calculated in real terms for 2005 in Euro.

Because of the different heat/ electricity demands the calculations are done for the three different climatic zones warm, moderate and cold. The difference for the cost calculations is in the operating hours of the systems. For simplifying reasons all other figures which are not directly dependent on the operation time of the systems are not changed. Using the results from chapter VI for the heat demand for space heating and hot water Figure VII-10 shows the calculated annual demand for a free-standing single-family home. The house is equipped with a good insulation standard and it is assumed to be that appropriate to construction in the year 2015. The heat demand for hot water and space heating is derived from a national model [Kraft, 2002]. Three different climatic zones are calculated with regard to chapter VI and compared with results from the report [Petersdorff et al., 2004].

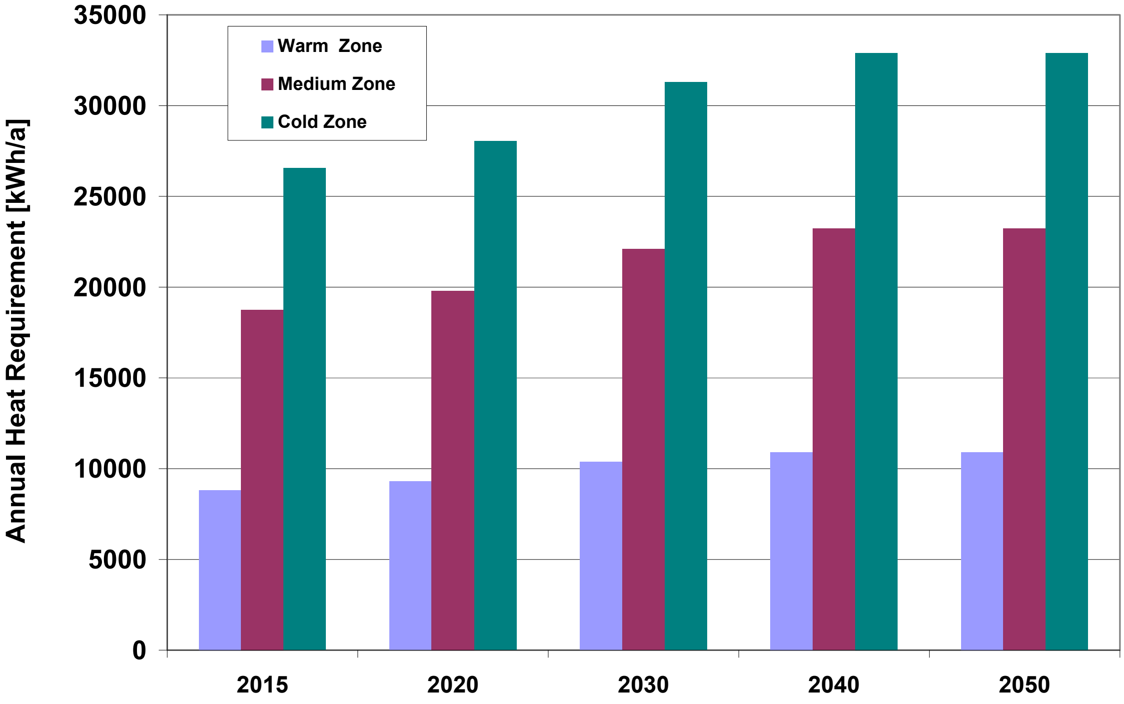


Figure VII-10: Assumed heat requirement of a free-standing single family house in different climatic zones

The different heat demand in the climate zones warm, moderate and cold assumes that the same insulation standard is applied in these regions. With this determination a comparison of calculated results for micro CHP in the different climatic zones is possible.

The scenario for the heat demand reflects two different effects: The first one is the increase of heated living space in average houses up till 2050. The second effect is the rising standard of house insulation and a resulting decrease of heat demand for space heating. This two assumptions together results in an increase of the annual heat demand till 2040 and after that a stagnation due to rising insulation standards worldwide.

Competing systems for the supply of a multi-family house are micro CHP systems with an internal combustion engine (ICE Micro CHP) and a low temperature PEM Fuel Cell (PEFC Micro CHP). The nominal thermal capacity is between 7 to 12 kW_{peak}. The systems are equipped with an additional burner for peak thermal power for winter conditions. It has a capacity of 30 kW and is an efficient gas boiler system.

Table VII-8 gives some details of the assumptions for the calculations of energy consumption, costs and emissions for the multi-family case. The data are estimated for the assumed market introduction phase in 2015. The efficiencies are based on details for units which are in demonstration stage and refer to the lower heat value of natural gas as input. The values for efficiency do increase in the course of the scenario run time. The heat and electricity generation capacity represents typical average values of systems near to the market or in market entry phase (see chapter IV and V). The different system specifications result in different operating hours of the CHP and peak burner systems.

	ICE Micro CHP. data derived from Dachs-Senertec	**PEFC Micro CHP** data derived from Vaillant Euro 2
Type of housing	**Multi**	**Multi**
number of households	4	4
Nominal electrical power (kW)	5.5	4.6
Nominal thermal power (kW)	10.8	6.6
Power to heat ratio	0.5	0.7
Electrical Efficiency [% LHV]	30	35
Heat Efficiency [% LHV]	56	49
Total efficiency [% LHV]	86	84
Peak burner nominal heat power (kW)	30	30
Total investment cost system [€]	22,700	28,000
Installation costs [€]	1000	1000
Fix costs (Maintenance etc) [€/a]	250	350
Var costs per heat (supplies wo fuel) [€/kWh]	0.001	0.003
Interest rate (%)	5	
Economic life time (years)	10	

Table VII-8: Scenario assumption for competing micro CHP systems for the multi-family house case 2015

Especially the costs of the systems are subject to great uncertainty. Corresponding to learning curves, the investment cost of the systems will decrease along the time scale. An additional sensitivity analysis and the calculation of overall costs and performance were performed to estimate possible ranges and they show, that the investment will not be the dominating factor, (see chapter VII.5).

