Performance of Residential Cogeneration Systems in Germany

A Report of Subtask C of
FC+COGEN-SIM
The Simulation of Building-Integrated
Fuel Cell and Other Cogeneration Systems

Annex 42 of the
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Participating countries in ECBCS:

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Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development to implement an international energy program. A basic aim of the IEA is to foster co-operation among the 24 IEA participating countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration.

Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of areas related to energy. The mission of one of those areas, the Energy Conservation for Building and Community Systems Programme (ECBCS), is to facilitate and accelerate the introduction of energy conservation and environmentally sustainable technologies into healthy buildings and community systems, through innovation and research in decision-making, building assemblies and systems, and commercialization. The objectives of collaborative work within the ECBCS research and development program are directly derived from the ongoing energy and environmental challenges facing IEA countries in the areas of construction, the energy market and research. The ECBCS addresses major challenges and takes advantage of opportunities in the following areas:

- exploitation of innovation and information technology;
- impact of energy measures on indoor health and usability; and
- integration of building energy measures and tools to changes in lifestyle, work environment alternatives and business environment.

The Executive Committee

Overall control of the program is maintained by an Executive Committee, which not only monitors existing projects but also identifies new areas where collaborative effort may be beneficial. To date, the following projects have been initiated by the Executive Committee on Energy Conservation in Buildings and Community Systems. Completed projects are identified by an asterisk (*).

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants' Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)

Annex 16: BEMS 1 – User Interfaces and System Integration (*)
Annex 17: BEMS 2 – Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multizone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HEVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM)
Annex 43: Testing and Validation of Building Energy Simulation Tools
Annex 44: Integrating Environmentally Responsive Elements in Buildings
Annex 45: Energy Efficient Electric Lighting for Buildings
Annex 46: Holistic Assessment Toolkit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings
Annex 48: Heat Pumping and Reversible Air Conditioning
Annex 49: Low Exergy Systems for High Performance Buildings and Communities
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings

Working Group – Energy Efficiency in Educational Buildings (*)
Working Group – Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group – Annex 36 Extension: The Energy Concept Adviser (*)

Annex 42

The objectives of Annex 42 were to develop simulation models that advance the design, operation and analysis of residential cogeneration systems, and to apply these models to assess the technical, environmental and economic performance of the technologies. This was accomplished by developing and incorporating models of cogeneration devices and associated plant components within existing whole-building simulation programs. Emphasis was placed on fuel cell cogeneration systems, and the Annex considered technologies suitable for use in new and existing single and low-rise, multi-family residential buildings. The models were developed at a time resolution that is appropriate for whole-building simulation.

To accomplish these objectives, Annex 42 conducted research and development within the framework of the following three Subtasks:

- Subtask A: Cogeneration system characterization and characterization of occupant-driven electrical and domestic hot water usage patterns.
- Subtask B: Development, implementation and validation of cogeneration system models.
- Subtask C: Technical, environmental, and economic assessment of selected cogeneration applications, recommendations for cogeneration application.

Annex 42 is an international joint effort conducted by 26 organizations in 10 countries:

Belgium	▪ University of Liège/Department of Electrical Engineering and Computer Science ▪ COGEN Europe ▪ Catholic University of Leuven
Canada	▪ Natural Resources Canada/CANMET Energy Technology Centre ▪ University of Victoria/Department of Mechanical Engineering ▪ National Research Council/Institute for Research in Construction ▪ Hydro-Québec/Energy Technology Laboratory (LTE)
Finland	▪ Technical Research Centre of Finland (VTT)/Building and Transport
Germany	▪ Research Institute for Energy Economy (FfE)
Italy	▪ National Agency for New Technology, Energy and the Environment (ENEA) ▪ University of Sannio ▪ Second University of Napoli
Netherlands	▪ Energy Research Centre Netherlands (ECN)/Renewable Energy in the Built Environment
Norway	▪ Norwegian Building Research Institute (NBRI) ▪ Telemark University College
United Kingdom	▪ University of Strathclyde/Energy Systems Research Unit (ESRU) ▪ Cardiff University/Welsh School of Architecture
United States of America	▪ Penn State University/Energy Institute ▪ Texas A&M University/Department of Architecture ▪ National Institute of Standards and Technology ▪ National Renewable Energy Laboratory ▪ National Fuel Cell Research Center of the University of California-Irvine
Switzerland	▪ Swiss Federal Laboratories for Materials Testing and Research (EMPA)/ Building Technologies Laboratory ▪ Swiss Federal Institute of Technology (EPFL)/Laboratory for Industrial Energy Systems ▪ Hexis AG (Hexis) ▪ Siemens Switzerland AG (Siemens)

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Jack Brouwer, National Fuel Cell Research Center, USA
Adam Hawkes, Imperial College London, UK
Morad Atif, Chairman ECBCS ExCo, Canada

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1 SUMMARY

Cogeneration devices, systems and buildings analysed

The aim of the research project ‘innovative CHP systems for energy supply in houses’ was to analyse whether CHP-systems are a reasonable (in terms of energy and emissions) and economically viable option for the energy supply of residential buildings in Germany. Therefore several MCHP systems were analysed, comprising two systems with ICE, one with stirling engine and one with a PEMFC.

First, experimental measurements were conducted on a test rig in the laboratory of the Institute for Energy Economy and Application Technology (IfE) of TU Munich. From these tests, considering typical daily profiles and characteristics of the heating period, daily energy balances of the CHP systems were determined. A projection to annual values was done and the energetic quality was expressed by characteristic parameters. The essential results of the tested CHP systems and their comparisons can be found in (Muehlbacher, Geiger 2007). The results formed the data basis for the comparison of systems and profitability analysis (Arndt and Mauch 2007).

Two building loads were considered: A 10-appartment multi-family house (MFH10) for the ICE and the PEMFC units, and a 20-appartment building (MFH20) for the Sterling unit.

In the first part of the system comparison, the primary energy demand and emissions of the CHP systems were compared to those derived from a number of combinations of heat and grid electricity supply: Heat supply according to (i) the current German building stock and (ii) best available technology (condensing gas boiler); grid electricity according to (i) fuel mix hat would have been used in place of the CHP system, (ii) average German mix and (iii) best available technology (combined cycle power facility). In the second part of the system comparison,, the primary energy and emissions were derived for CHP systems with assumed equal power rating, thus eliminating the influence of different power capacities of the CHP systems. Additionally, a profitability analysis was carried out.

Major results and conclusions

Figure 1-1 shows the specific primary energy consumption of the CHP systems analysed (assuming the German electricity mix) compared to the reference system ‘stock’ (average building stock heating system, German electricity grid). **Figure 1-2** shows the corresponding CO_2 emissions for these cases. Reductions in primary energy consumption from 19.1% to 27.9 % and reductions in CO_2-emissions from 21.8 to 31.3 % were obtained by use of the CHP systems. Even compared to the reference system with ‘best available technology’, the primary energy consumption was reduced by 5.2 to 12.7 % and the CO_2-emissions were reduced by 5.9 to 13.5 %.

The system comparison confirms that use of CHP can reduce primary energy and CO2-emissions in comparison to separate generation of electricity and heat. The profitability analyses, based on current economic conditions in Germany indicate that the generated electricity from the CHP system should be used as far as possible within the building itself..

With the detailed measurements and analyses conducted, the dynamical processes and interaction of individual elements of the CHP systems as well as the reaction of the CHP-systems to heating, hot-water and electrical load profiles were analysed.

Comparative tests of additional CHP systems could strengthen the findings and results of this study, since more advanced small CHP systems have since entered the market. Further research and optimisation work should also focus on CHP electrical efficiency performance improvements and control strategies for CHP systems.

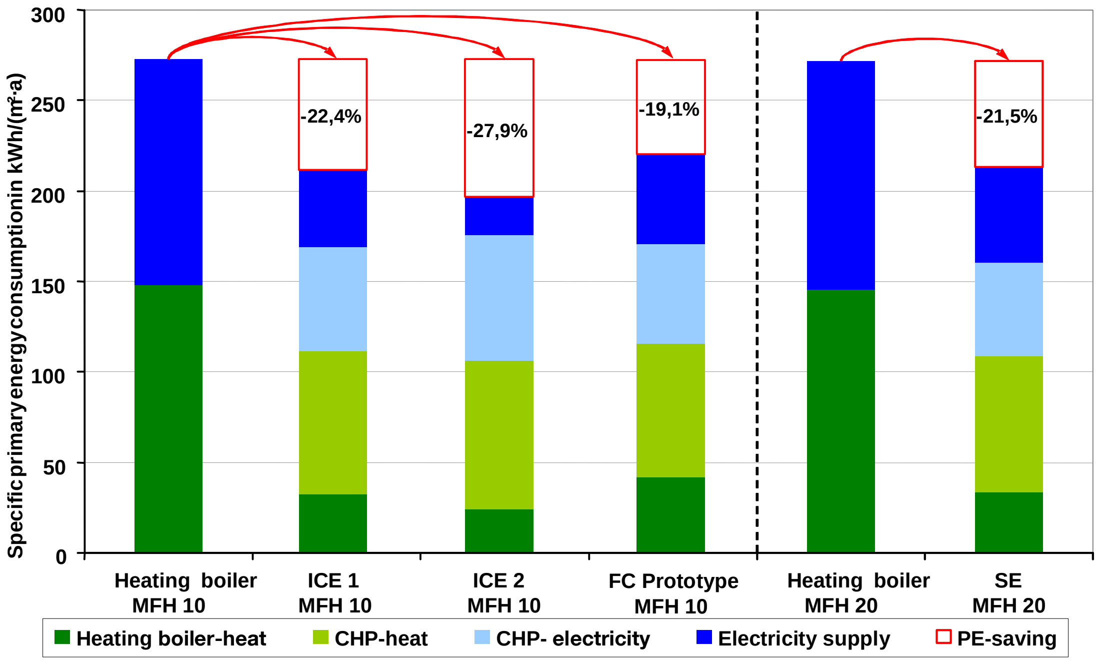

Figure 1-1 **Specific primary energy consumption of the energy supply of the reference system and the CHP systems (combination 'Average building stock heating system, German electricity grid')**

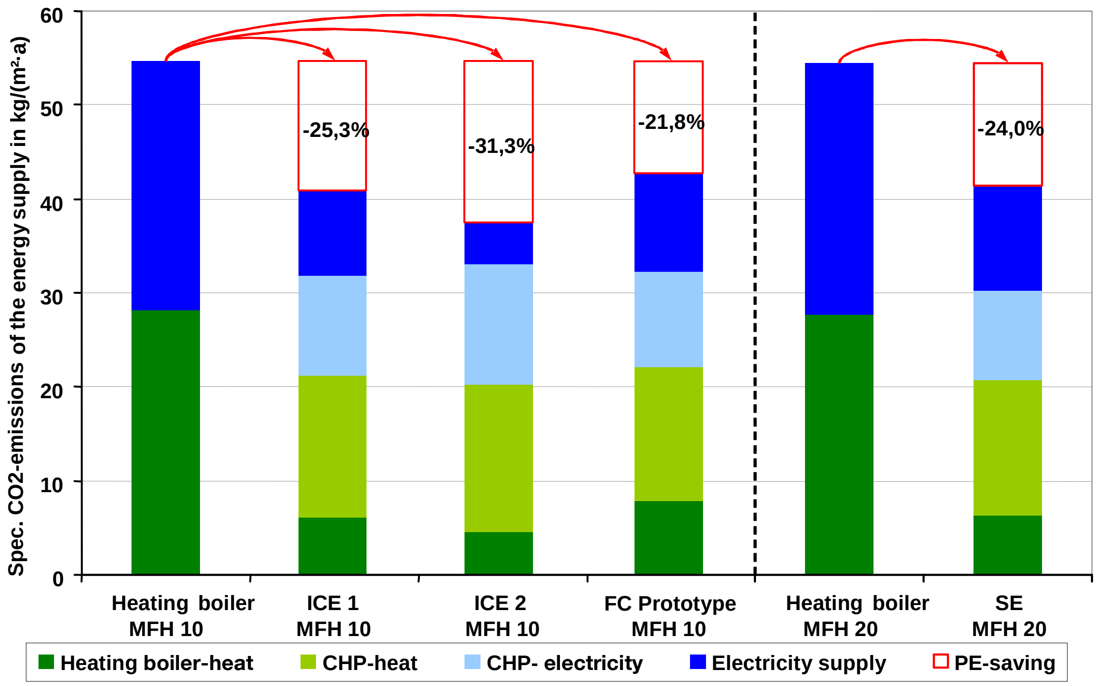

Figure 1-2 **Specific CO2 emissions of the energy supply of the reference system and the CHP systems (combination 'Average building stock heating system, German electricity grid')**

2 INTRODUCTION

2.1 Motivation

In Germany residential buildings are commonly provided with separate electricity and heat supply. Usually the electricity is provided by an energy supply company and the energy required for space heating and domestic hot water supply is produced by conventional low temperature boilers or condensing boilers.

Currently CHP systems with high power ratings (MW up to 100s of MW) are mainly employed for industry and district power and heating supply. Smaller systems (kW range), mostly with internal combustion-engines are applied in public and administration buildings, hotels and multi-family houses.

Due to the emergence and commercialization of new technologies and the development of systems with smaller power rating, more CHP systems have become technically and economically feasible in smaller residential buildings. Yet the energetic assessment and comparison of various CHP systems is difficult because of the wide range of power ratings, disparate usage conditions and temporal thermal and electrical demand profiles as well as different technology commercial readiness. At the moment, it is possible to assess CHP systems through operating experience of similar devices in use and by using technical data from manufacturers. However, this information is insufficient to make statements about practical suitability, profitability and energetic efficiency. The CHP system cannot be assessed without overall examination of its energy efficiency as applied to the thermal and electrical demand profiles of a practical application.

This is the primary reason the research project ‚Innovative CHP-systems for household energy supply' was initiated with the sponsorship of the energy research trust Baden-Wuerttemberg and the State Ministry of Economic Affairs and Employment. Project partners were the energy supply companies Bayerngas (Munich), E.ON Energie (Munich), E.ON Ruhrgas (Essen) and RWE Fuel Cells (Essen) and the system manufacturers PowerPlus Technologies (Remscheid), SenerTec (Schweinfurt), SOLO Stirling (Sindelfingen) and Vaillant (Remscheid). The work was carried out at the Research Institute for Energy Economy in collaboration with the Institute for Energy Economy and Application Technology of Technical University Munich.

2.2 Purpose and objectives

The goal of this research project was to implement comparative tests of CHP systems under conditions as they occure in the residential sector. For this sector, CHP systems with combustion engines, Stirling engines, fuel cells or micro gas turbines are feasible for the cogeneration of heat and power in multi-family residences. Through detailed measurements and analyses, a data base was created that allowed a detailed comparisons between the various CHP systems and the current electrical grid, heating and domestic hot water (DHW) technologies as well as best available technology. Comparisons of both primary energy and carbon dioxide (CO_2) emissions were to be made.

Furthermore, the potential for an optimisation of CHP systems to improve performance and profitability was to be identified through variation of relevant operating and system parameters.

2.3 Scope

The performance assessment task concentrated on a decentralized, building-integrated energy supply in the residential sector. The focus was on the performance of the cogeneration system in its interaction with the building (or a cluster of buildings connected via a local network) and occupant loads in terms of control and energy management.

This study did not cover topics of quality of electric power supplied to the grid, power quality management, the control and power management aspects of a cluster of cogeneration devices (virtual power facility); neither did the current study attempt to optimize individual components or the respective control system within a particular cogeneration device.

2.4 Performance Assessment Methodology

This report is part of Subtask C of Annex 42. It is one of five studies performed in subtask C on the performance of residential cogeneration systems applied in houses and/or apartment buildings in different countries in the world (Canada, Germany, Italy (2), and Switzerland). All five studies are based upon a common Performance Assessment Methodology (PAM). In order to be able to read this report without prior knowledge of the Annex 42 PAM, the relevant elements are repeated within this report.

2.5 Target Audiences

This report aims at the following readership:

- engineers and researcher involved in energy system analysis and HVAC design
- users of the building simulation programmes that have been improved and amended in Annex 42
- manufacturers of cogeneration devices who want to analyse potential applications and performance of their products
- energy supply and contractor companies who want to gauge the potential for residential cogeneration with a view to assessing its impact on the electricity supply network

3 TERMINOLOGY

Symbol	Description	Unit
η_{el}	System electrical efficiency	%
η_{th}	System thermal efficiency	%
η_{total}	System total efficiency	%
σ	CHP coefficient	-
CHP	Combined heat and power	
$d_{el,CHP,demand}$	Electrical CHP-fraction	-
$d_{el,CHP,production}$	Share of generated useful electricity	-
$d_{th,CHP}$	CHP thermal fraction	-
$d_{th,PB}$	Peak boiler thermal fraction	-
DHW	Domestic hot water	
FE	Final Energy	kWh
g_{el}	Electrical utilisation ratio	-
g_{th}	Thermal utilisation ratio	-
g_{fuel}	Total utilisation ratio	-
$k_{electricity,conventional}$	Cost of electricity from public grid	€, €/kWh
$k_{heat,conventional}$	Costs of heat from a conventional heating system	€, €/kWh
PE	Primary energy	kWh
$P_{el,net}$	Electrical net power	kW_{el}
$P_{reverse\ feed\text{-}in}$	Electrical reverse feed-in into the grid	kW_{el}
P_{rated}	Rated power	kW_{el}, kW_{th}
$Q_{BS,loss}$	Heat losses buffer storage	kWh_{th}
Q_{fuel}	Fuel heat consumption	$kWh_{lower\ heating\ value}$
$\dot{Q}_{fuel}$	Fuel power	$kW_{lower\ heating\ value}$
Q_{SH}	Room heat consumption of the supply object	kWh_{th}
$Q_{DHWS\text{-}loading}$	Energy amount for hot water storage loading	kWh_{th}
Q_{th}	Thermal usable heat energy	kWh_{th}
$\dot{Q}_{th}$	Thermal usable heat power	kW_{th}
T_V	Utilisation time	h
$W_{el,net}$	Net electricity generation	kWh_{el}
W_{useful}	Net useful energy generation	kWh_{el}
$W_{el,Building}$	Electricity consumption of the supply object	kWh_{el}
W_{feed}	Energy feed-in	kWh_{el}
$W_{delivery}$	Delivered energy	kWh_{el}
$W_{el,CHP,useful}$	CHP useful electricity generation in kWh	kWh_{el}

4 DEFINITIONS

In this section, terms and key parameters for CHP and CHP systems and their performance are redefined. Furthermore the mathematical and physical context and formulae that describe governing processes are listed, which are used for calculations and data evaluation.

Decentralised generation

Decentralised energy supply is energy provision by systems close to the consumer. In decentralised systems, energy is not supplied by central large-scale power plants but by several smaller energy conversion facilities. Hence, a multitude of small power facilities would be placed in the vicinity of multiple consumers. The result is a changing energy systems infrastructure that could change the requirements of grid operation, energy management and protection technologies. Note that central and decentralised energy supply do not rule out each other but rather can exist in parallel and complement each other.

An essential difference with regard to the classification of decentralised energy generation systems is the prognosis and planning of the generated power respectively. Especially renewable energy technologies are difficult to plan with regard to generated power. A better prognosis (weather, wind, and radiation forecasts) increases the reliability of the power generation of these systems.

Combined heat and power CHP

Combined heat and power is the simultaneous conversion of input energy in one energy system into multiple target energies, i.e. mechanical, electrical energy, heating and/or cooling energy. These target energies are supplied to the final consumer /Scha 01/.

CHP is applied in the industry where much power is required (MW to 100s of MW), especially in sectors where heat is essential to industrial processes or for the provision of district heating. In these sectors, big back-pressure and extraction condensation turbines have been a fixed part of the energy supply for decades. In the trade, commerce and services sector and in residential buildings, CHP systems are applied mainly in the form of combustion-engineered CHP's with power ratings from kW to MW. CHP systems are only feasible if the end-use of both products is near the point of conversion. Thus, residential CHP systems may have primary energy and emissions advantages compared to separate provision of electricity from the grid and heating through local combustion of delivered fuel.

Micro-CHP

The term micro-CHP is not clearly defined. Publications show different statements about size and power of micro-CHP systems respectively. A differentiation regarding the electrical rated power seems reasonable, whereas the upper limit for classification as "micro" needs to be discussed.

The "Arbeitsgemeinschaft für sparsamen und umweltfreundlichen Energieverbrauch e.V. (ASUE)" states that a generally accepted definition of the power rating of micro-CHP does not exist at the moment. The micro-CHP brochure of the ASUE demonstrates new developments of motor-driven systems and fuel cells with the power <10 kW_{el} and gas turbine systems with the power <100 kW_{el} /ASUE 01/. The Federal Association of cogeneration states an upper limit for micro-CHP systems at an electrical power of 15 kW /BKWK 05/. In /Pehnt 04/, the author defines micro-CHP as the coupled electricity and heat generation in a single supply object on the basis of small energy conversion units with an electrical power below 15 kW. Another definition can be found in the CHP-directive

2004/8/EG, article 3 of the European Parliament and the European Council. There, micro-cogeneration unit is defined as a CHP system with a maximum capacity of less than 50 kW_{el} /RL 04/8/EG, BRL 04/8/EG/. To summarise, the re is not an accepted definition of micro-CHP and determination of the power upper limit for micro-CHP systems as a function of various system technologies is not desired or useful. /Pehnt 04/ presents an interesting way to categorize CHP by the object of supply (e.g., residence), but tempers the results slightly because the individual supply objects are also not well defined. Therefore, the current study uses the classification of micro-CHP systems exclusively based on their electrical power output with the reasonable selection of 15 kW_{el} as the maximum output rating:

Systems for electricity generation and/or cogeneration where the generated heat is also supplied, that have rated electrical power output of not more than 15 kW are called micro-CHP systems herein..

Electric load-following operation
The CHP system acts to meet the dynamics of electricity demand of the supplied object. If the electricity consumption is more than the electrical rated power and below the minimum power, the electricity is supplied from the grid. Electricity feed-in to the utility grid does not take place. This operation is reasonable from an energy economical point of view as long as the generated heat can be used in the object directly or buffered in a heat storage.

Heat load-following operation
The CHP-system is designed to meet the dynamics of heat demand of the supplied object. If the heat demand exceeds the thermal rated power, the heat is supplied by an auxiliary burner. If necessary, the electricity is provided by the grid and fed into the grid respectively.

Utilisation time
The utilisation time results from the ratio of useful energy output and rated power of the systems related to a given time period, normally one year.

$$T_V = \frac{W_{useful}}{P_{rated}} \qquad \text{Equation 4-1}$$

W_{useful} Net useful energy output in kWh
P_{rated} Rated power in kW

Electrical, thermal and total system efficiency
The electrical system efficiency η_{el} and thermal system efficiency η_{th} of the CHP system and the peak boiler is defined by the ratio of net electrical power or thermal power related to the respective input fuel power (lower heating value HU).

$$\eta_{el} = \frac{P_{el,net}}{\dot{Q}_{fuel}} \qquad \text{Equation 4-2}$$

$$\eta_{th} = \frac{\dot{Q}_{th}}{\dot{Q}_{fuel}} \qquad \text{Equation 4-3}$$

$P_{el,net}$ Net electrical power in kW_{el}
$\dot{Q}_{th}$ thermal power in kW_{th}
$\dot{Q}_{fuel}$ Fuel power in $kW_{lower\ heating\ value}$

The total efficiency η_{total} can be determined by summing up the electrical and thermal system efficiency:

$$\eta_{total} = \frac{P_{el,net} + \dot{Q}_{th}}{\dot{Q}_{fuel}} = \eta_{el} + \eta_{th} \qquad \text{Equation 4-4}$$

Electrical, thermal and total utilisation ratio

The electrical utilisation ratio g_{el} and the thermal utilisation ratio g_{th} are defined by the ratio of net electricity generation or useful heat generation respectively and fuel consumption in the same time period. The considered time period takes into account all start-up and rundown procedures.

$$g_{el} = \frac{W_{el,net}}{Q_{fuel}} \qquad \text{Equation 4-5}$$

$$g_{th} = \frac{Q_{th}}{Q_{fuel}} \qquad \text{Equation 4-6}$$

$W_{el,net}$ Net electricity generation in kWh_{el}

Q_{th} Useful heat generation in kWh_{th}

Q_{fuel} Fuel consumption in $kWh_{lower\ heating\ value}$

The total utilisation ratio g_{fuel} of the CHP device is the ratio of the summarized net electricity generation and useful heat generation compared to the fuel consumption in the same time period.

$$g_{fuel} = \frac{W_{el,net} + Q_{th}}{Q_{fuel}} = g_{el} + g_{th} \qquad \text{Equation 4-7}$$

CHP coefficient

The CHP coefficient σ of the CHP system results from the ratio of net electrical power and usable thermal power. The reciprocal value is the heat coefficient.

$$\sigma = \frac{P_{el,net}}{\dot{Q}_{th}} \qquad \text{Equation 4-8}$$

Electrical CHP-fraction

The electrical CHP-fraction $d_{el,CHP,demand}$ describes the generated useful electricity generation $W_{el,CHP,useful}$ through the CHP systems related to the total electricity demand in the same time period /Arn 07, Schr 07/:

$$W_{el,CHP,useful} = \int_0^t \left(P_{el,CHP} - P_{reversefeed-in}\right) dt \qquad \text{Equation 4-9}$$

$$d_{el,CHP,demand} = \frac{W_{el,CHP,useful}}{W_{el,building}} \qquad \text{Equation 4-10}$$

$P_{reverse\ feed-in}$ Electrical reverse feed-in into the grid in kW_{el}

$W_{el,building}$ Electricity consumption of the supply object in kWh_{el}

Electrical CHP-production fraction

The electrical CHP-production fraction $d_{el,CHP,production}$ describes the share of generated useful electricity $W_{el,CHP,useful}$ from the CHP system related to the generated electricity amount of the CHP-system in the same time period /Arn 07, Schr 07/:

$$d_{el,CHP,production} = \frac{W_{el,CHP,useful}}{W_{el,net}} \qquad \text{Equation 4-11}$$

Thermal CHP- and PB- fraction

The thermal fractions $d_{th,CHP}$ and $d_{th,PB}$ respectively describe the share of the generated useful heat $Q_{th,CHP}$ and $Q_{th,PB}$ produced by the CHP system and peak boiler respectively related to the total heat demand in the same time period. The thermal CHP-fraction $d_{th,CHP}$ can be calculated as follows:

$$d_{th,CHP} = \frac{Q_{th,CHP}}{Q_{SH} + Q_{DHWS-loading}} \qquad \text{Equation 4-12}$$

Q_{SH} Consumption for space heating of the supply object in kWh

$Q_{DHWS-loading}$ Consumption for DHW storage loading in kWh

The thermal peak boiler fraction d_{thPB} can be calculated accordingly. Since there are losses within the CHP system (e.g. buffer storage), the sum of $d_{th,CHP}$ and $d_{th,PB}$ is always more than 1.

Actual costs of energy

When determining the actual costs of energy, the costs of all aspects of the supply system are considered in relation to the generated amount of useful energy at the point of use. CHP systems present the challenge of how the the input energy and costs are split amongst the products of electricity and heat the are provided. An elaborate discussion of the common evaluation methods and derivation of the following method is presented in /Arn 07/.

The selected method of the current project is based on the split of the energy costs of the CHP system in proportion to the actual costs of heat $k_{heat,conventional.}$ of a conventional heating system and the electricity delivery costs $k_{electricity,conventional}$ (mixed price for household customers), as supplied to the same end-use application. The equations that express this method are as follows:

$$k_{heat} = \frac{A_{N,total} - A_{N,V,electricity}}{Q_{heat} + W_{CHP-electricity} \cdot \left(\frac{k_{electricity,conventional}}{k_{heat,conventional}} \right)} \qquad \text{Equation 4-13}$$

$$k_{electricity} = k_{heat} \cdot \left(\frac{k_{electricity,conventional}}{k_{heat,conventional.}} \right) \qquad \text{Equation 4-14}$$

The ratio of actual costs and delivery costs for heat and electricity via conventional systems respectively are projected upon the respective energy type supplied by the CHP system. The actual costs of heat k_{heat} are calculated according to the Equation 4-13 and the actual costs of electricity $k_{electricity}$ are calculated according to the Equation 4-14.

Present value method and amortisation

The present value method considers the discounted revenues (reflux of capital) and the investment (purchase disbursement) to determine value of a purchase or investment. The net present value at the end of the life-span demonstrates the amount that can be saved to get the same revenues as for an interest yield with specific interest rates. A positive net present value states that the investment is more economical compared to a financial investment with the specific interest rate considered.

The payback period gives information about the number of years necessary to produce revenues, that exeed the costs of an investment. The static amortisation calculation a, taking into account investment and revenue in actual money without any time-value of money considerations. The dynamical amortisation calculation takes into account the discounting of revenues versus time so that the cash values at the time of investment are equal to the net present value of the investment. Dividing the net present value by the modulus of the net present value at the beginning of the useful life results in the standardised net present value. /SchTer 97/.

Internal rate of return

The internal rate of return is the calculated interest rate achieved when the cash value is zero at the end of the useful life of the investment. The investment is advantageous if the internal rate of return is greater than the interest rate desired by the investor. Only the interest yield of the asset linked to the invested object is taken into account. /SchTer 97/.

5 METHODOLOGY

At first, the CHP systems to be tested were analysed in detail. Criteria used to evaluate the systems included technical properties, suitability for automatic operation during comparative analyses and system configurations recommended by the manufacturers. Because the tested CHP systems were designed for different power ratings, a scalable building was defined. Hence, the total heat load could be varied while maintaining overall building physics and specific properties. Thus, an adaptation of the building to best suit the technical data of each of the CHP systems was possible. The size of the building was scaled, so that 25% of the peak thermal power demand could be met by the CHP system.

5.1 Experimental Work on the Test Rig

At the Institute for Energy Economy and Application Technology of TU Munich, an existing test rig designed for the analysis of heat generators was enhanced to enable testing of the CHP systems. Alterations of the control and the hydraulic system were made as well as installing connections for grid feed-in and power measurement.

Measured data was recorded and stored at 1 second intervals over the full duration of each experiment. In special situations (e.g. starting procedures) the measurement resolution could be cut down to 100 milliseconds.

A core piece of the current research project was experimental evaluation on the test rig to obtain basic data (e.g. energy consumption, degrees of efficiency, emissions etc.) for comparative analysis of the CHP systems. A complete CHP system is comprised of the CHP device itself, a peak boiler, usually one or more buffer storages that store either combined or separate heat for space heating and DHW supply and the system control. The CHP devices that were tested in this manner were designed and supplied by the manufacturers.

Because of contractual restrictions and proprietary information concerns of some manufacturers all of the cogeneration devices were considered as “black boxes.” No attempts were made in the current project to modify or improve the performance of the CHP devices themselves. This is also the reason for not including measured internal parameter values, such as temperatures and flow rates of internal heat exchangers or the gross DC electrical production from the cogeneration device, in the current report.

Table 5-1 gives an overview of technical properties, technology and system configuration of the four tested CHP systems.

Table 5-1: Technical Properties of the tested CHP-systems

System	ICE 1	ICE 2	SE	FC
Technology	Combustion engine	Combustion engine	Stirling engine	PEM-fuel cell
Electrical power[1)]	1,3 - 4,7 kW	5,5 kW	2 – 7,5 kW	1,5 - 4,6 kW
Thermal power[1)]	4,0 - 12,5 kW	12,5 + 0,8 kW	8 - 22 kW	3,0 - 9,1 kW
Storage type, -volume	BS 1.000 l HWS 500 l	BS 1.000 l HWS 500 l	2 x CS 1.000 l	(2 x HWS 500 l)

BS.. buffer storage, CS..combined storage, HWS.. hot water storage
[1]) manufacturer's data

5.2 Critical data for model validation

As shown in **Table 5-2**, apart from the empty and charged mass of the heat exchanger the desired static measurements that are critical to model validation could be achieved. In the case of the mass of both the cogeneration device and the balance of plant (BOP) components information is provided on basis of manufacturer's data because scales were not available in this size.

It was possible to get the fuel composition from the natural gas provider. Because of the small variance in natural gas composition observe, only one record per day was considered sufficient resolution.

Table 5-2: Static measurements of critical data for model validation

No	Data	possible	not possible	Source / Comment
1.1	Mass of cogeneration device, not including the balance of plant components (e.g. pumps, storage).	X		Manufacturers data
1.2	Empty and charged mass of heat exchanger (exhaust-gas-to-air or water-to-water) used for capturing thermal output.		X	
1.3	Total mass of cogeneration device.	X		Manufacturers data
1.4	Composition of fuel (molar fractions of CH_4, C_2H_6 C_3H_8, higher hydrocarbons, N_2, CO_2).	X		Natural gas provider

The time-varying measurements of critical data for model validation are shown in **Table 5-3**.

The consumption rate of natural gas was determined by measuring the gas volume, pressure and temperature (necessary for transferring into standard conditions). The temperature of air supplied to the CHP device was measured in the housing of the BOP. Because the CHP devices are considered as "black boxes" it was only possible to measure the temperature of the exhaust gases and flow rate, outlet and return temperatures of the CHP device. The exhaust gas composition of the CHP device was determined by an emission analyser that could measure the concentrations of CO_2, N_2, O_2, CH_4 and CO. The outdoor air temperature was provided to the thermal sensor of the CHP system by a programmable temperature generator.