For the single house application the competing systems are a Stirling engine (Stirling Micro CHP) like the ”Wispergen”, low temperature PEM (PEFC Micro CHP) like the “Baxi beta” and high temperature SOFC system (SOFC Micro CHP) like the “Hexis”. Because of the lack of data it was not possible to estimate values for a high temperature PEM system. These systems are in a very early developing stage of development and the tests of the new membranes are looking very promising, see chapter VII.5

We assumed that all systems are equipped with a highly efficient 10 kW peak burner system. The micro CHP systems for single-family houses have lower heat and electricity capacities. The specific costs per installed unit of electrical capacity are higher than the systems for multifamily house. The reason for this is the need for auxiliary systems like reformers, pumps, safety systems which are necessary for operation and are not scalable with the electricity output of the total system. Table VII-9 points out important 2015-values for the cost and emission calculations.

	Stirling Micro CHP data derived from Wispergen	**PEFC Micro CHP** data derived from Baxi beta	**SOFC Micro CHP** data derived from Hexis
Type of housing	**Single**	**Single**	**Single**
Nominal electrical power (kW)	1.0	1.5	1.0
Nominal heat power (kW)	7.7	2.4	2.4
Power to heat ratio	0.1	0.6	0.4
Electrical efficiency [% LHV]	10	32	26
Heat efficiency [% LHV]	77	49	62
Total efficiency [% LHV]	87	81	88
Peak burner nominal heat power (kW)	10	10	10
Total investment cost system [€]	8.100	12.300	11.400
Installation costs [€]	500	500	500
Fix costs (Maintenance etc) [€/a]	150	150	300
Var costs per heat (supplies wo fuel) [€/kWh]	0.001	0.001	0.002
Interest rate (%)	5		
economic life time (years)	10		

Table VII-9: Scenario assumption for competing micro CHP systems for the single-family house case 2015

The CO_2 emission reduction results from comparison of the combined generation of heat and power in comparison with heat production via condensing boiler and electricity from the public grid. Heating appliances for single and multi-family houses are driven according to the heat demand for space heating and hot water consumption. The typical operation time per year in the moderate zone is in the range of 2000 h.

For the calculation of the operation time of the Micro CHP systems we used a model for calculation of the annual heat demand for houses in different climatic zones with a time resolution of 15 minutes for a one year period. For the calculation of energy consumption and CO_2 emissions it was assumed that the CHP systems are operated in a heat lead way. The Micro CHP systems for the multi family house case are equipped with thermal heat storage of 500 l water content and for single houses respectively 200 l. This results in operation hours per year for the CHP systems in 2015 for the single family house (multi family in brackets):

Warm zone: 1100 – 6500 h/a (2200 – 3400 h/a),

Medium zone: 2500 – 6600 h/a (3900 – 4500 h/a) and

Cold zone: 3300 – 6600 h/a (4700 – 4700 h/a).

For peak demand we assume for all CHP units an integrated peak burner system with thermal power of 10 kW for single- family and 30 kW for multi-family houses. The peak burner system is assumed to be as efficient as a natural gas burner appliance.

This results in additional operation hours per year for the peak burner in 2015 for the single family house (multi family in brackets):

Warm zone: < 400 h/a (< 200 h/a),

Medium zone: < 1000 h/a (< 700 h/a) and

Cold zone: 400 – 2000 h/a (1000 – 1400 h/a).

The emission of natural gas consumption is calculated with 202 g/kWh_{NG} according to the lower heat level. This is taken together with the assumptions of Table VII-8, Table VII-9 and the assumed development of prices and technical data (see Figure VII-9). A selection of the results for the CO_2 avoidance in the warm zone of the different micro CHP systems in comparison to the reference system is displayed in Figure VII-11.