Table 5-3: Time-varying measurements of critical data for model validation

No.	Data	possible	not possible	Source / Comment
2.1	Electrical demand placed upon cogeneration device (W).		X	
2.2	Net AC electrical output from cogeneration device (after parasitic losses, battery losses, and losses from power conditioning unit) (W).	X		as a result of the heat driven operation
2.3	Natural gas consumption rate (m^3/s at standard temperature and pressure).	X		
2.4	Air supply rate to cogeneration device (kg/s).		X	
2.5	Temperature of air supplied to cogeneration device (°C).	X		measured in the housing
2.6	Humidity of air supplied to cogeneration device (RH or T_{dp}).		X	
2.7	Flow rate of liquid water supplied to cogeneration device (kg/s).		X	
2.8	Flow rate of exhaust gases through gas-to-water heat exchanger or flow rate of water on cogeneration side of water-to-water heat exchanger (kg/s).		X	
2.9	Temperature of exhaust gases as they enter gas-to-water heat exchanger or temperature of entering water on cogeneration side of water-to-water heat exchanger (°C).		X	
2.10	Temperature of exhaust gases as they exit gas-to-water heat exchanger or temperature of exiting water on cogeneration side of water-to-water heat exchanger (°C).	X		only at gas-to-water heat exchanger
2.11	Flow rate of water on balance-of-plant (BOP) side of gas-to-water or water-to-water heat exchanger (kg/s).	X		
2.12	Temperature of entering water on BOP side of gas-to-water or water-to-water heat exchanger (°C).	X		
2.13	Temperature of exiting water on BOP side of gas-to-water or water-to-water heat exchanger (°C).	X		
2.14	Exhaust gas composition (molar fractions of CO_2, N_2, Ar, O_2, H_2O, CH_4, H_2, CO etc).	CO_2, N_2, O_2, CH_4, CO	H_2O, H_2, Ar	only of CHP device
2.15	Ambient air temperature (°C).		X	given to test bench
2.16	Ambient air humidity (RH or T_{dp}).		X	

Regarding the control characteristics of the cogeneration devices themselves, the current project could only deduce some information about the particular CHP device's control strategy from external experimental measurements. Because of competitive reasons not every manufacturer disclosed the details of their system controls.

Due to the heat load-following operation used in the current testing it was impossible both to operate the CHP devices with a constant electrical output and to vary the temperature of the water supplied to the CHP device’s heat exchanger. Therefore the first set of tests (tests appropriate for validating specific algorithms) could not be applied.

The overall CHP system control strategy manipulated the CHP device output to maintain the temperature of the water in the buffering tank within a pre-defined range. The heat demand of both the space heating system and the DHW system was delivered by the buffering tank. One of the tests appropriate for parameter identification is achieved by operating the cogeneration device when started from cold conditions and monitored until steady-state operation is achieved.

Figure 5-1 shows the measuring points of the CHP device. Additionally the pressure of the natural gas (numbered as 2.X) was measured.

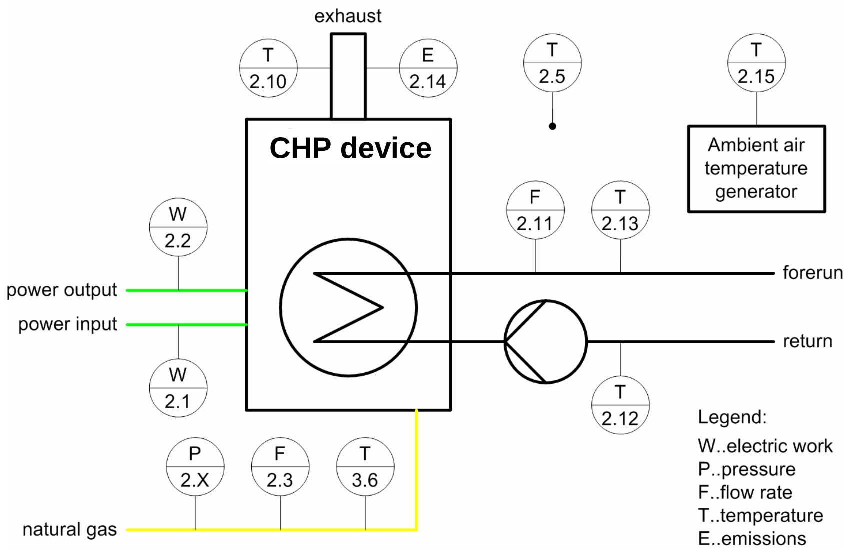

Figure 5-1: Measuring points of the CHP device

5.3 Technical and Economical Analysis

Paralell to the experimental work on the test rig cogeneration in Germany in general was analysed including a description of various CHP-technologies and study of the legal and economical framework for enabling use of CHP. In addition, research was conducted to determine and define load profiles for electricity and heat required of CHP systems in multifamily residences.

The results of the test rig trials were analysed with detailed data sets recorded within the scope of a comparison of the systems. To assess CHP systems, variants of a conventional heat and electricity supply were defined as a reference. Due to the power rating of the analysed CHP systems, the reference variants referred to the energy supply of multifamily residences.

Furthermore, the results of the test rig trials were used to predict the overall end-use efficiency of the energy supply with CHP systems. A common dynamic method is described in the VDI guide line 2067 / VDI 2067-1/. This calculation strategy using the annuity method was applied for the economic analyses of selected supply systems. A calculation programme developed accordingly considered payback periods and actual energy costs as well as energy price sensitivities.

Another goal of the simulation work was to show dynamic processes that result from the interaction of respective components of CHP systems and the reaction of CHP systems to the requirements of the heating, hot-water and electrical load profiles. Initially, the methodical simulation concept was identified by analysing the relevant parameters of CHP systems and the additional components. By means of the test rig results, the simulation could be validated and calibrated. The simulation served as a platform for quick implementation and evaluation of system changes and optimisation. Potentials for improvement of the operating performance and the energy efficiency could be analysed.

6 EXPERIMENTAL ANALYSIS ON THE TEST RIG

The test rig was built to conduct benchmark tests for cogeneration systems under reproducible, realistic simulated operating conditions of residential buildings. A multitude of parameters such as heat load of the building and the domestic hot water (DHW) system, the thermodynamic behaviour of the radiators, the size of the implemented heating buffer and DHW storages could all be carefully controlled and varied. The test rig was designed to simulate the demand of space heating and DHW preparation of residential buildings up to a maximum thermal output of 70 kW. A picture of a part of the test rig shows **Figure 6-1**.

Figure 6-1 CHP test rig at the Institute for Energy Economy and Application Technology of TU Munich

6.1 Applied Load Profiles for Space heating and Domestic Hot Water Supply

To show the diurnal and seasonal influences on the CHP operation, load profiles for space heating demand and DHW consumption were used representing typical days during summer, transition and winter time. These load profiles were derived from a measuring campaign in various residential buildings in Germany and applied to determine the heat load during the experiments on the test rig. Examples of these load profiles are shown in **Figure 6-2** and **Figure 6-3.** .

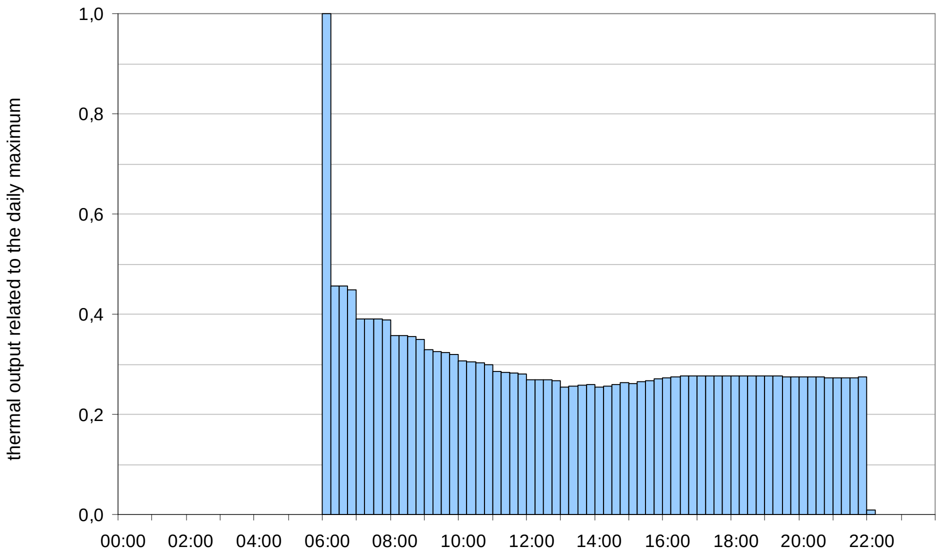

Figure 6-2: **Space heating demand of a residential building (bright winter day) /Muehl 02a/**

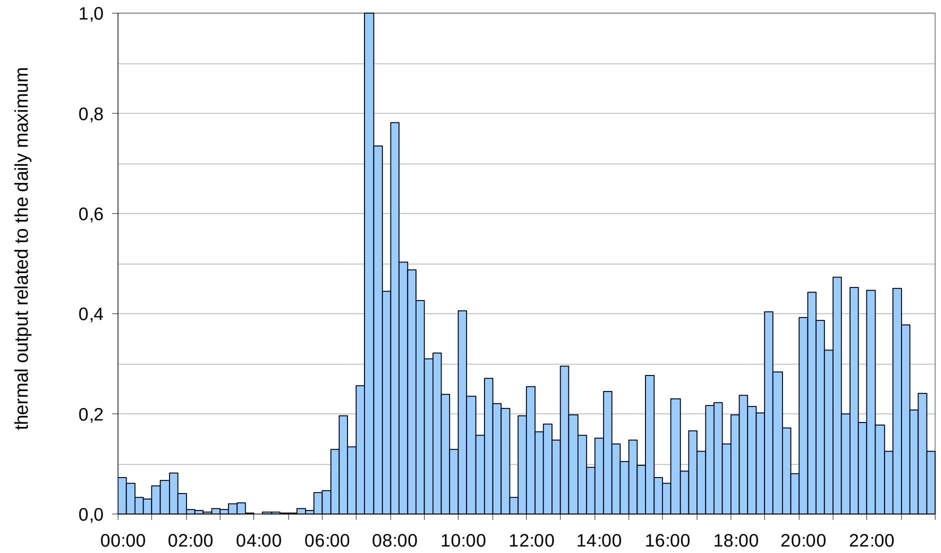

Figure 6-3: **DHW demand of a residential building (weekday, without losses by circulation and storage) /Muehl 02a/**

6.2 Output from the Test rig Measurements

The measuring equipment of the test rig collects all relevant temperatures, water flows, the consumption of natural gas and the generation of electricity with a time scale of one data record per second. The testing of a single day takes about 3 to 4 days of test rig operation in order to get reliable and reproducible results.

Figure 6-4 shows an example of the data output from the experiments A detailed description can be found in /Muehl 07/.

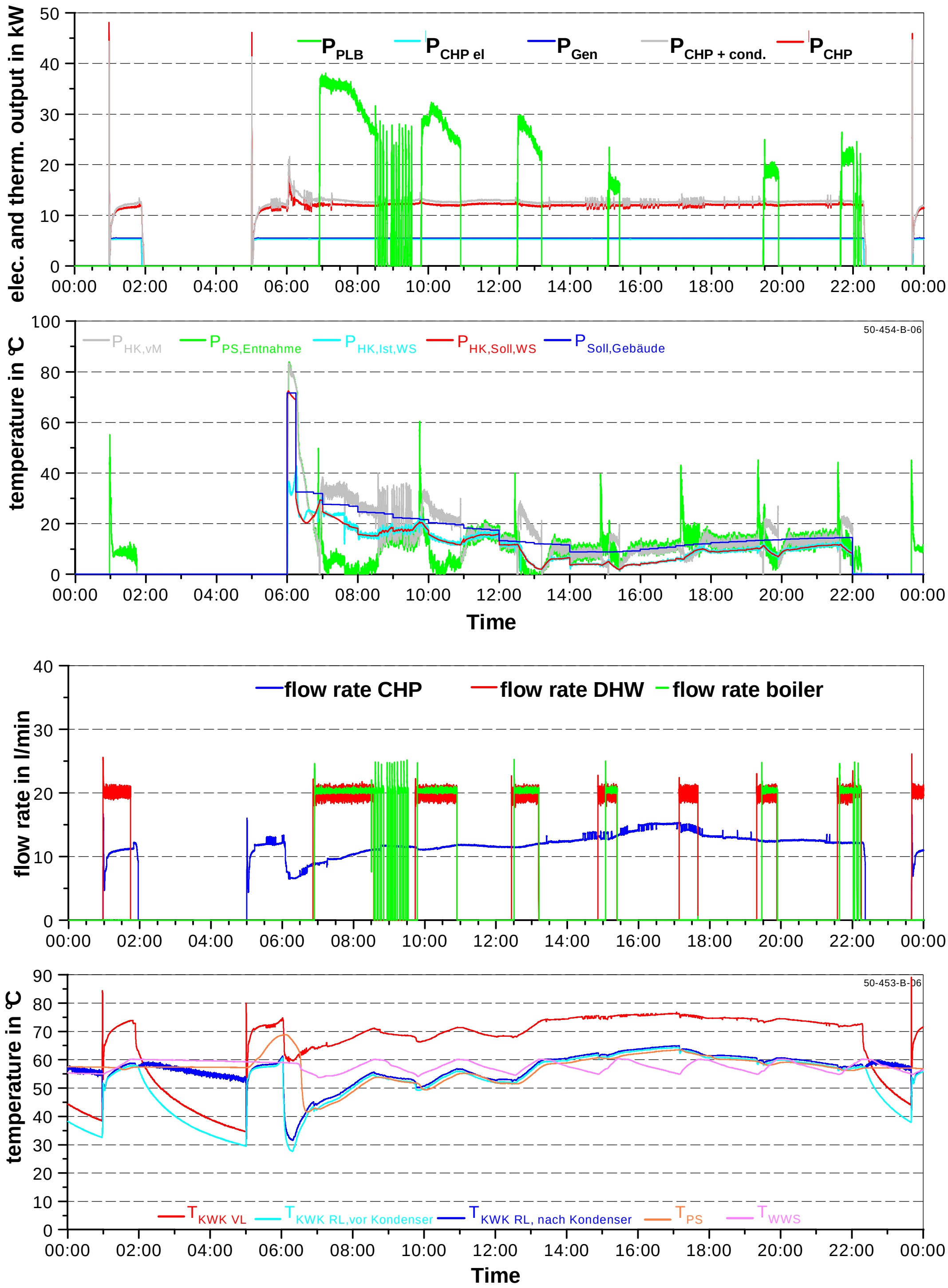

Figure 6-4: Measured Data for ICE 2 operation on a winter day

The daily balances of the building's heat demand for space heating and DHW, the heat output from CHP device and peak boiler, the electrical feed-in and the losses are shown in **Figure 6-5** for the ICE 1, ICE 2and SE system. As expected, the heat demand and production as well as the electricity generation sinks with rising outside temperature from winter to summer season. Although the results of the different CHP systems look very similar there are remarkable differences. The ICE 1 system has the ability to modulate the electrical power output between 1.5 and 4.7 kW and therefore is the only one that doesn't need to start up the peak boiler during the clear transition day. Due to the longer start up time of the SE device the peak boiler of this system has to be used to a higher extend compared to the other systems.