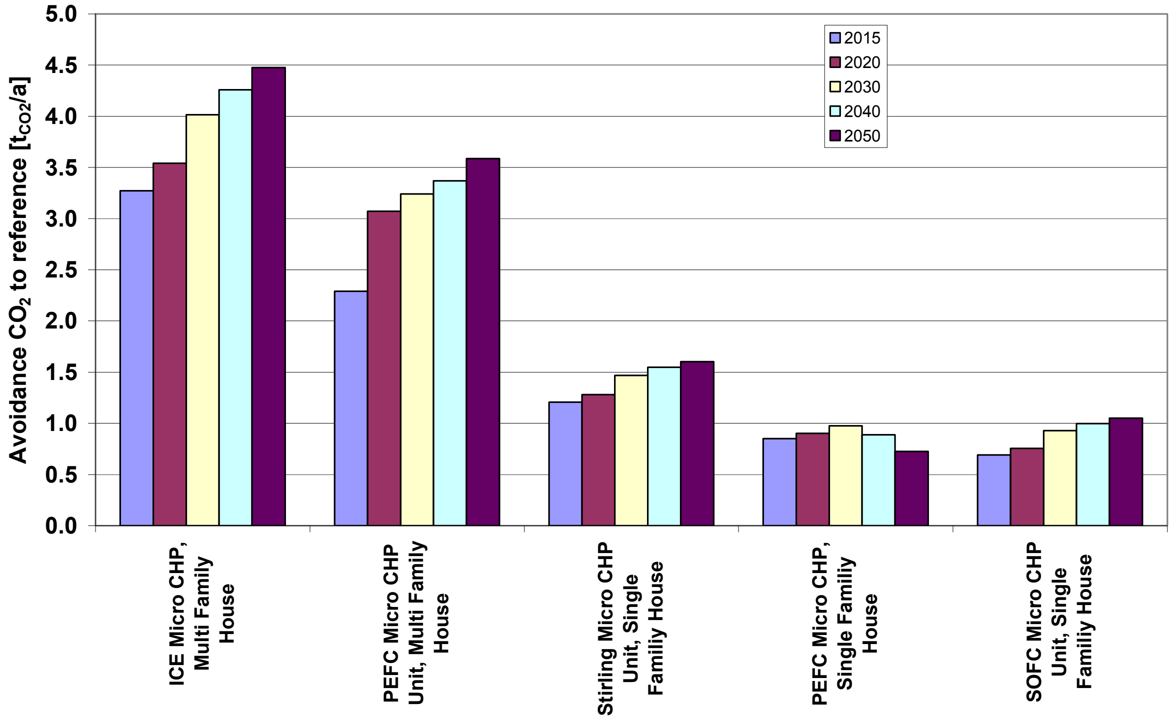


Figure VII-11: Avoided CO_2 per system in the warm climatic zone

The scenario calculations derive figures for the CO_2 avoidance resulting from the installation of one Micro CHP system in comparison to the reference system. The emission avoidance is from 2.3 to 4.5 t CO_2 avoided per year for the multi-family house case and from 0.7 to 1.6 CO_2 avoided per year for the single-family house. All of the systems apart from the PEFC CHP system show growing CO_2 avoidance with time for the assumptions on which the scenarios are based. There is a small decrease of CO_2 avoidance for the PEFC system due to the different development of electrical efficiency and CO_2 emissions for electricity from the grid. In this case the effect of lower CO_2 emissions from the grid for the reference systems exceeds the savings of the fuel cell system.

For the medium and warm climatic zone there are similar tendencies but with lower CO_2 avoidance. The reason for this is the increase in the peak burner operation time because of higher heat demand for the houses. In detail the CO_2 avoidance is 2.6 to 3.9 t_{CO2}/a for the multi-family house and 0.5 to 1.0 t_{CO2}/a for the single-family house respectively for the cold zone 2.0 to 3.5 t_{CO2}/a for the multi-family house and no CO_2 saving (Stirling system) to 0.9 t_{CO2}/a for the single-family house.

The resulting CO_2 avoidance costs are displayed in Figure VII-12. The assumed developments in the scenario result in decreasing CO_2 avoidance costs with time for all technologies except PEFC in the last time period. Negative values means that the total costs of system operation of the Micro CHP system is lower than the operation of a condensing boiler and electricity supply from the grid. The highest avoidance costs are for the PEFC and SOFC CHP systems for single family houses because of their high investment costs.

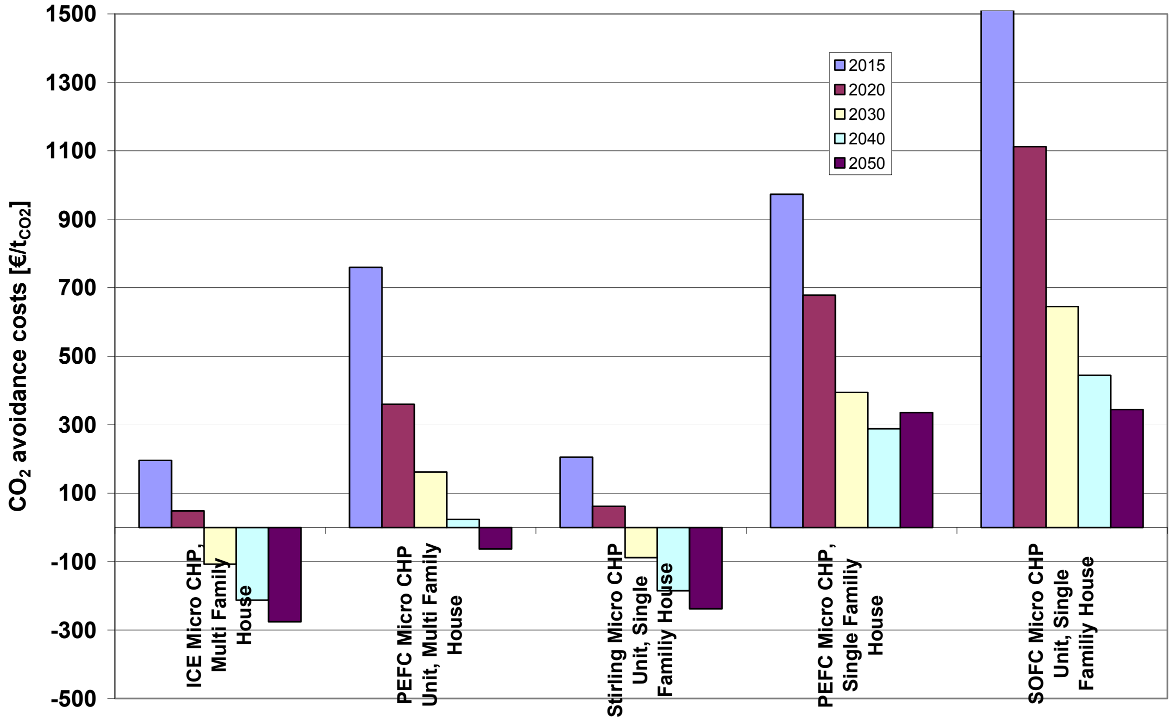


Figure VII-12: CO_2 avoidance costs of the scenario calculation for the warm zone

The gradual reduction in the avoided CO_2 emissions of the PEFC systems for single-family houses because of the factors mentioned earlier means there is a slight increase in cost from 2040 to 2050. For the single family case only the Stirling CHP appliances reach negative avoidance costs. This is due to the over 30% lower investment costs of the system in comparison to the Fuel Cell system. Because of the uncertainties especially in the cost assumptions a sensitivity analysis is performed in chapter VII.5.

VII.5 Sensitivity Analysis and Acceptable Costs[12]

To get information on the robustness of the calculated results all parameters were changed using a “ceteris paribus” analysis. This analysis method changes one parameter while retaining the values of all other parameters the same. The change of parameters effect the cost and emission calculation results in different ways. For the assumed calculation method and relationship of parameters the results are especially sensitive to variation of electricity price from the grid, assumed investment costs for the micro CHP systems and CO_2 emissions coming from the electricity generation of power plants. For all other parameters the calculations show much lower sensitivity.

Figure VII-13 points out the effect of higher electricity prices for households. For the calculations it is assumed that the credit for feeding electricity into the public grid is the same as for consuming electricity from the grid (or 100% use of the produced kWh from Micro CHP). The CO_2 avoidance costs decrease in the range of 15 to 30 % for an increase of the electricity price about 60 %. The assumed reference price for OECD in the year 2015 is 0.11 €/kWh.

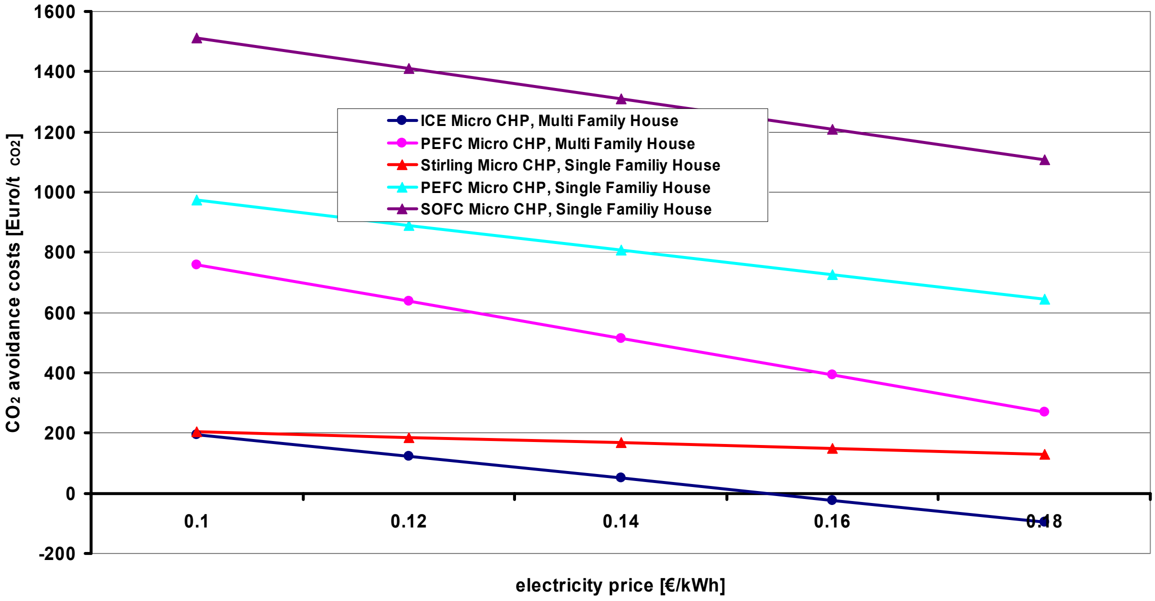


Figure VII-13: Variation of electricity prices in 2015 and resulting CO_2 avoidance costs

The electricity generation for the reference system is estimated by the average power plant mix of the IEA World Energy Outlook [IEA, 2006b] for the OECD. The CO_2 emissions for 2015 are 0.47 gCO_2/kWh. In chapter VII.3 for the in depth analysis the CO_2 avoidance is calculated against electricity from coal fired power plants with an

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[12] Acceptable costs indicate the level at which a new technology reaches a break-even point in comparison to conventional technologies. They can be derived from the marginal costs of the optimal solution

average efficiency of 38 %. This results in CO_2 emission for electricity from the grid of 910 g/kWh$_{el}$. In order to illustrate the effect of different power plant mixes the emission factor was changed from the assumed OECD-2015-mix to that for coal power plants alone. The graphs in Figure VII-15 show the results, there is a strong

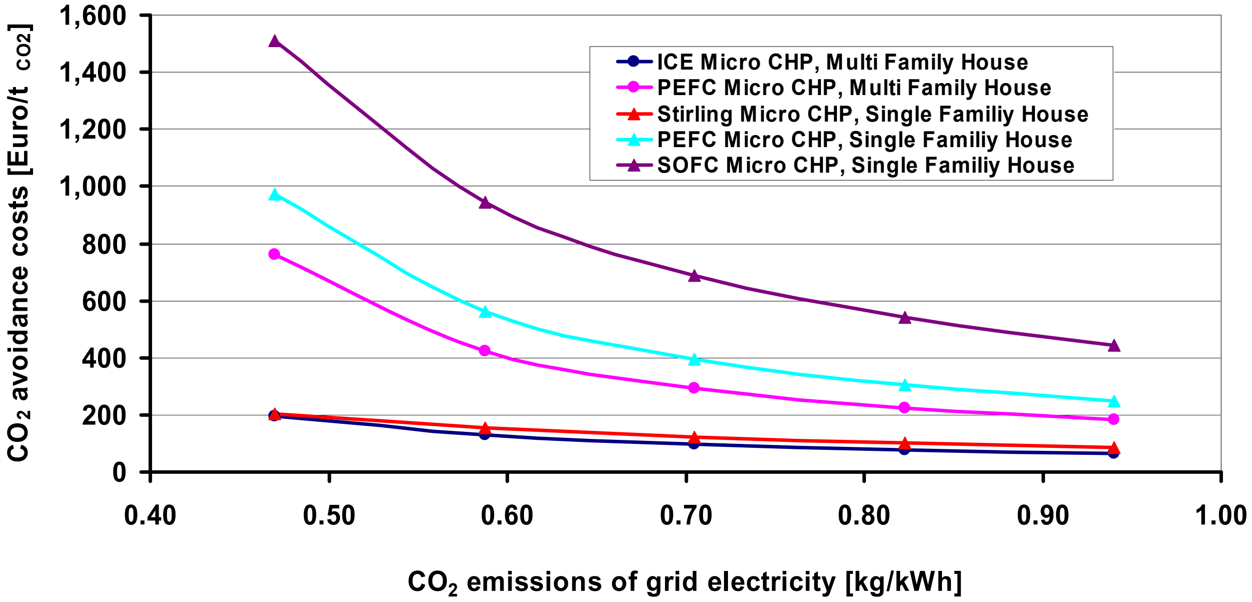

Figure VII-14: Variation of CO_2 avoidance costs with assumed emissions of grid electricity production in 2015

decrease in CO_2 avoidance costs when higher emission factors for the power plant from which electricity is displaced are assumed.

The investment costs for the Micro CHP systems are uncertain because the systems up till now are not widely introduced into the market. Due to this fact there is no reliable market price available except for reciprocating engines. The effect on the CO_2 avoidance costs is displayed in Figure VII-15.