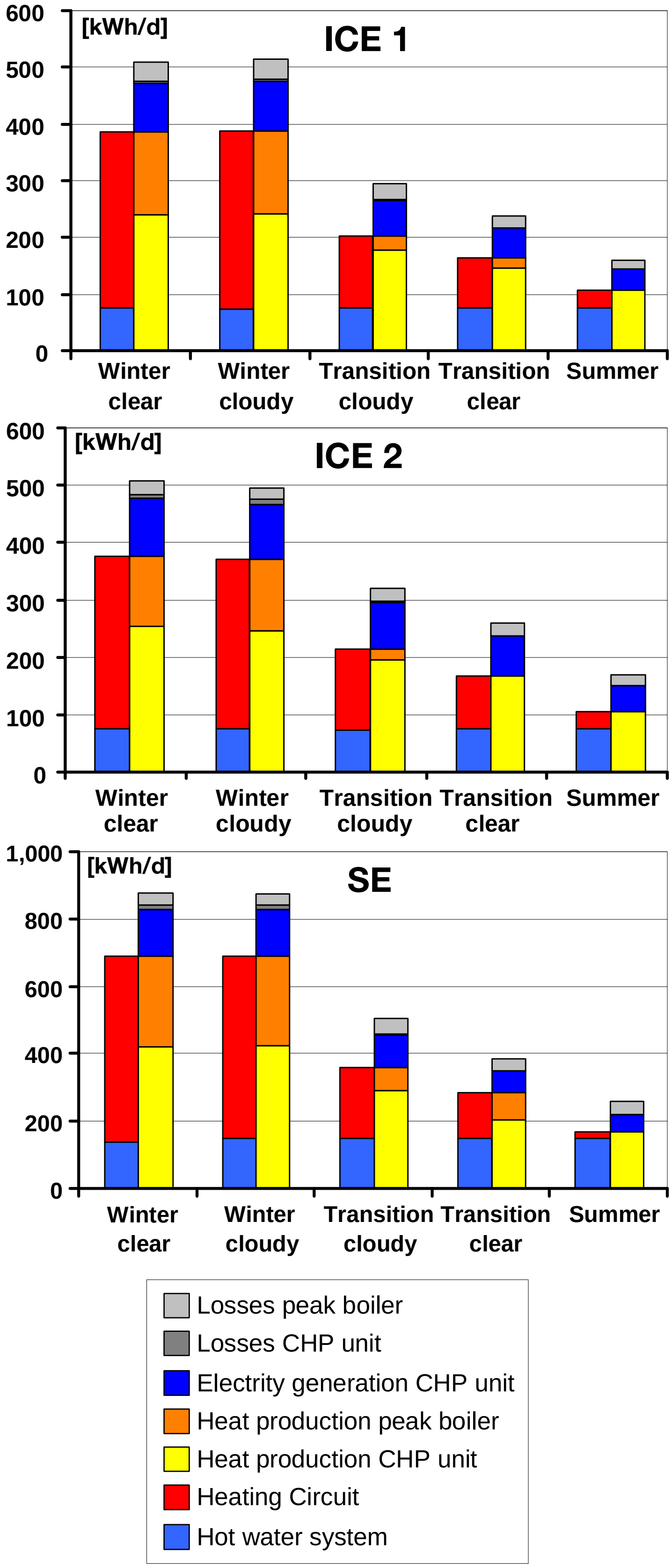

Figure 6-5: Experimental Results of the type day measurements

To project the results obtained from the measurements on basis of type days to annual values, some more parameters have to be taken into account: the outdoor temperature - as it has an significant influence on the residential energy demand - and the dependency between outdoor temperature and demand for space heating.

Average daily values of the outdoor temperature were taken from an existing test reference year for southern Germany (TRY8).

The relation between outdoor temperature and space heating demand could be derived from a previous measuring campaign and TRNSYS simulation of different residential buildings /Muehl02a/ As shown in **Figure6-6** a good approximation can be obtained using a sigmoidal function.

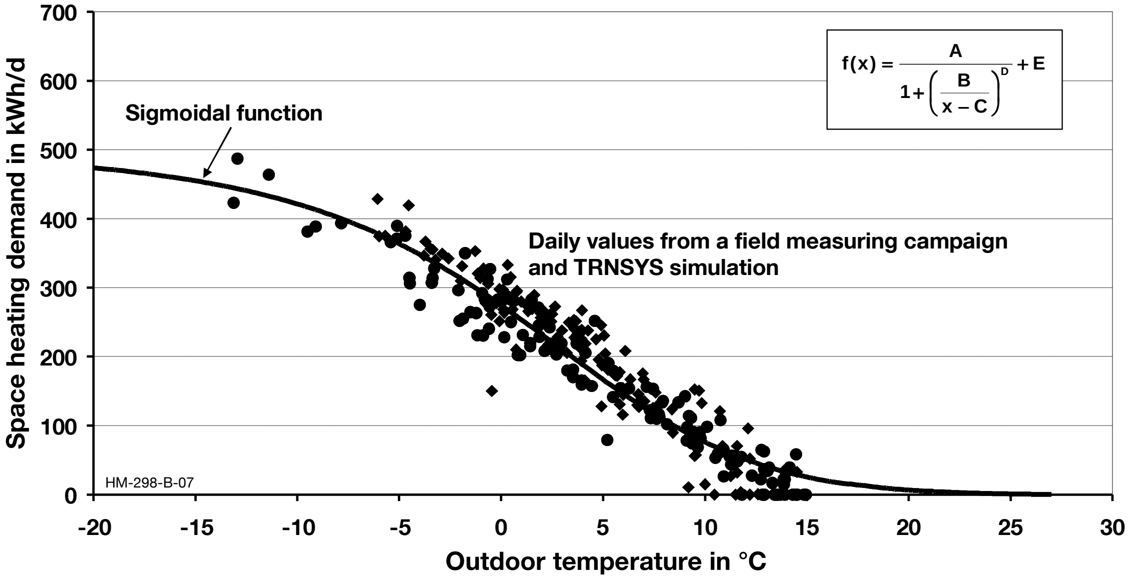

Figure 6-6: Relation between outdoor temperature and space heating demand

The allocation of the heat demand to CHP device and to peak boiler in dependence of the outdoor temperature is shown in **Figure 6-7**. The red curve shows the demand for space heating and hot water supply including distribution and storage losses. The yellow curve describes the heat production of the ICE 2 CHP device. It can be divided into three sections:

1. During summer time with high outdoor temperatures and low heat demand, the CHP device completely delivers the required heat, mainly used for DHW preparation.
2. Although the CHP device could completely deliver the required amount of heat, the peak boiler is operated when the outdoor temperatures falls below 8°C. This is due to the morning peak of the heat demand that exceeds the rated output of the CHP device.
3. On very cold days with outdoor temperatures lower than -11°C the CHP device operates 24 h/d with its maximal output of 330 kWh/d. The remaining required heat has to be supplied by the peak boiler.

The three sections of the curve are determined with help of the results from the type day measurements as show the columns in Figure 6-7. The difference between heat demand and heat production of the CHP device has to be delivered by the peak boiler as shows the orange curve.

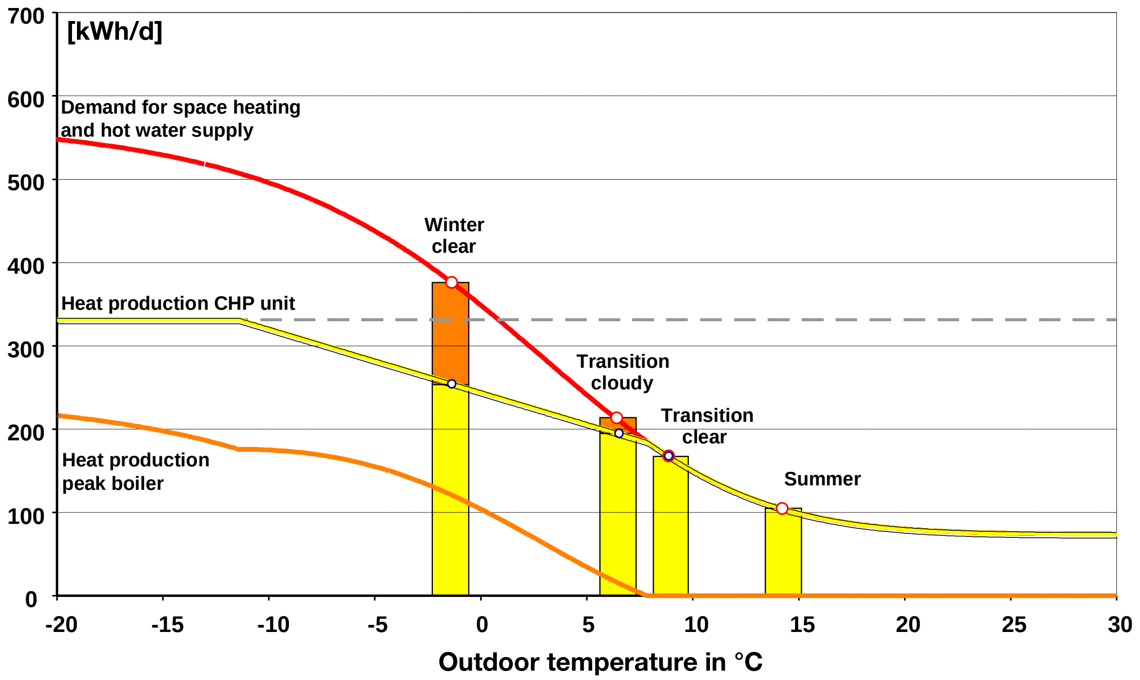

Figure 6-7: Allocation of the heat demand to CHP device and peak boiler for the ICE 2 system

To calculate the consumption of natural gas from the heat production of CHP device and peak boiler the mean daily efficiencies depending on the daily heat/electricity output as shown in **Figure 6-8** have been used. To determine the curves the results from the type day measurements have been used as indicated by the points in the diagram.

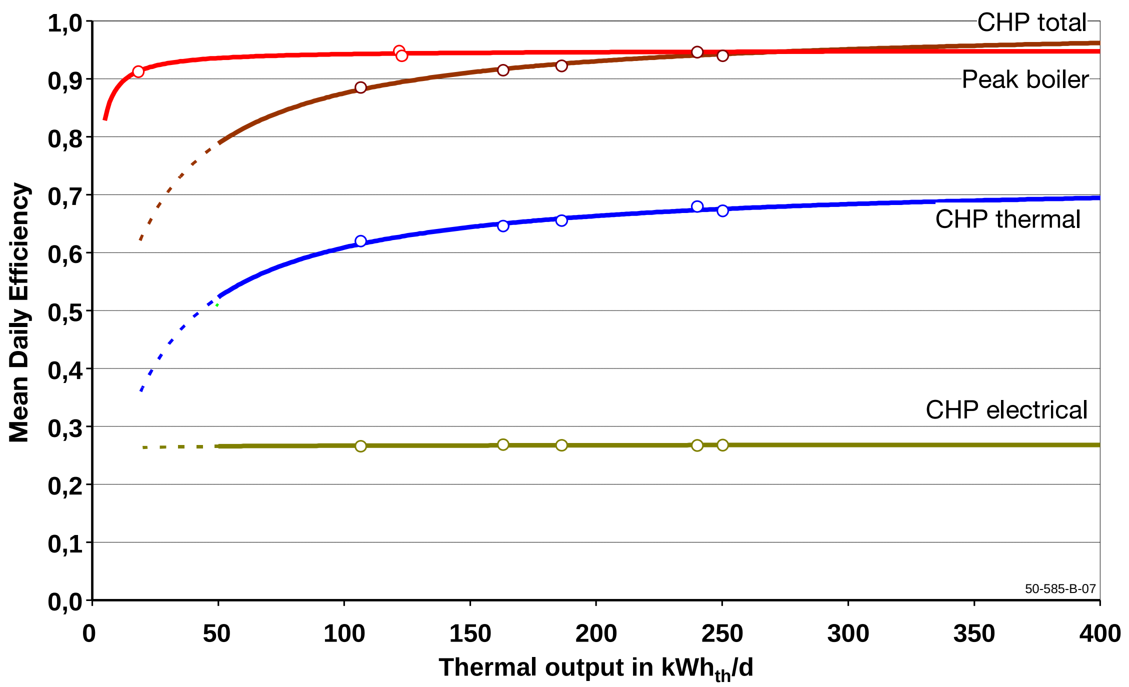

Figure 6-8: Mean daily efficiency of ICE 2 CHP device and Peak boiler

The average daily outdoor temperatures of a standard year for southern Germany were then used to determine the heat demand for space heating and DHW preparation and the production of these energies by CHP device and peak boiler. As shows **Figure 6-9** for the ICE 2 system, these values were first calculated on a day by day basis and later summarised to get annual results.

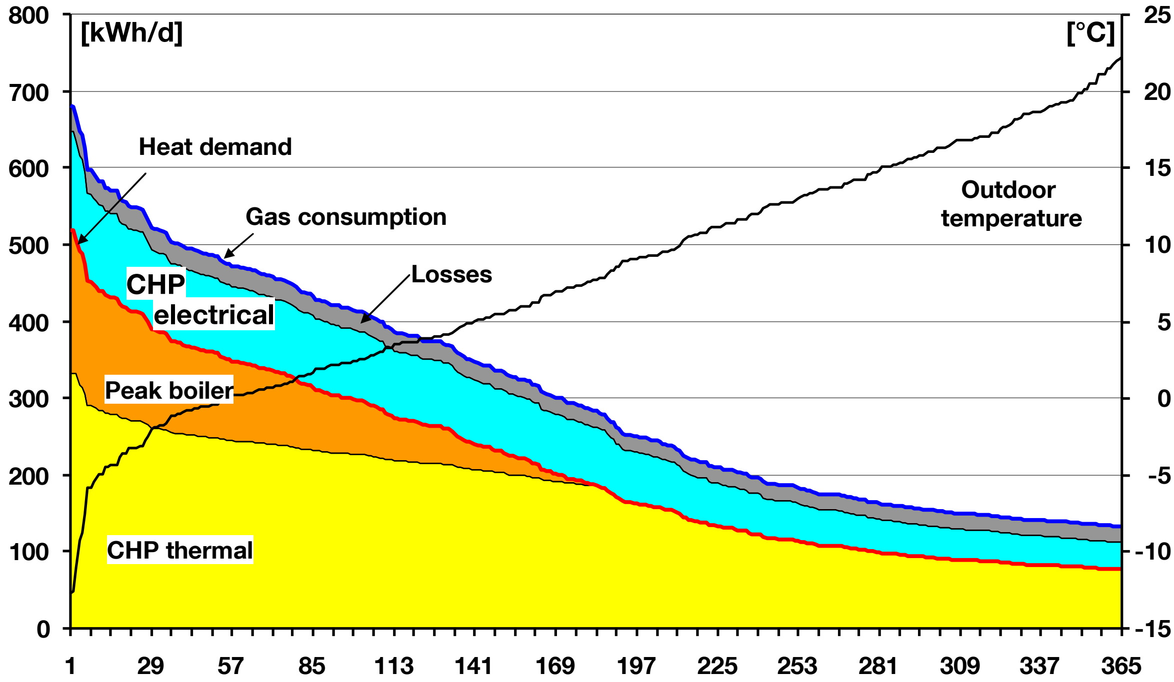

Figure 6-9: ICE 2 system operation during a standard year – ranged by the outdoor temperature

The described methodology was applied to the ICE 1, ICE 2 and SE systems in order to derive annual values. The measured fuel cell system (FC) was a prototype that could not be tested dynamically, only stationary measurements were done. However annual data could be derived by putting together sections of start, stop and steady operation intervals of this device.

The essential results of the tested CHP devices can be found in **Table 6-1**. and act as data basis for the comparison of the systems and the profitability analysis in the following sections.

Table 6-1 Annual balances derived from the experimental tests and calculated values

Name	Unit	ICE 1	ICE 2	FC [1)]	SE
CHP-system					
$W_{el,CHP}$	kWh/a	20.358	25.637	18.658	35.862
$Q_{th,CHP}$	kWh/a	57.681	62.718	51.893	109.796
$Q_{fuel,CHP}$	kWh/a	86.688	95.963	82.037	159.541
$g_{el, CHP}$	%	23,5	26,7	22,7	22,5
$g_{th,CHP}$	%	66,5	65,4	63,3	68,8
$g_{fuel,CHP}$	%	90,0	92,1	86,0	91,3
$P_{th,CHP}$ / $P_{building}$	%	23,8	25,3	21,6	21,5
Peak load boiler					
$Q_{th,PB}$	kWh/a	19.720	14.301	25.508	39.197
$Q_{Gas,PB}$	kWh/a	20.292	15.204	26.238	41.477
$g_{th,PB}$	%	97,2	94,1	97,2	94,5
Consumer					
Building	-	MFH 10 [2)]	MFH 10 [2)]	MFH 10 [2)]	MFH 20 [2)]
Q_{SH}	kWh/a	49.881	49.881	49.881	95.148
$Q_{DHWS\text{-}loading}$	kWh/a	23.641	23.641	23.641	48.153
$Q_{BS,loss}$	kWh/a	3.878	3.497	3.878	5.692
$W_{el,building}$	kWh/a	30.844	30.844	30.844	61.688
W_{useful} [3)]	kWh/a	18.708	18.774	17.146	33.980
$W_{delivery}$ [3)]	kWh/a	12.136	12.070	13.698	27.708
W_{feed} [3)]	kWh/a	1.650	6.863	1.512	1.882
$d_{el, CHP,demand}$ [3)]	%	60,7	60,9	55,6	55,1
$d_{el, CHP,production}$ [3)]	%	91,9	73,2	91,9	94,8
$d_{th, CHP}$	%	78,5	85,3	70,6	76,6

1) Assumption: same value as for ICE1, as no measurements are available for the FC-system
2) Results for other objects cannot be deviated from determined measurement results
3) CHP-electricity-alternative: ‚User' model

7 SIMULATION OF CHP-SYSTEMS AND COMPARISON WITH SEPARATE ELECTRICAL AND THERMAL ENERGY SUPPLY

CHP systems have the potential to save primary energy and CO_2-emissions compared with separate generation of electricity and heat. On the one hand, local fuel consumption increases in CHP systems in order to meet thermal demand and generate electricity. On the other hand, total primary energy demand and CO_2-emissions can be decreased because of reduced electricity supply from the grid, which produces electricity primarily in central power plants that are not amenable to cogeneration (i.e., generator heat is wasted).