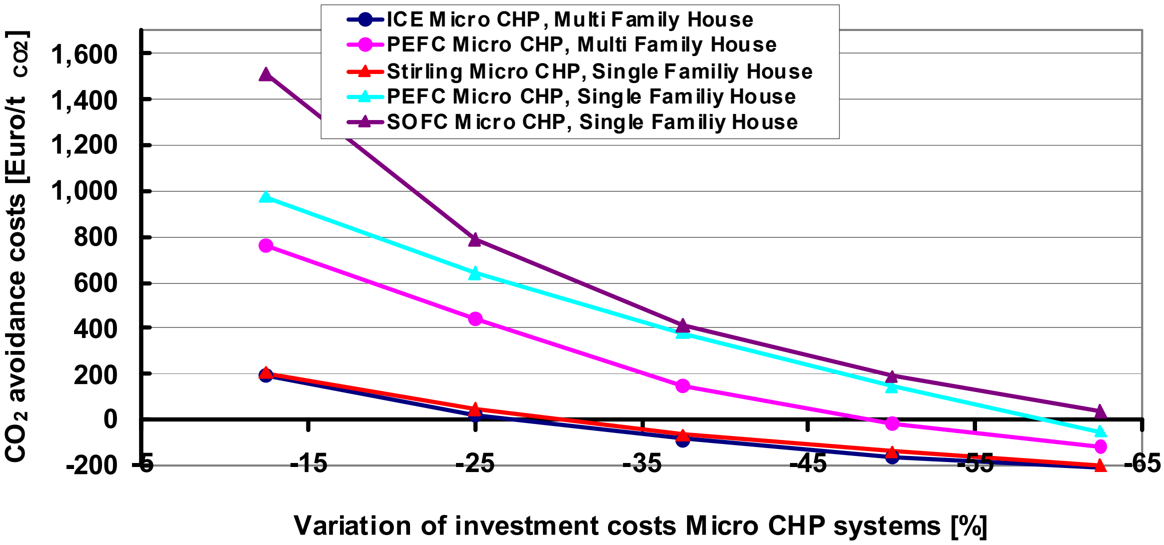

Figure VII-15: Variation of investment costs Micro CHP systems in 2015 and resulting CO_2 avoidance costs

The estimated economic lifetime of ten years results in affordable costs for micro CHP systems depending on the system performance for the multi-family house supply situation from 14,000 and 16,000 € respectively single-family house from 4000 to 6000 € for the investment costs of the total micro CHP system. The affordable costs are the investment costs (assumed reduction to 2015) of the specific systems where the curves have their intersection point with the zero x-axis.

VII.6 CO_2 reduction potentials by the use of fuel cell house heating appliances

With the considerations for the market introduction and uptake of fuel cell heating systems we assumed a successful development of marketable and competitive systems within the next 6 to 7 years, which can be operated reliably at home. In order to find out, whether and by how much it is possible to contribute to the reduction of carbon dioxide emissions in the residential sector, we assume a market launch in 2014. This is based on assessment of Japanese and European prospects which are somewhat different. In Japan the application of small fuel cell systems for the residential sector is widely advanced and ~2,200 units are already in operation. All these units are part of a large-scale demonstration project. For Japan a cumulated installed capacity of 10 GW by ~2020 is expected, while the HFPeurope Implementation Plan sees a cumulated sold capacity of 8 to 16 GW_{el} until 2020. [HFP-Imp, 2007]

Considering these expectations we fit our market penetration calculations to the expected ranges. To calculate the market adoption of the fuel cell house heating systems in OECD countries a typical logistic function was chosen which describes the correlation between the market penetration of a product and the time until saturation. Two scenarios were developed, a low one where the fuel cell systems will reach a market share of 5% and a high one where the share reaches 20% of all house heating systems sales, see left part of Figure VII-16. In both scenarios the introduction starts in 2014 and reaches its saturation in 2030, whereby the sales will not remain at the 2030 values but will increase further on according to the total sales of house heating systems.

In the low scenario the market introduction starts with nearly 6,000 units in 2014. The sales graph exhibits an initial exponential rise and then has a point of inflection at around 2020, the cumulated capacity of operated FC units will be 0.4 GW_{el}. Up to 2020 the yearly sales will raise relatively moderate, so that 20 million FC appliances are in operation in 2050.

The high scenario is characterized by a more dynamic development of the fuel cell system sales. It starts with nearly 70 thousands in 2014, comes up to 0.9 million units in 2020 (cumulated 4 GW_{el}) and reaches 3.2 million sold units in 2050, so that 83 million units are operated with a cumulated capacity of 124 GW_{el}.

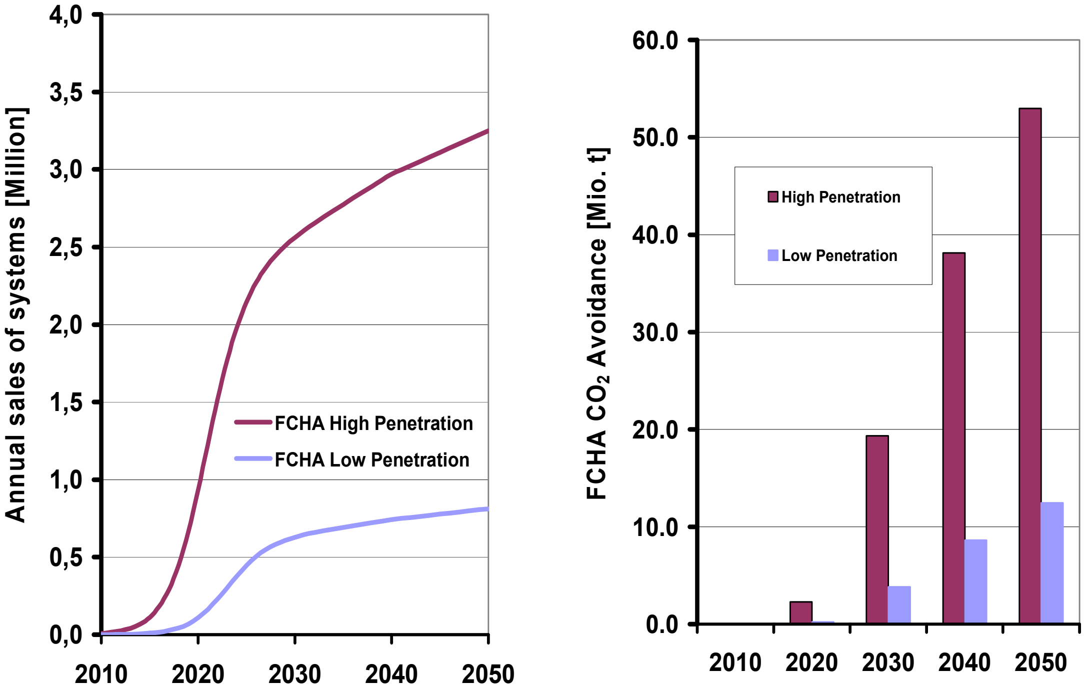

Figure VII-16: Sales of Fuel Cell Heating Appliances (FCHA) and CO_2 avoidance, OECD

The CO_2 reduction potential is calculated in comparison to state of the art natural gas fired boilers and electricity consumption out of the grid. For the development of energy prices, CO_2 emissions of the power plant sector etc. the scenario of the IEA [IEA 2006] are assumed and supplemented (see chapter VII.4).

Under these assumptions the CO_2 reduction from the deployment of Fuel Cell Heating Appliances in the residential sector can reach between 14 to over 50 million tonnes of CO_2, see right-hand chart in Figure VII-16. That corresponds to a reduction of emissions from 1 to nearly 4 % of the emissions in the residential sector of the OECD. For consideration of different climatic zones in the OECD an arithmetic average system for the warm, moderate and cold zone is used. This average system is derived from the single systems in chapter VII.4 by taking a mean of systems for the multi-family and the singe-family case. The CO_2 avoidance of the systems to the reference is calculated for the OECD mix of power plants

VIII Summary

Focus of the study was to analyse the question if the use of small fuel cell systems (micro combined heat and power units) in single or multi family houses can contribute substantially to the reduction of carbon dioxide emissions from the residential sector in OECD countries. At present the residential CO_2 emissions are in the range of 1,500 million tons per year.

The launch respectively the use of fuel cell systems would be a change for the energy supply system, as they belong to the category combined heat and power technologies. The application of cogeneration systems is very rare in the residential sector, though a couple of heating manufacturer is developing such small systems, especially for the application in single family houses.

The carbon dioxide emissions respectively the comparison of the CO_2 emissions of the fuel cell home supply and the reference supply system - heat by a modern condensing boiler and electricity from grid - is of prime importance. For the in-depth Fuel Cell technology case analysis, coal is chosen as source for electricity generation because of its high share at the world power generation (~40% world, ~38% OECD countries) and the substitution of coal power plants by fuel cell units should cause a noticeable emission reduction.

Because the development of small fuel cell systems for the application in single family houses is intensively researched and part of country specific R&D strategies, the analysis focuses at this application segment. On the basis of the expectations of international and national panels to market launch and penetration, two cases are developed.

The first one assumes that the market penetration of fuel cell systems will go ahead slow and that the yearly sales volume will increase from ~6,000 units in 2014 to 812,000 units in 2050, so that a stock of nearly 20 million FC-CHP systems will be in operation in 2050.

The second case, the higher one, is characterised by a massive introduction of fuel cell appliances into the market with nearly 70,000 units in the starting year 2014. The sales achieve an exponential rise and ~2.5 million units per year in 2030, respectively 3.2 million units in 2050, so that approximately 80 million units will be in operation in 2050.

In the technical analysis the fuel cell supply strategy is compared with a conventional supply system. The heat energy demand of two house types with different insulation standards has to be supplied. The house with a low insulation standard has a heat energy demand of 32,947 kWh per year while the other one with an innovative insulation standard has a heat energy demand of 8,809 kWh per year. The operation of the fuel cells follows mainly the heat energy demand whereby its yearly operation time is lengthened by integrated hot water storage. The carbon dioxide emission as well as the energy carrier consumption of the two supply strategies are calculated and compared.

The comparison of the FC-CHP supply strategy and the reference shows an avoided carbon dioxide emission per 100,000 GWh fuel cell electricity of ~4% whereby the electricity from the fuel cells substitute electricity from coal power plant. The avoidance of primary energy consumption is a second effect which results in a energy reduction of ~8% per 100,000 GWh FC power.

Further the in-depth technology case analysis shows that an optimised system design (heat demand adapted power output, heat storage etc.) can lead to high Fuel Cell operating hours and less peak burner utilisation. The data for the Fuel Cell systems leads to no clear preference for a certain system.

In a second analysis block, "Cross Sectional Analysis", different micro FC-CHP systems are compared with “conventional” micro CHP technologies supplying the demand of a 4 dwellings multi family house and a single family house.

The CO_2 avoidance in comparison to the assumed reference system (modern natural gas condensing boiler and electricity supply from the grid) and the resulting avoidance costs are sensitive to the investment for CHP systems, to grid electricity CO_2 emissions and electricity costs.

For the assumed scenarios for micro CHP systems acceptable costs in the range of 14,000 to 16,000 € per device for multi-family houses and of 4,000 to 6,000 € per device in the case of single family houses are calculated. The CO_2 avoidance of CHP systems strongly depends on climatic conditions and the insulation standard of the buildings, too. As a result CO_2 avoidance costs in the scenarios have a very broad range depending on system performance, assumed technology development and climatic conditions.

Pending on the market shares of the Cross Sectional Analysis a reduction potential for CO_2 in the residential sector is calculated to about 1 % (low scenario) resp. 4 % (high scenario) for the total residential sector in OECD countries. If the electricity generated by small CHP units substitute coal fired power plants the avoidance effects are higher.

IX Recommendations

The analysis shows that the CHP technologies have a problem being installed in low energy houses, as the heat consumption is relatively low, so that it is not easy to use the produced heat. The low heat demand limits the yearly operation hours of the fuel cell, so that this system cannot lead its trump, the high electrical efficiency.