To assess the energy and economic performance of the various CHP-technologies, a reference technology had to be selected as a basis of comparison. /AGFW 01/ highlights that there is no definitive basis for the selection of a reference system that is accepted by all. There is no empirical solution or way to prove which reference system is best. Thus, the reference system must simply be well defined to present a useful construct for evaluation.

The CHP-directive 2004/8/EG, article 4 and appendix III of the European Parliament and Council specifies a method to determine the efficiency of CHP-processes. It says that the efficiency of the separate generation of electricity and heat which is to be replaced by CHP should be determined. It is important to take into account that the same categories of primary energy sources should be compared and that each CHP system should be compared with the best available technology for separate generation of heat and electricity in the year of construction of the CHP system' /RL 04/8/EG/.

Initially, various relevant factors required to determine the energy economy of CHP systems were established and compared. For this purpose, the Cumulative Energy Demand (KEA) was analysed for the operation to evaluate the overall energetic behaviour and the emissions of the CHP systems in comparison with conventional technologies.

7.1 Methodology and basic conditions of the comparison of systems

In the following, the primary energy inputs and emissions of the CHP-systems were compared with conventional technologies. The comparison of systems was carried out according to the following basic conditions:

The assessment of the CHP-systems was based on the results of chapter 1 which addressed the balance of the energy flows (natural gas and electricity consumption).

An integral energetic assessment of the use phase was carried out by means of the efficiency method (see /Arn 07/).

Only the bottom line of external procurement and reverse feed-in was evaluated with primary energy factors and specific emissions of **Table 7-1**.

The Cumulative Energy Demand of manufacturing (KEA_H) and disposal (KEA_E) was neglected in the following. The resulting error was below 2 % according to the results in /wiba 00/.

At first, various factors relevant for energy and economic assessment of CHP-systems were determined and compared. For this reason, the Cumulative Energy Demand (KEA) for the operation was analysed as a basis of an integral energetic assessment as well as the emissions of CHP-systems in comparison with conventional technology.

7.2 Basic data

Since different types of energy sources (electricity, natural gas and heating oil respectively) were applied in particular systems, comparisons of systems are made only to the primary energy. That means that the energy input and the emissions for the typical provision of respective final energy sources were considered.

Table 7-1 illustrates basic data for the assessment of natural gas and heating oil provision respectively. The primary energy input and emissions for electricity in Germany in 2002 are based on the analysis of statistical measured data and GEMIS /Destatis 04, FfE 06, GAB 99, GEMIS 4.2/.

The following emissions species were examined for the comparison of energy supply alternatives: carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), non-methane containing volatile hydrocarbons (NMVOC), nitric oxide (NO_x), nitrous oxide (N_2O) and sulphur dioxide (SO_2). The effects of these emissions on the biosphere differ significantly and are not . fully understood. Carbon dioxide-, methane- and nitrous oxide emissions are greenhouse gases that have a global effect[2)]. Volatile hydrocarbons, nitric oxides and carbon monoxide affect the formation of photochemical oxidants (e.g. tropospheric ozone) that affects regional air quality, and the rest of the analysed contaminants typically affect local regions.

Table 7-1: Specific primary energy input and emissions for the provision of natural gas and heating oil in Germany to consumer /GAB 99, GEMIS 4.2, WI 05/

	Specific primary energy input	CO_2	CO	CH_4	NMVOC	NO_X	N_2O	SO_2
Unit	kWh_{PE}/kWh_{FE}	g/kWh_{FE}	mg/kWh_{FE}	mg/kWh_{FE}	mg/kWh_{FE}	mg/kWh_{FE}	mg/kWh_{FE}	mg/kWh_{FE}
Provision to consumer								
Natural gas industry	1,13	15,67	69,50	351,1	10,99	110,0	2,07	6,39
Natural gas household	1,14	15,86	70,43	849,5	70,43	110,8	2,08	6,50
Heavy oil industry	1,14	38,45	49,26	296,8	59,59	131,1	1,03	228,4
Heating oil household	1,16	42,77	51,08	301,7	60,62	136,6	1,18	240,3

2) Specific greenhouse potential according to IPCC (Intergovernmental Panel on Climate Change): carbon dioxide CO_2 = 1, methane CH_4 = 21, nitrous oxide N_2O = 310

7.3 Alternatives for separate electrical and thermal energy provision

For comparison of CHP systems with separate electricity and thermal energy provision, several alternatives for comparison with uncoupled heat and electricity provision were defined as a reference. These reference cases were used to evaluate the energy conversion of CHP systems that were determined through the basic conditions and measurements of the current study. Due to the rated power of the analysed CHP systems and the fact that CHP systems could potentially be operated in these buildings, the reference alternatives are those used for current energy supply in existing residential buildings (multifamily residences) and new buildings that include heating and hot water distribution systems.

7.3.1 Alternatives of heat supply

The comparative alternatives of the heat supply were based on conventional central heating systems that meet both the heating and hot water demand. This type of heating constitutes a share of 69,3 % (see **Figure 7-1**) of the occupied units in residential buildings according to /Stat 04/. The energy sources are mainly natural gas (47,7 %) and heating oil (31,9 %).

Heating systems that use electricity for heating purposes (e.g. night storage heater, flow heater) were neglected in the comparative alternatives, as the necessary heating distribution systems that are required for CHP systems are non-existent. 13,7 % of the residences that are supplied by district heating were not taken into account either, as the provided heat is already generated by more than 80 % efficient CHP systems /AGFW 03/.

Alternatives for heating supply were: (1) the current installed base of central heating systems fired by natural gas and heating oil and (2) the best available technology (gas condensing technology) in Germany in 2003.

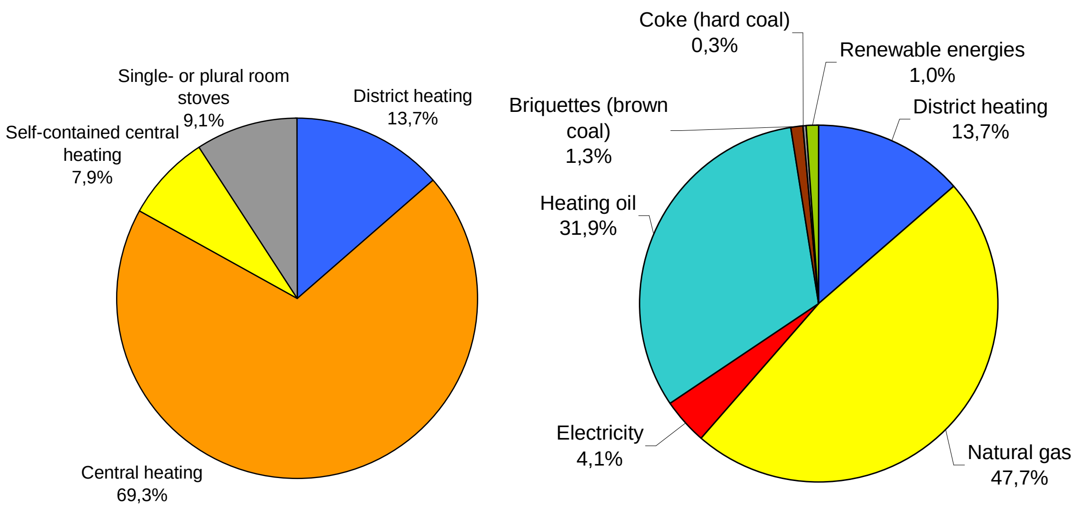

Figure 7-1: Predominant way of heating and input final energy of the occupied flats in residential buildings /Stat 04/

Current stock of heat generation

This supply alternative describes the prevailing type of space heating supply. Boilers heated by natural gas and heating oil with different technology and age were considered. Table 7-2 shows the number of conventional heat generators in Germany classified by construction date, energy source and burner technology as supplied by the boiler statistics of the chimney sweeper guild of 2003, the most important directives and studies. /BVS 03, ConGB 03/

The boiler statistics of 2003 are comprised of small combustion plants up to 10 MW heat capacity that were regulated by the first regulation of the Federal Immission Control Act. However, these statistics do not distinguish between combustion plants in residential buildings and those in companies, which makes the analysis of the survey difficult. Considering that 77,2 % of all flats in residential buildings (38,59 million) are supplied with block-, central- or self-contained central heating (see Figure 7-1) and that there are on average 2,2 flats per building, 13,54 million of the 17,01 million combustion plants are assumed to be installed in residential buildings. The remaining 3,5 million systems are assumed to be installed in 2,93 million companies of industry, service and trade /Stat 04/. It has not been established whether the power rating of combustion plants installed in non-residential buildings are significantly different from those installed in residential buildings.

Table 7-2: Number of conventional heat generators classified by construction dates /BVS 03, ConGB 03/

	Energy source	**Fuel oil**		**Natural gas**				
	Burner technology	**Vaporising burner**	**Spraying burner**	**Burner without fan**	**Burner with fan**	**Combustion plants independent from compartment air**	**Condensing boilers**	**Total**
	Unit	1.000 units	1.000 units	1.000 units	1.000 units	1.000 units	1.000 units	Mill. units
Construction date	**until 31.12.1978**	2,5	894,8	350,5	75,0	-	-	1,32
	1.1.1979 - 31.12.1982	0,9	472,4	461,5	75,7	-	-	1,01
	1.1.1983 - 30.9.1988 / 2.10.1990	2,9	1.073,7	1.113,6	140,1	99,7	-	2,43
	1.10.1988 / 3.10.1990 - 31.12.1997	8,4	2.725,7	3.519,2	345,7	654,7	513,0	7,77
	1.1.1998 - 31.12.2002	3,2	1.061,9	1.123,1	128,1	361,6	1.160,0	3,84
	1.1.2003 - 31.12.2003	1,3	146,0	137,8	14,7	34,7	307,0	0,64
	Total	19,2	6.374,5	6.705,7	779,3	1.150,7	1.980,0	17,01

The majority of the 17 million heating appliances are oil spraying burners (37,5 %) and atmospheric gas burners without fans (39,4 %). From 1998 onwards, the share of newly installed gas condensing boilers is higher than that for other burner technologies. Relating the number of appliances of one construction date to the period of time, it can be determined that the peak rate of installation was reached between 1988/90 and 1997 with around one million appliances per year. The average age of the appliances used thus ends up being 12 years.

Figure 7-2 illustrates the allocation of heating appliances by percentage of the power classes of conventional heat generators. The more simply designed burner constructions (oil vaporising burner, gas burner without fan) dominate the small power class (11-25 kW), whereas the more complex and efficient technologies (oil vaporising burner, gas burner with fan) are preferentially applied for in the power classes at or above 25 kW. Ambient air independent combustion plants are primarily used in the 11-25 kW size class. This category is primarily comprised of gas heaters, which are applied as self-contained central space heating in flats. 96 % of them produce between 11 kW and 25 kW of thermal power. But this power is mainly necessary for provision of domestic hot water in short time. The trend of gas condensing boiler with smaller power can be explained through the reduced heat demand of newer buildings with these units.

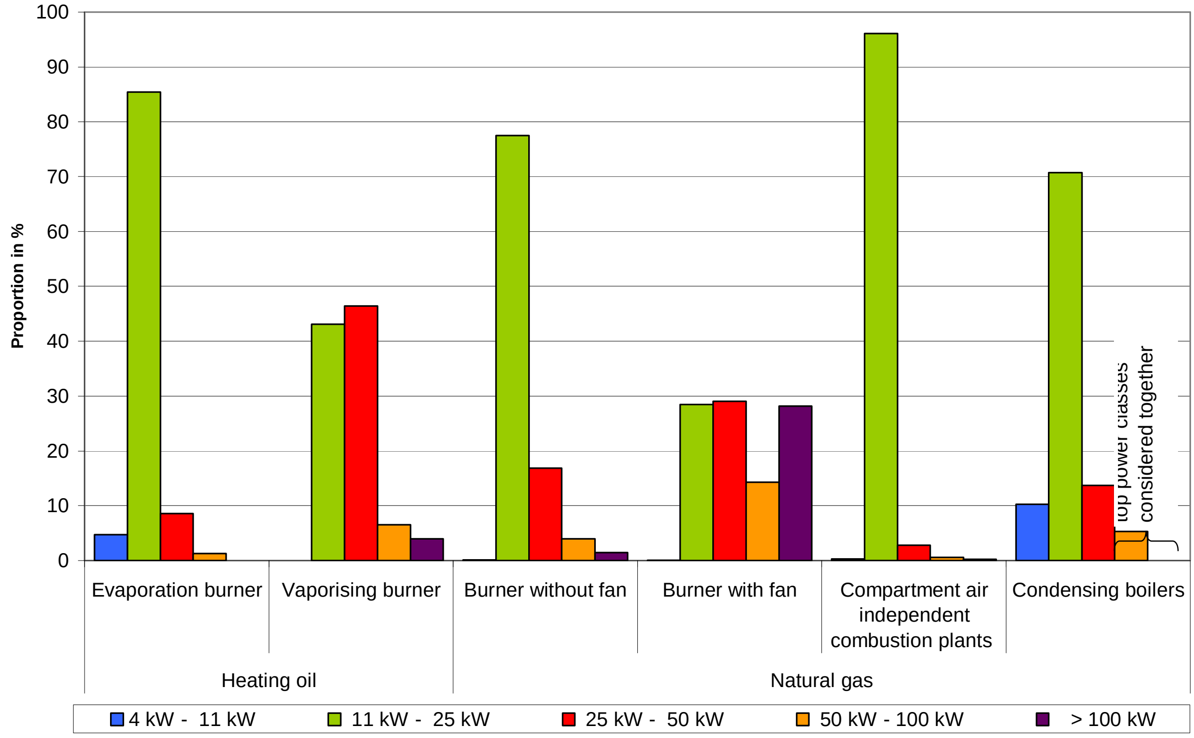

Figure 7-2: Allocation by percentage of conventional heat generators depending on power classes /BVS 03/

Each of the heating devices technologies can be allocated with typical efficiency factors subject to age, power and typical burner operating time considering combined heating and hot water supply and by means of published studies and current measurements /Muehl 02a, FFE 97-07/. The useful energy supply of the final energy consumption and related efficiency factor are shown in **Table 7-3**. The average efficiency factor of the heat generators is 80,2 %. Considering the efficiency factor from an energy source point of view it adds up to 80,4 % with a slight advantage for oil fired heating plants (80,0 % with natural gas). The reason for this difference is because natural gas boilers with atmospheric burner and without fans dominate (see Table 7-2) and they exhibit a lower degree of efficiency than burners with fans and gas condensing boilers respectively. Units fired by heating oil are mainly equipped with spraying burners (99,7 % of the existent oil heaters, see Figure 7-2).

Table 7-3: Provision of useful energy, final energy consumption and efficiency factor of conventional heat generators according to construction dates /BVS 03, ConGB 03, Muehl 02a/ /BVS 03, ConGB 03, Muehl 02a/

		Useful energy	Final energy	Efficiency factor
	Unit	TWh/a	TWh/a	-
Construction dates	**Until 31.12.1978**	78,1	111,1	0,703
	1.1.1979 - 31.12.1982	50,8	71,3	0,713
	1.1.1983 - 30.9.1988 / 2.10.1990	98,4	128,5	0,766
	1.10.1988 / 3.10.1990 - 31.12.1997	274,0	331,7	0,826
	1.1.1998 - 31.12.2002	128,3	145,8	0,880
	1.1.2003 - 31.12.2003	20,4	22,4	0,908
	Total	649,9	810,8	0,802

The emissions of conventional heat generators are listed in **Table 7-4** considering construction date and actual stock of boilers. There is a consistent decrease of specific emissions over the years. Only the CH_4-emissions doubled since 1978 which is due to the increase of share of gas heaters.