The actual development, rising gas prices, and the public funding of new heating solutions (e.g. combination of condensing gas boiler with solar thermal collectors respectively other renewable based systems like wood pellet stoves and others) will complicate the introduction of systems like fuel cells, which will not be available before the next decade.

It seems to be necessary, that the governments spend financial subsidies, as far as fuel cell systems will be available for market introduction.

Furthermore it must be analysed, if it will be possible to feed surplus heat into a local heat grid so that the yearly operation hours can be increased with the consequence, that the advantage of the fuel cell technology becomes more effective.

The analysis concentrated on the application of fuel cell devices in single family houses and multi family houses with few dwellings. It should be asked, if larger building can be more suitable for fuel cells devices, devices which will have larger capacities. It can be expected that especially the higher heat demand in larger buildings should have a positive influence on the operation time. In addition large buildings have less space restrictions, so that larger water buffers can be integrated to extend the operation hours of the fuel cell system. An additional advantage can be seen by the fact, that a larger system is a reliable supplier for a local heat grid.

It should be mentioned, that the advantage of fuel cells, with regard to low emissions, is reduced, as far as carbon poor energy carrier are used for power generation and that is valid for clean coal power (CCS) too.

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XI Annex

Companies:

Acumentrics	USA	http://www.acumentrics.com
Alternative Fuel Systems. Ltd.	UK	http://www.afs.uk.com
Aperion Energy Systems	USA	http://www.aperionenergy.com
Astris Energi. Inc.	Canada	http://www.astris.ca
Axane	France	http://www.axane.fr
Ballard Power Systems	Canada	http://www.ballard.com
Baxi INNOTECH(former: efc)	Germany	http://www.baxi-innotech.de
Ceramic Fuel Cells Limited	Australia. UK	http://www.cfcl.com.au
Ceres Power Ltd.	UK	http://www.cerespower.com
CS Fuel Cell	Korea	*not available*
Ebara Ballard	Japan	http://www.ebara.co.jp
Elcogen AS	Estland	http://www.elcogen.ee
Electro Power Systems	Italy	*not available*
Eneco	UK	http://www.eneco.co.uk
Fuel Cell Power	Korea	*not available*
Fuel Cell Technologies Ltd.	Canada	http://www.fuelcelltechnologies.ca
Fuji Electric Co. Ltd	Japan	http://www.fujielectric.co.jp
GreenVOLT Corp.	Canada	*not available*
Helion Fuel Cells	France	http://www.helion-fuelcells.com
Hexis	Switzerland	http://www.hexis.ch
Hydra Fuel Cell	USA	*not available*
Hydrogenics Corp.	Canada	http://www.hydrogenics.com
IdaTech	USA	http://www.idatech.com
Independent Power Technologies	Russia	http://www.independentpower.biz
Inhouse	Germany	http://www.schalt-und-regeltechnik.de/
Intelligent Energy	UK	http://www.intelligent-energy.com
Intensys	Belgium	http://www.intensys.com/
Ishikawajima-Harima Heavy Ind.	Japan	http://www.ihi.co.jp
Japan Energy Corp.	Japan	http://www.j-energy.co.jp
Kyocera	Japan	http://www.kyocera.co.jp
Lynntech. Inc.	USA	http://www.lynntech.com
Matsushita Electric Industrial	Japan	http://www.panasonic.co.jp/
MER Corporation	USA	http://www.mercorp.com
Mitsubishi Electric	Japan	http://global.mitsubishielectric.com
Nuvera	Italy	http://www.nuvera.com
Phocos	Germany	http://www.phocos.com
Plug Power. Inc.	USA	http://www.plugpower.com
ReliOn (formerly Avista Labs)	USA	http://www.relion-inc.com/
Sanyo Electric Co.	Japan	http://www.sanyo.co.jp
Schatz Energy Research Center	Switzerland	http://www.humboldt.edu/~serc/index.shtml
Teledyne Energy Systems Inc.	USA	http://www.teledynees.com
Toshiba	Japan	http://www.toshiba.co.uk
Toyota	Japan	http://www.toyota.com
Vaillant	Germany	http://www.vaillant.de
Viessmann Werke GmbH	Germany	http://www.viessmann.com
ZTEK Corp.	USA	http://www.ztekcorp.com

Heating Degree Days and Heat Demand

Month	HDD [Kd]	d_m [d]	ΔT_m [K]	$\overline{\dot{Q}_B}$ [kW]	$\dot{Q}_T$ [kW]
Jan	391	31	12.6	4.2	3.1
Feb	304	29	10.5	3.5	2.6
Mar	240	31	7.7	2.6	1.9
Apr	117	20	5.9	2.0	1.5
May	24	20	1.2	0.4	0.3
Jun	0	0	0.0	0.0	0.0
Jul	0	0	0.0	0.0	0.0
Aug	0	0	0.0	0.0	0.0
Sep	23	23	1.0	0.3	0.2
Oct	24	15	1.6	0.5	0.4
Nov	169	25	6.8	2.3	1.7
Dec	276	31	8.9	3.0	2.2
Year	1567	228	6.9	2.3	2.3

Table XI-1: Specific Values for the Warm Zone (e.g. Greece)

Month	HDD [Kd]	d_m [d]	ΔT_m [K]	$\overline{\dot{Q}_B}$ [kW]	$\dot{Q}_T$ [kW]
Jan	561	31	18.1	4.6	3.8
Feb	453	29	15.6	3.9	3.3
Mar	415	31	13.4	3.4	2.8
Apr	245	26	9.4	2.4	2.0
May	184	25	7.3	1.9	1.5
Jun	60	11	5.5	1.4	1.1
Jul	29	6	4.8	1.2	1.0
Aug	12	3	3.8	1.0	0.8
Sep	89	18	4.9	1.2	1.0
Oct	219	29	7.5	1.9	1.6
Nov	401	30	13.4	3.4	2.8
Dec	519	31	16.7	4.2	3.5
Year	3186	270	11.8	3.0	2.5

Table XI-2: Specific Values for the Moderate Zone (e.g. Germany)