Table 7-4: Specific direct emissions of conventional heat generators depending on construction date /BVS 03, ConGB 03, GEMIS 4.2/

		CO_2	CO	CH_4	NMVOC	NO_x	N_2O	SO_2
	Unit	g/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}
Construction dates	**Until 31.12.1978**	355,4	100,3	1,61	4,24	106,0	2,6	293,5
	1.1.1979 - 31.12.1982	328,9	90,4	2,79	4,03	107,0	2,3	204,1
	1.1.1983 - 30.9.1988 / 2.10.1990	304,3	84,9	2,74	3,95	99,9	2,1	182,4
	1.10.1988 / 3.10.1990 - 31.12.1997	272,2	76,7	3,14	3,87	93,8	1,8	129,4
	1.1.1998 - 31.12.2002	249,9	70,6	3,29	3,72	88,8	1,6	98,6
	1.1.2003 - 31.12.2003	239,6	65,9	3,29	3,35	86,2	1,5	85,8
	Total	286,1	80,3	2,90	3,89	96,0	1,9	155,5

To obtain the total emissions of conventional heat generators per kWh heat to the consumer as illustrated in **Table 7-5**, the direct emissions of Table 7-4 need to be summed up with the indirect emissions of the fuel supply. The same must be accomplished for the energy supply. The energy demand for heat generation in boilers must be summed with the energy input for the provision of the energy sources (see Table 7-1). For the provision of one kWh of heat, a total amount of 5,08 MJ of primary energy (equals 1,41 kWh) needs to be provided

Table 7-5: Specific primary energy demand and total emissions of conventional heat generators per kWh released heat to consumer /BVS 03, ConGB 03, GAB 99, GEMIS 4.2, WI 05/

	Specific primary energy demand	CO_2	CO	CH_4	NMVOC	NO_x	N_2O	SO_2
Unit	kWh_{PE}/kWh_{th}	g/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}
Plants fired with heating oil only	1,39	375,8	147,5	301,8	64,5	226,6	3,75	586,8
Plants fired with natural gas only	1,42	264,1	137,8	854,7	74,4	211,6	3,50	8,43
Total	1,41	313,8	142,1	608,9	70,0	218,3	3,61	265,6

Best available technology for heat generation: gas condensing boilers

The technological development of condensing gas boiler technology is the most advanced technology available today. The market share of gas condensing boilers in Germany in 2003 was 57,7 % of the natural gas heating market, 19 of 20 of these devices were fixed to the wall and the rest were fixed on the floor/ConGB 03/.

A condensing boiler consists mainly of a combustion chamber and a condensing heat exchanger in which the combustion products are cooled down to the point at which water vapour contained therein condenses on the heat exchanger surface (condensing technology). The energy gain through condensation of the water, or conversely the exhaust latent heat loss, depends upon the return temperature of the heat transferring medium.

The annual average efficiency achieved by this best available technology for heat generation, which can be applied for space heating and hot water provision, was determined only for the latest natural gas condensing boilers of Table 7-2. The annual average efficiency that results is 94,0 % /Gei 05, BDH 04/. The specific direct emissions of the best available gas condensing boilers are illustrated in **Table 7-6**

Table 7-6: Specific direct emissions of gas condensing boilers /ConGB 03, GEMIS 4.2/

	CO_2	CO	CH_4	NMVOC	NO_x	N_2O	SO_2
Unit	g/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}
Gas condensing boilers	211,3	53,6	4,3	2,8	85,8	1,2	1,6

To obtain the total emissions of gas condensing boiler per kWh heat to consumer such as shown in **Table 7-7**, the direct emissions of Table 7-6 need to be summed up with the indirect emissions of fuel provision. For the provision of one kWh of heat, 4,36 MJ of primary energy (equals 1,21 kWh) needs to be input. 82,6 % is the degree of efficiency for the provision.

Table 7-7: Specific primary energy demand and total emissions of gas condensing boilers per kWh heat to consumer /ConGB 03, GAB 99, GEMIS 4.2, WI 05/

	Specific primary energy demand	CO_2	CO	CH_4	NMVOC	NO_x	N_2O	SO_2
Unit	kWh_{PE}/kWh_{th}	g/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}	mg/kWh_{th}
Gas hot water devices	1,21	227,2	124,1	853,8	73,2	196,6	3,26	8,14

7.3.2 Alternatives of electricity supply

The alternative of consumer generated electricity in CHP systems is the currently prevalent central generation in large-scale power plants followed by transmission and distribution of such to the end-user. Many different reference systems are used in publications that assess CHP electricity generation and their characteristics related to energy economy and specific emissions. In general, CHP systems are typically compared with old replaceable technologies, average currently available technologies or the best available new power plant technologies. Furthermore, specifically defined reference plants or local grid mixes of plants, like for instance the total electricity generation mix in Germany, are also used as reference cases for comparison to CHP systems.

This report presents three alternatives of electricity generation that were each applied in the comparative analyses of CHP systems. These alternatives include: (1) an energy economic analysis that determines the most likely plant mix that is replaced by the operation of CHP systems, (2) the electricity generation mix in Germany, and (3) the best available technology of central electricity generation (i.e., natural gas combined cycle power plants).

Substitution mix by feed-in of CHP electricity

The voluntary agreements of the German economy in 2001 and the CHP law of 2002 intend to reduce annual carbon dioxide emissions in Germany by up to 23 million tonnes (at least 20 million tonnes) by 2010 compared to 1998 through the use of combined heat and power /BMWA 01, KWKModG/.

The target of the voluntary agreement is to improve the market conditions that existed for CHP systems in the year 1998. The aims of the CHP-law are the limited protection and modernisation of CHP systems, the development of electricity generation in small CHP systems and the market launch of the fuel cell. The aims of both instruments affect the determination of the reference system of uncoupled electricity generation in such a way that it can be assumed that the generated CHP electricity replaces capacity of existing plants. Thus, analysis remains necessary to determine where the CHP electricity ranks in the liberalised market according to the Merit-Order[3)] and which plants therefore could be asked to reduce output or be switched off ..

3) The Merit Order is the sequence of employment of plants depending on variable costs

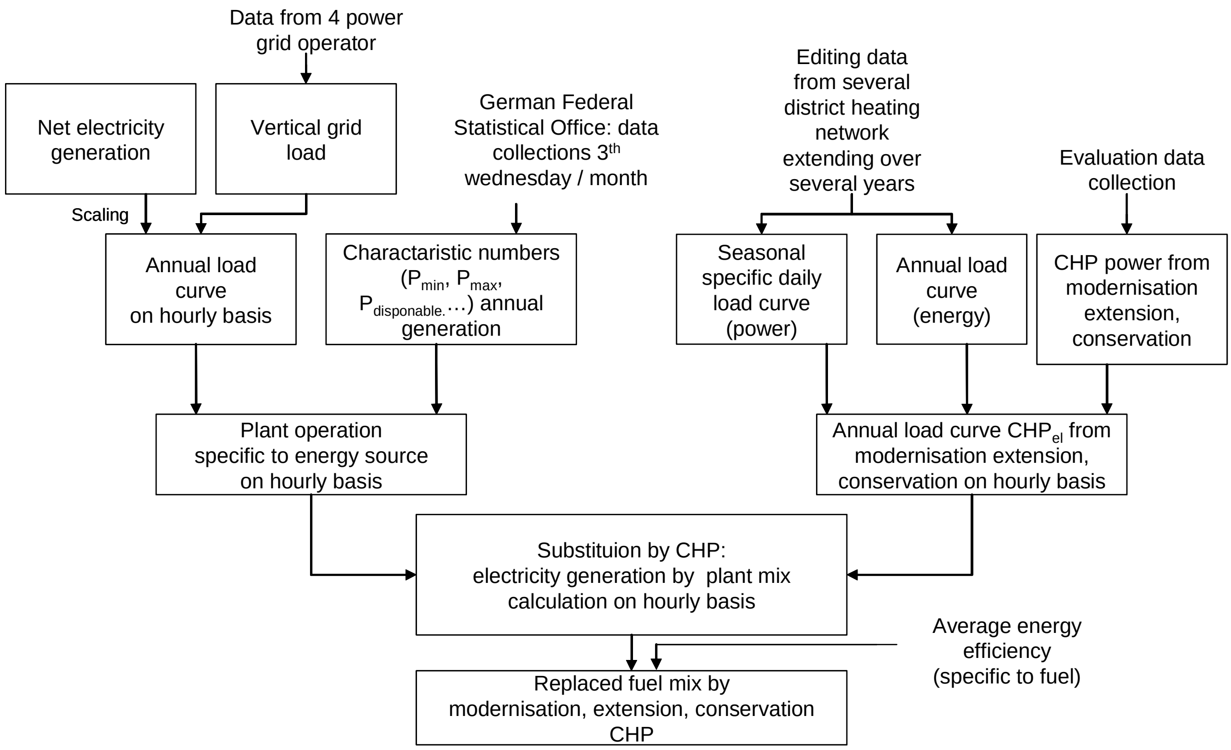

Figure 7-3: Methodology to determine the replaced fuel mix by CHP /CO2KWK 05/

At the FfE, typical plant use has been modelled on an hourly basis. On the basis of data profiles acquired for CHP cogeneration in this study, one can determine for each hour the type of plant mix that would most likely be replaced by CHP power. This methodology is illustrated in **Figure 7-3**.

To determine the uncoupled reference, the annual load curve of the German electricity generation was established by means of the vertical grid load[4)] and the net electricity generation. By means of the so called Wednesday balances of the year 2002 /VIK 04/, the plant operation for basic-, medium-, and peak load was determined. Furthermore, proportions of gas power plants were identified, which were considered to be not replaceable. Reasons for this included, for instance, CHP- electricity generation that was used primarily to provided heat or power control that could not be delivered by gas power plants.

By using the typical CHP electricity generation data, one can generate profiles of the corresponding general electricity supply and balanced electricity generation of CHP- plants to determine an annual load curve for CHP-displaced electricity generation, which has been calculated.

The developed model was based on pro-rata replacement of the hourly available energy source specific plant power through CHP- electricity. Initially, the plants based on coal, gas and mineral oil were substituted. Only if the replaceable capacities of plants did not suffice, brown coal and nuclear power plants were substituted by CHP- electricity.

In **Figure 7-4**, energy source specific electricity shares of the determined substitution mix are illustrated. To determine direct emissions, the average energy source specific net degree of efficiency of /VWEW 02/ and /VIK 04/ was calculated for the power plants. The total net degree of electrical efficiency of the substitution mix is 38,6 % /CO2KWK 05/.

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4) Sum of all transfers from transfer grids over directly connected transformer and all wires to the grid and final consumers

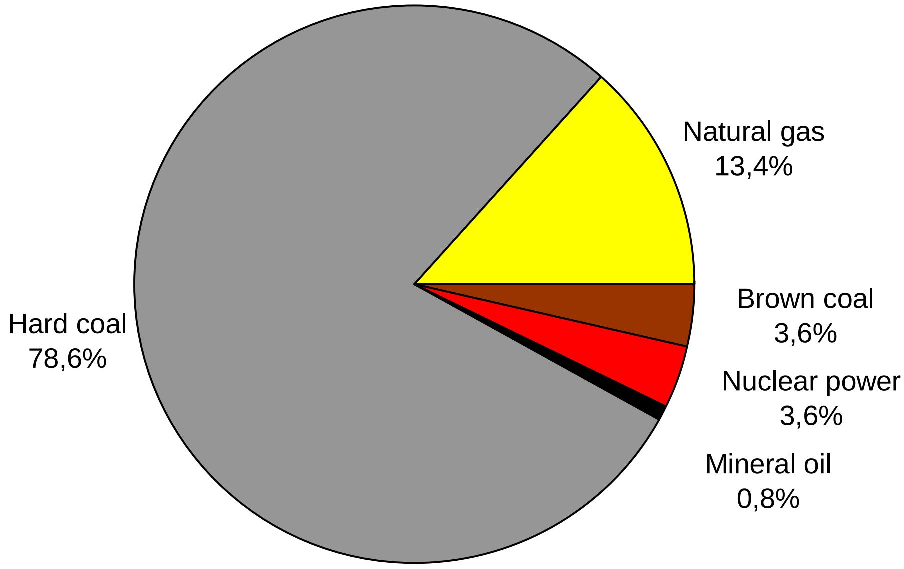

Figure 7-4: Energy source specific electricity shares of the substitution mix

Table 7-8: Specific direct emissions of the substitution mix /GEMIS 4.2, VWEW 02/

	CO_2	CO	CH_4	NMVOC	NO_x	N_2O	SO_2
Unit	g/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}
Hard coal	905,7	152,8	14,76	25,65	478,0	42,98	629,1
Gas	412,35	251,5	33,40	105,3	1.230,5	13,02	3,20
Brown coal	1.240,3	224,9	16,64	16,64	865,9	33,74	585,5
Nuclear power	0	0	0	0	0	0	0
Mineral oil	851,9	313,3	32,89	32,89	469,9	32,89	961,1
Total	820,3	165,0	16,99	35,13	576,5	37,02	525,2

Table 7-8 shows specific direct emissions of the substitution mix. The CO_2-emissions of the substitution mix are 820 g CO_2/kWh_{el}.

Sensitivity analyses related to input parameter show that the reference value even with differing CHP-electricity amount and different CHP- generation profile is determined to be constant throughout time.

To get total emissions of the substitution mix per kWh electricity to consumer (see **Table 7-9**), the direct emissions of Table 7-8 need to be added to the indirect emissions of fuel supply and this sum needs to be divided by the degree of efficiency of the distribution network. To provide 1 kWh of electricity, 10,35 MJ of primary energy (equals to 2,76 KWh) need to be supplied. This results in a degree of electrical supply efficiency of the supply of 36,2 %.

Table 7-9: Specific primary energy expenditure and total emissions of the substitution mix per kWh of electricity to consumer /GAB 99, GEMIS 4.2, VWEW 02, WI 05/

	Specific primary energy input	CO_2	CO	CH_4	NMVOC	NO_x	N_2O	SO_2
Unit	kWh_{PE}/kWh_{el}	g/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}
Coal	2,71	999,9	205,8	3.137,1	35,89	668,1	46,85	876,0
Gas	2,86	474,1	441,0	924,9	138,8	1.574,9	18,96	19,57
Brown coal	2,87	1.339,6	249,9	35,57	18,03	937,4	36,44	631,6
Nuclear power	3,32	27,65	32,76	50,66	4,12	119,8	1,0	105,3
Mineral oil	2,84	992,7	452,1	770,3	182,3	820,0	37,21	1.578,6
Total	2,76	902,6	233,5	2.562,0	48,7	776,1	40,68	727,0

Electricity generation mix in Germany

Since the liberalisation of the electricity market in 1998, a regional balance of electricity generation is difficult to determine due to allocation reasons. By implementing electricity trade, surplus amounts of electricity can be sold to Germany or other places in Europe more easily. Additional demand can be covered by trade via the stock exchange and OTC[5)]. In the year 2005, 53,4 TWh were imported and 61,9 TWh exported. Since the net electricity generation for general supply is 497,5 TWh, the import is 10,7 % and the export is 12,4 % (from /Stat 05, AGEB 06/).

The electricity generation mix shows how electricity is generated in Germany. **Figure 7-5** illustrates the gross electricity generation according to input energy sources for 2005.

Around 60 % of the gross electricity generation is generated by fossil fuel combustion and 26 % by nuclear energy sources. Renewable energy sources, such as wind and hydro-electric power, contribute approximately 9 %. The remaining sources, such as waste and biomass fuels, contribute 5 % of the gross electricity generation.

5) At the OTC trade, commercial actions are conducted directly, in which prices are determined itself (no stock exchange, no broker)

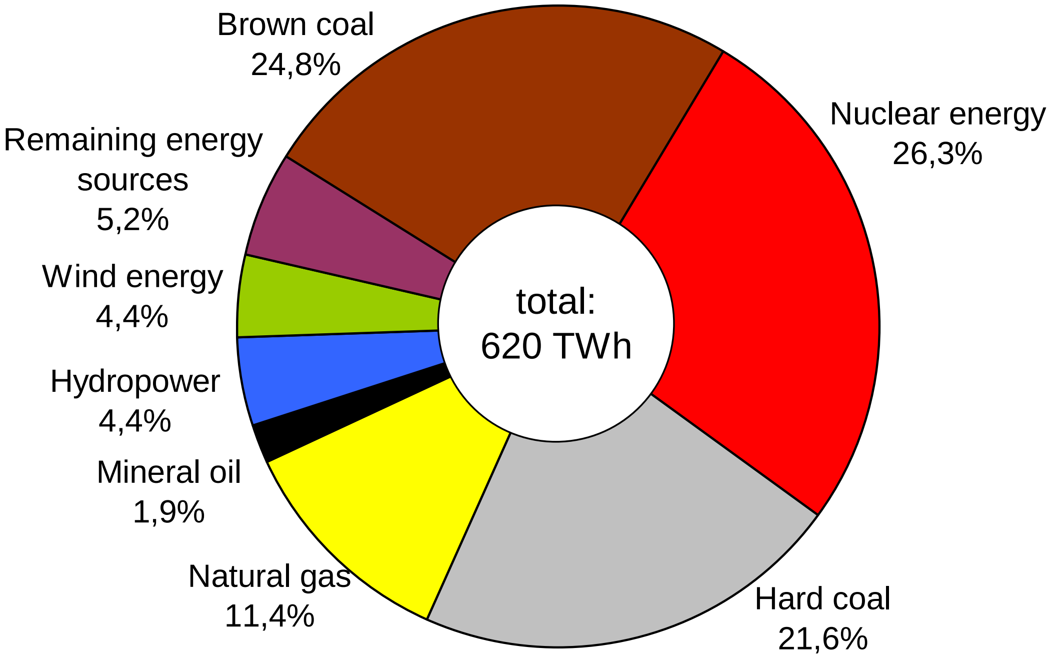

Figure 7-5: Gross electricity generation depending on energy sources for 2005 /AGEB 06/

Table 7-10: Specific direct emissions of the electricity mix in 2005 in Germany /GEMIS 4.2/

	CO_2	CO	CH_4	NMVOC	NO_x	N_2O	SO_2
Unit	g/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}
Total	564,5	144,4	13,5	32,9	517,6	20,5	295,5

Analogous to section 2.3.2.1 the total emissions of the electricity mix are calculated and presented in **Table 7-11**. 11,54 MJ of primary energy (equal to 2,93 kWh) need to be supplied to provide 1 kWh of electricity. This results in a degree of efficiency of supply of 34,2 %.

Table 7-11: Specific primary energy input and total emissions of the electricity mix 2005 in Germany per kWh electricity to consumer /GAB 99, GEMIS 4.2, WI 05/

	Specific primary energy input	CO_2	CO	CH_4	NMVOC	NO_x	N_2O	SO_2
Unit	kWh_{PE}/kWh_{el}	g/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}
Total	2,93	621,8	226,9	808,0	57,1	707,3	23,4	394,5

Best available technology for electricity generation: gas and steam power plants

Currently best available technology are gas and steam power plants with a net efficiency of 55 % /GE-MIS 4.2/. In gas and steam power plants, electricity is generated by a gas turbine and the hot exhaust is being used for steam generation via a steam generator. This steam generates more electricity in a steam turbine.

Table 7-12: Specific direct emissions of gas powered gas and steam power plants /GE-MIS 4.2/

	CO_2	CO	CH_4	NMVOC	NO_x	N_2O	SO_2
Unit	g/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}
Total	361,0	274,8	27,5	27,5	549,6	16,5	2,8

Table 7-12 illustrates direct specific emissions of gas powered gas and steam power plants. The total emissions of the gas powered gas and steam power plant per kWh electricity to consumer are shown in **Table 7-13** and are calculated along the lines of section 5.3.2.1 and 5.3.2.2 respectively. 7,78 MJ of primary energy (equals 2,16 kWh) need to be input for the provision of 1 kWh of electricity. This results in a degree of efficiency of supply of 46,2 %.

Table 7-13: Specific primary energy input and total emissions of gas powered gas and steam power plants per kWh electricity to consumer /GAB 99, GEMIS 4.2, WI 05/

	Specific primary energy input	CO_2	CO	CH_4	NMVOC	NO_x	N_2O	SO_2
Unit	kWh_{PE}/kWh_{el}	g/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}	mg/kWh_{el}
Total	2,16	410,3	422,6	701,5	50,0	789,6	21,3	15,2

7.3.3 Summary and combination possibilities of reference alternatives

All reference alternatives of separate heat and electricity generation described in previous sections are summarised by means of the specific energy input and CO_2-emissions presented in **Table 7-14**.

Table 7-14: Summary of the reference alternatives of separate energy generation in the comparison of systems

		Distribution		Use		Total	
		Specific energy input	CO_2^- emissions	Specific energy input	CO_2- emissions	Specific energy input	CO_2- emissions
	Unit	kWh_{PE}/ kWh_{FE}	g/ kWh_{FE}	kWh_{FE}/ kWh_{NE}	g/ kWh_{NE}	kWh_{PE}/ kWh_{NE}	g/ kWh_{NE}
Heat supply	Current stock of heating systems	1,13	26,0	1,25	286,1	1,41	312,1
	BVT heat (gas-hot water)	1,14	21,9	1,06	211,3	1,21	233,2
Electricity supply	CHP substitution mix	1,13	87,9	2,45	818,6	2,76	906,5
	Electricity mix in Germany	1,10	61,9	2,66	559,9	2,93	621,8
	BVT electr. (gas and steam)	1,19	49,3	1,82	361,0	2,16	410,3

From the possible six combinations of the two heating reference cases and the three electricity supply alternatives, three combinations were selected for the majority of the current effort. These three reference cases are presented in **Table 7-15**. Only the alternatives that considered (1) an energy economic analysis to determine CHP-substituted electricity, (2) current electricity generation stock, and (3) 'best available technology' were used. These three options were combined with the two specific heat provision reference cases as shown in Table 7-15 for all comparative analyses of the CHP systems.

Table 7-15: Combination possibilities of heat and electricity supply alternatives in comparison of systems

		Heat supply	
		Current stock of heating systems	Best available technology (gas condensing boiler)
Electricity supply	Substitution mix by CHP- electricity feed-in	EW	-
	Electricity mix in Germany	Stock	-
	Best available technology (gas powered gas and steam power plants)	-	BVT

EW' means that the feed-in of the CHP system with the CHP substitution mix is evaluated and the electricity supply assessed with the Germany mix of generating technologies. The combination 'Stock' involves an offsetting with the Germany mix for both the CHP electricity feed-in and the electricity supply. The evaluation of the CHP electricity feed-in for the 'BVT' combination happens with the Germany mix, the electricity supply is offset with the BVT electricity (best available technology of natural gas combined cycle plants).

7.4 Primary energy and emissions

All energy flows that are necessary to supply respective buildings with electricity and heat were part of the calculations concerning primary energy consumption. The allocation of the primary energy input for CHP-facilities was accomplished according to the efficiency methodology (see /Arn 07/). The buildings that were supplied electricity and heat separately required a primary energy demand for heat generation required by heating boilers and for the electricity supply. In buildings that were supplied by CHP, the primary energy demand was split into four fractions: the consumption of the CHP system was assigned to heating and electricity generation and the primary energy demand of the peak boiler gas and auxiliary energy were considered. Furthermore, the remaining electricity supply was evaluated and the CHP electricity feed-in was credited. CO_2-reductions only partly contribute to national CO_2-reduction commitments because a certain fraction of the reductions is achieved abroad due to the pre-chain of electricity provision from abroad.

7.4.1 Primary energy and emissions comparison of the measured CHP-systems

Initially, the primary energy and emissions comparison was made on the basis of the measured performance of CHP systems. The measured energy consumption data is reported in Table 6-3 and Table 6-4 of /Muehl 07/.

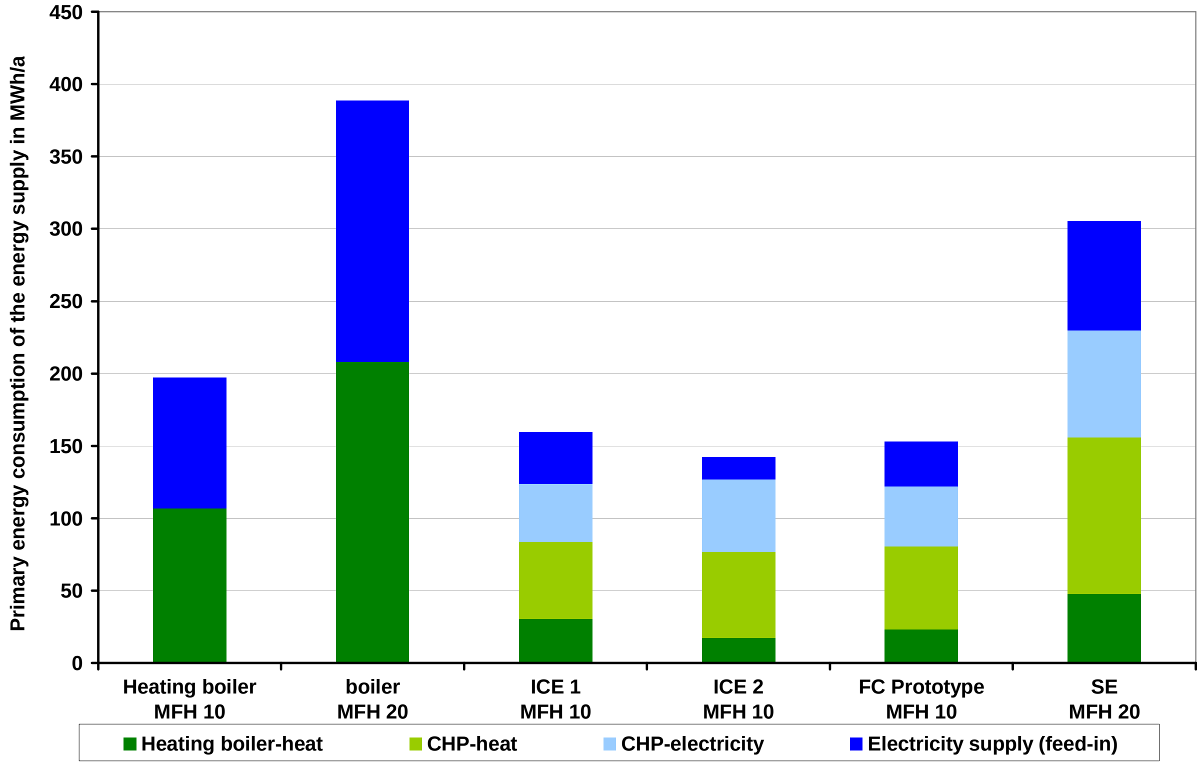

Figure 7-6: Primary energy consumption of the energy supply of reference – and CHP alternatives (combination ‚stock')

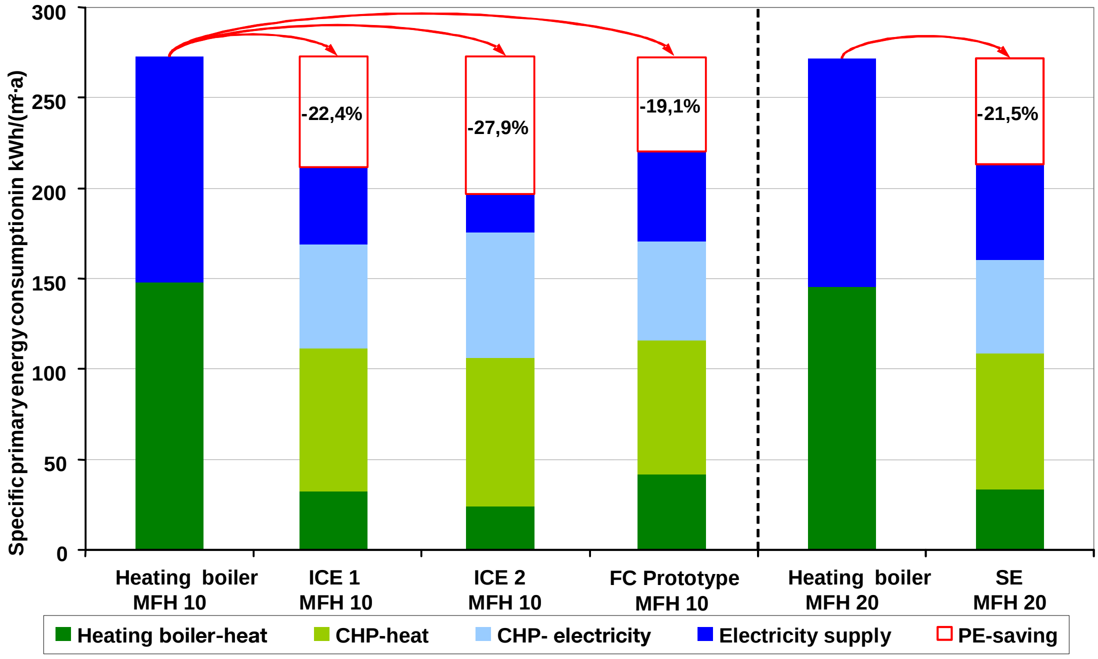

Figure 7-7: **Specific primary energy consumption of the energy supply of reference- and CHP alternatives (combination ‚stock')**

Figure 7-6 illustrates primary energy consumption of conventional energy supply with heating boilers and electricity supply as well as CHP alternatives with the reference alternative combination 'stock'. Note that the primary energy consumption of the CHP alternatives, which were necessary for energy supply were between 19,1 and 27,9 % below the 'stock' alternatives for separate electrical and thermal energy supply.

Considering the results on specific primary energy consumption presented in **Figure 7-7,** conventional alternatives were determined to consume 272,8 kWh/(m^2a) for MFH 10 and 271,5 kWh/(m^2a) for MFH 20. The specific primary energy consumption results of the CHP alternatives undercut this reference by 52,1 kWh/(m^2a) up to 76,0 kWh/(m^2a). CHP alternatives are different not only with regard to the amount of specific primary energy demand but also the breakdown of primary energy demand (i.e., types of primary energy sources used).

The results for CO_2 emissions are similar to primary energy consumption results. **Figure 7-8** shows CO_2-emissions of the energy supply for the 'stock' reference and the CHP alternatives. The CO_2 emissions of the CHP alternatives are between 21,8 and 31,3 % below the reference cases with separate energy supply.

Figure 7-9 illustrates specific CO_2 emissions of the energy supply for the 'stock' reference and the CHP alternatives. The reference cases cause a CO_2 discharge of 54,6 (MFH 10) and 54,4 kg/(m^2a) (MFH 20), respectively. The CO_2 emissions from the CHP alternatives are from 11,9 to 17,1 kg/(m^2a) below that.

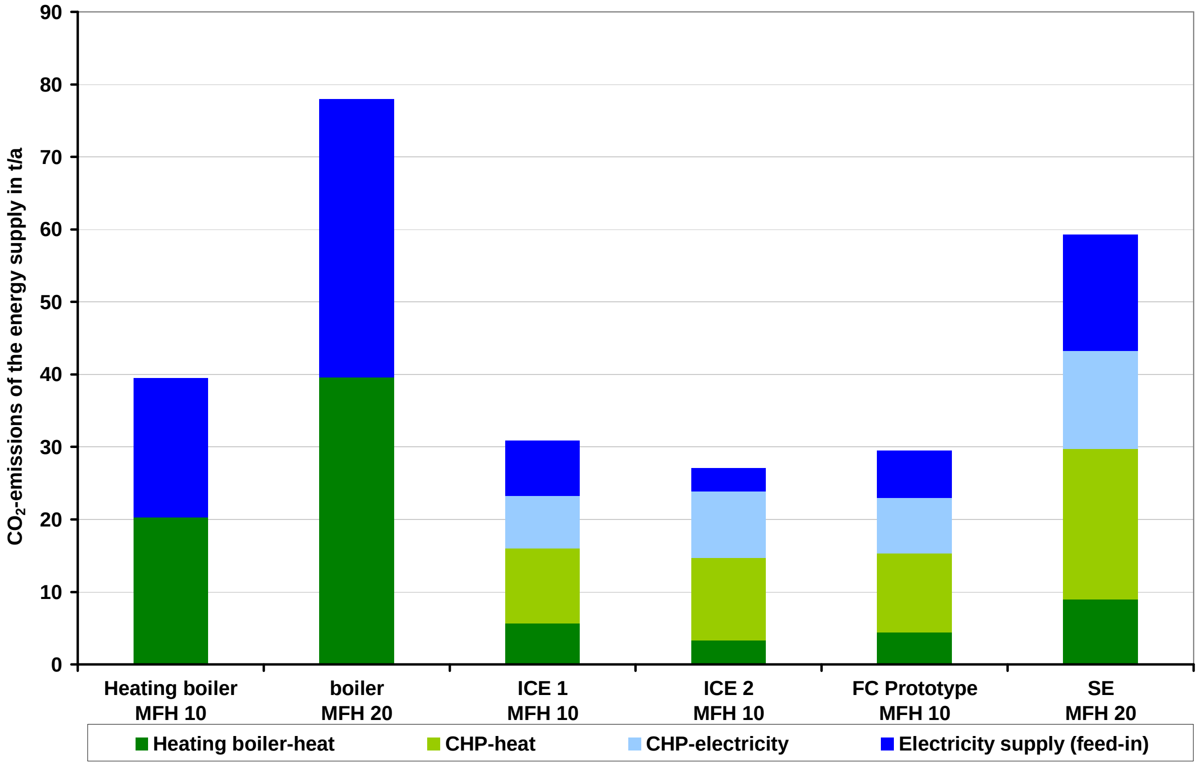

Figure 7-8: **CO_2-emissions of the energy supply of reference- and CHP alternative (combination ‚stock')**

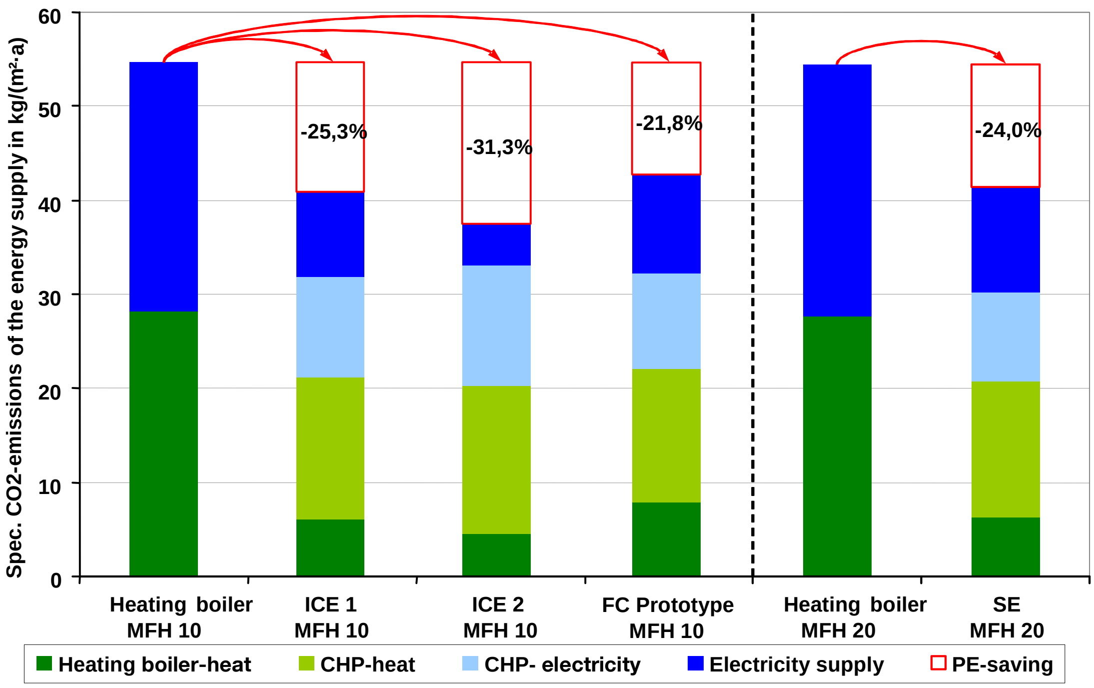

Figure 7-9: **Specific CO_2-emissions of the energy supply of reference- and CHP alternatives (combination ‚stock')**

All of the overall primary energy demand and CO_2-emissions results of conventional energy provision with heating boilers and grid electricity and the CHP alternatives are presented in **Table 7-16** Note that the CHP alternatives always provide positive primary energy use and CO2 emissions reductions compared to the reference cases. Note also that only the data marked in orange of the alternative ‘stock’ were considered and presented in Figure 7-6 through 7-9.