Month	HDD [Kd]	d_m [d]	ΔT_m [K]	$\overline{\dot{Q}_B}$ [kW]	$\dot{Q}_T$ [kW]
Jan	869	31	28.0	3.4	2.8
Feb	788	29	27.2	3.3	2.7
Mar	676	31	21.8	2.7	2.2
Apr	484	30	16.1	2.0	1.6
May	323	31	10.4	0.3	1.0
Jun	190	25	7.6	0.9	0.8
Jul	21	6	3.5	0.4	0.4
Aug	122	20	6.1	07	0.6
Sep	237	30	7.9	1.0	0.8
Oct	470	31	152	1.9	1.5
Nov	661	30	220	2.7	2.2
Dec	695	31	224	2.7	2.2
Year	5536	325	170	2.1	2.1

Table XI-3: Specific Values for the Cold Zone (e.g. Finland)

HDD : Heating Degree Days

d_m : Number of Heating Days (when $T_o < 15°C$) for the Corresponding Month

ΔT_m : Monthly Average Temperature Difference

$\overline{\dot{Q}}$: Heat Demand

Source: [Eurostat, 2005]. own calculations

Final Energy Consumption of Households for Space Heat

	FEC total [TWh]	Share SH [%]	FEC SH [TWh]
Finland	56.52	58	32.72
Germany	820.01	77	632.77
Greece	62.83	71	44.67

Source: [Enerdata, 2003]

Table XI-4: Calculations of the Final Energy Consumption of Households (FEC) for Space Heat (SH)

Ratio between Single and Multi Family Houses k_{HH}

	Households per Dwelling		Source or Calculation
	1-2	3 and more	
HPD [%]	45.2	54.8	[Bundesregierung, 2005]
AH	1.2	3.2	conservatively estimated
SRF [%]	28	11	SRF = X_{RF} / AH
RSS [%]	43	42	RSS = SRF + X_{FW}
k_{HH}	0.85		$k_{HH} = RSS_{1-2} + RSS_{3\text{ and more}}$

Table XI-5: Ratio between Single and Multi Family Houses for the Moderate Zone (Germany)

HPD : Households per Dwelling

AH : Average Number of Households per Dwelling

SRF : Share of Roof and Floor per Household

RSS : Relative Share of Space Heat

X_{RF} : Share of Roof and Floor in the Constant of Proportionality Φ_B

X_{FW} : Share of Facade and Window

k_{HH} : Ratio between Single and Multi Family Houses

X_{RF} = 35% can be calculated with Table VI-2 and Table VI-3.

=> X_{FW} = 100%- X_{RF} = 65%

	Cost effectiveness - simple payback
biomass systems	N/A - capital expenditure higher
solar photovoltaic systems	generated energy does not repay the installation cost
solar hot water systems	8 to 20 years generally quoted
ground source heat pumps	8 - 15 years
ais source heat pumps	8 - 15 years
absorption heat pumps	8 - 15 years
micro heat and power systems	estimated at around 3 - 5 years
fuel cells	prices of commercial models still to be confirmed

source: A review of microgeneration and renewable energy technologies, NHBC Foundation, brepress, January 2008, ISBN 978-1-84

Table X-6: Payback for microgeneration and renewables in domestic application

Systemforschung und Technologische Entwicklung im Forschungszentrum Jülich

Viele der im Brennpunkt des gesellschaftlichen Interesses stehenden Fragen lassen sich nur durch eine fachübergreifende Systemanalyse beantworten. Dabei sind häufig naturwissenschaftlich-technische, ökonomische und ökologische Subsysteme, die miteinander in Wechselwirkung stehen, gleichzeitig zu untersuchen. Die Programmgruppe Systemforschung und Technologische Entwicklung (STE) greift diesen Ansatz auf und konzentriert sich mit ihren Arbeiten auf Fragen zur langfristigen Ausrichtung der Energiewirtschaft, auf ausgewählte ökonomisch bzw. ökologisch relevante Stoffströme in Techno- und Geosphäre sowie auf elektronische Informationsverarbeitung und Kommunikation und dadurch verursachte Veränderungen in der Gesellschaft. Auf diesen Gebieten analysiert die STE die Folgen technischer Entwicklungen und erstellt wissenschaftliche Entscheidungshilfen für Politik und Wirtschaft. Grundlagen dafür sind die methodische Weiterentwicklung von Werkzeugen der Systemanalyse und ihre Anwendung sowie die Zusammenarbeit von Wissenschaftlern unterschiedlicher Fachrichtungen.

Systems Analysis and Technology Evaluation at the Research Centre Jülich

Many of the issues at the centre of public attention can only be dealt with by an interdisciplinary systems analysis. Scientific, economic and ecological subsystems which interact with each other often have to be investigated simultaneously. The Program Group Systems Analysis and Technology Evaluation (STE) takes up this approach and concentrates its work on issues concerning the long-term orientation of the energy economy, on selected economically or ecologically relevant material flows in the technosphere and geosphere as well as on electronic information processing and communications and the changes in society brought about by these technologies. In these fields, STE analyses the consequences of technical developments and provides scientific aids to decision making for politics and industry. This work is based on the further methodological development of systems analysis tools and their application as well as cooperation between scientists from different disciplines.

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STE Research Report

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Institute of Energy Research (IEF)
Systems Analysis and Technology Evaluation (STE)

CALCULATION SPREADSHEETS

Spreadsheets were developed as part of the study in order to calculate the market penetration and CO2 emissions reduction and to be able to alter key parameters. These are very detailed sheets which are not accompanied by any user manual. They included in the CD for future reference and use by those who might want to delve more deeply into the analysis presented in the report. All the files are contained in a zipped folder on the CD.

The folders
-High_Penetration_Scenario,
-Low_Penetration_Scenario and
-High_Penetration_Scenario_High_Insulation_Standard

contain two Excel-files each.

The Excel-File CO2_avoidance_costs_xxxx contains the technology, price etc. development up till 2050 for the systems

The file market_penetration_xxxx a possible launch of a FCHA market.
It includes three diagramms with development of sold systems, electricity generation capacity and avoided CO2 emissions and reduction potentials.

The Excel-File Single_Technology_Penetration_Scenario represents the analysis of a scenario where the technical parameters can be changed in order to see how the CO2 reduction potential is affected.