Less savings resulted from the reference combination ‚BVT’ since the energy supply of separate generation happened in an energy efficient way. However, the primary energy consumption of the CHP alternatives were between 5,2 and 13,5 % and CO_2-emissions between 5,9 and 13,5 % lower.

The greatest primary energy savings were between 18,0 and 26,4 % and CO_2-reductions between 29,0 and 40,9 % in the combination ‚EW’. Here, the maximum possible amounts of CHP electricity with the greatest specific CO_2-emissions were credited, which resulted almost in a CO_2-reduction by one third on average.

Table 7-16: Primary energy consumptions and CO_2-emission of the energy supply of the reference- and CHP alternative

	Reference alternative											
Supply system	**EW**				**Stock**				**BVT**			
	KEA MWh/a	Δ %	CO_2 t/a	Δ %	KEA MWh/a	Δ %	CO_2 t/a	Δ %	KEA MWh/a	Δ %	CO_2 t/a	Δ %
Heating boiler MFH 10	197,2	-	39,5	-	197,2	-	39,5	-	158,3	-	30,0	-
Heating boiler MFH 20	388,9	-	78,0	-	388,9	-	78,0	-	311,8	-	59,2	-
ICE 1 MFH 10	151,2	21,2	32,5	32,8	153,0	22,4	29,5	25,3	144,8	8,5	27,3	9,2
ICE 2 MFH 10	141,3	26,4	28,6	40,9	142,2	27,9	27,1	31,3	138,1	12,7	26,0	13,5
FC Prototype MFH 10	157,2	18,0	34,4	29,0	159,5	19,1	30,9	21,8	150,3	5,2	28,3	5,9
SE MFH 20	301,0	20,5	66,9	30,3	305,4	21,5	59,3	24,0	285,4	8,5	53,8	9,2

7.4.2 Comparison of primary energy and emissions of CHP-systems with equal power rating

To reduce the influence of the different power ratings of CHP systems, the comparison of the primary energy and emissions were conducted on the basis of CHP systems with equal power rating. Their energy amount is taken from the Table 6-4 in /Muehl 07/. All CHP systems were standardised to a maximum heat generation of 300 kWh/d or 12,5 $kW_{th.}$ In this case, it is not necessary to demonstrate both, the absolute and specific primary energy consumptions and CO_2-emissions respectively. The absolute values of primary energy consumption and the CO_2 emissions for CHP systems with equal power rating are listed in **Table 7-17** for the reference alternative ‘stock’. Furthermore, only one application, the MFH-10, is necessary to make the comparisons. Note that positive differences (Δ) in primary energy consumption and CO_2 emissions denote reductions due to use of CHP systems compared to the reference system.

Table 7-17: Primary energy consumptions and CO_2-emission of the CHP systems calculated to equal power rating

Supply system	KEA in MWh/a	Difference Δ in %	CO_2-Emissionen in t/a	Difference Δ in %
ICE 1	153,0	22,4	29,5	25,3
ICE 2	142,2	27,9	27,1	31,3
FC Prototype	159,5	19,1	30,9	21,8
SE	305,4	21,5	59,3	24,0

Figure 7-10 shows the specific primary energy consumption of the energy supply of the reference case 'stock' and the CHP alternatives with equal power rating in the same application. In principle, these results should exhibit the same trend as that presented inFigure 7-7. The measured CHP systems show similar reductions in primary energy consumption compared to the reference case, even when corrected for power rating. The only difference is that the primary energy consumption changes show less dispersion. The primary energy consumption of the CHP systems is between 20,1 and 26,2 % below the 273 kWh/(m^{2}a) of the reference alternative with heating boiler and grid electricity supply.

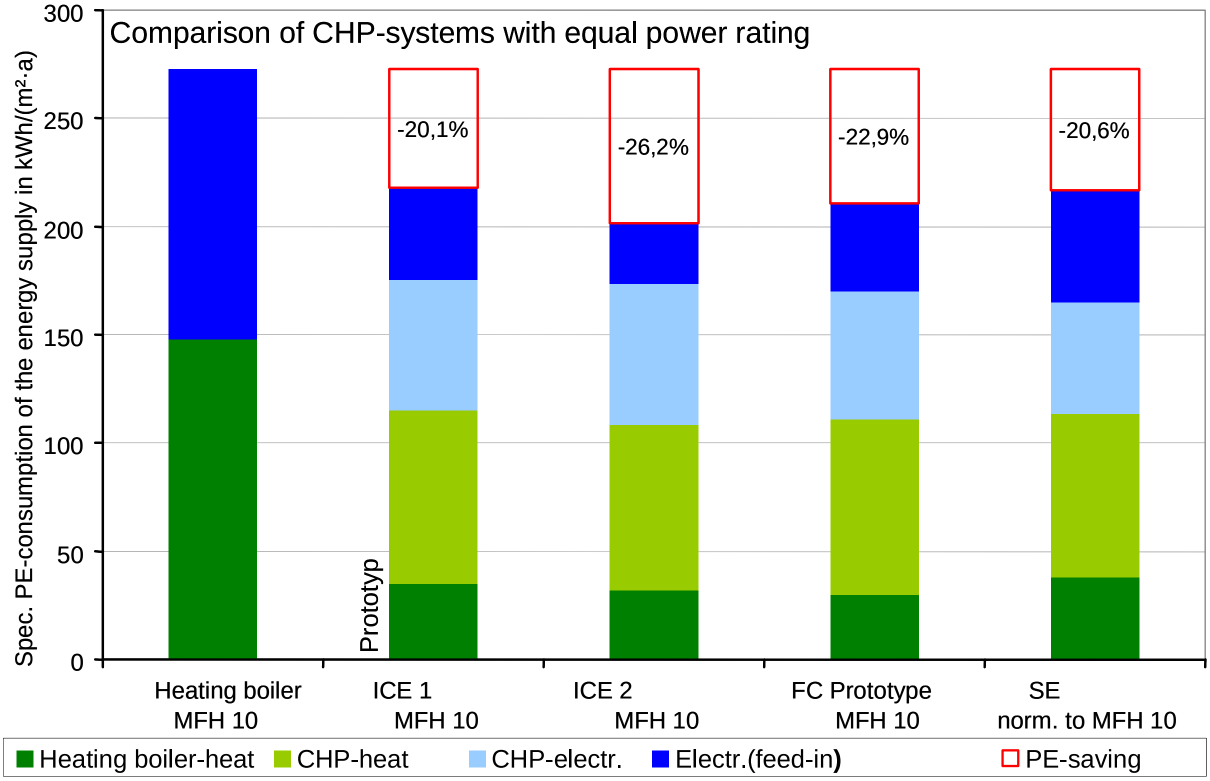

Figure 7-10: Specific primary energy consumption of the energy supply of reference and ‚same power' CHP- alternative (combination ‚stock')

The specific CO_2 emissions of the energy supply of the reference 'stock' and CHP alternatives with equal power rating are also in closer proximity in **Figure 7-11** due to the correction for power rating. The range is between 23,1 and 29,5 % below the specific CO_2 emissions of the reference alternative of around 55 kg/(m^{2}a).

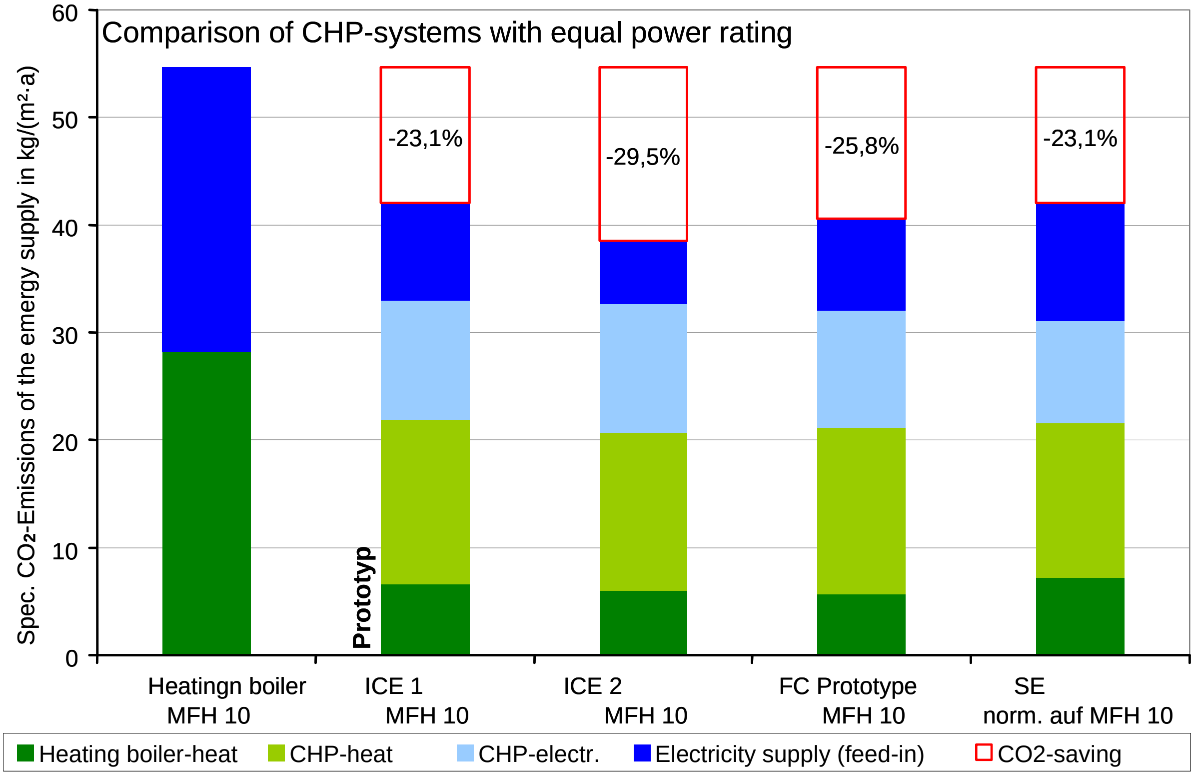

Figure 7-11: Specific CO_2-emissions of the energy supply of the reference- and CHP alternative with equal power rating (combination ‚stock')

7.5 Profitability analysis

There are different methods of the financial and investment theory that can be used to analyse the profitability of investments. The annuity method is valid for comparisons of different supply systems because respective total costs are given as annual costs that depend upon respective capital, operational and consumption costs.

7.5.1 Profitability of CHP-systems

Basic data

Within the scope of this project a method for the assessment of the profitability of CHP systems has been developed. The methods used include the actual cost of energy, net present value and amortisation methods presented in the previous sections.

Characteristic energy values and results from test rig trials and investment-[6)], assembly- and maintenance- costs checked with the manufacturers were taken as input data. The specific interest rate considered in all computations is 5 %.

The energy prices considered are average values of the German gas and electricity prices for household consumers in the year 2005. They were determined by the mixed prices (including basic price and tax) for electricity and gas household consumers that were published by /BdE 06/ as illustrated in **Figure 7-12**.

6) These are catalogue prices for the systems available on the market, for the PEM-fuel cell Euro 2 by Vaillant (prototype), costs of 15.00 € were applied.

Since the prices given were based on an annual consumption of 3.500 kWh electricity and 27.000 kWh gas respectively, an estimate of the partitioning of costs amongst basic, variable, and power costs had to be developed. The feed-in rate for CHP generated electricity was on average 10,08 ct/kWh in the year 2005. The energy costs listed in Table 5-18 influence the basic data in the profitability analysis.

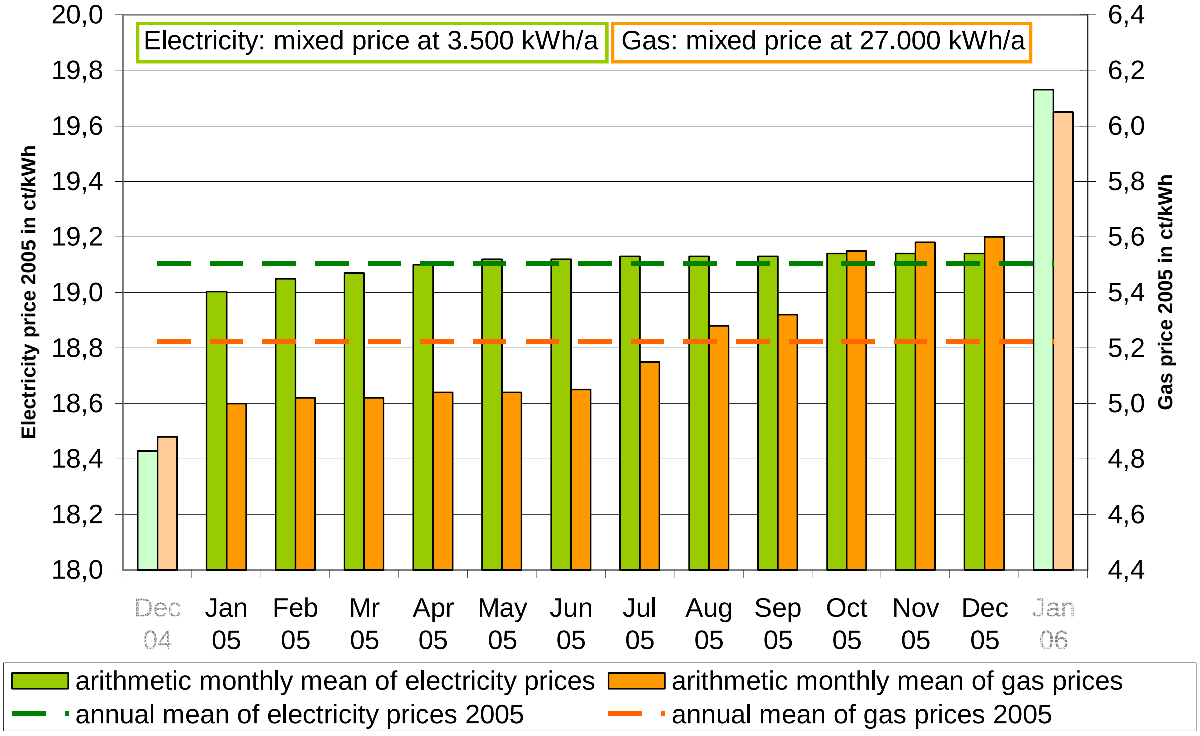

Figure 7-12: Mixed prices (including basic price and tax) for electricity and gas household consumers in the year 2005 /BdE 06/

Table 7-18: Basic data of the profitability analysis (mean values 2005)

	Variable costs	**Basic costs**	**Power costs**	**Feed in rate**
Unit	**ct/kWh**	**€/Month**	**€/(kW·Month)**	**ct/kWh**
Electricity	16,9	6,50	-	CHP surcharge: 5,11 Common price: 4,59 Comp. –payment: 0,38
Gas	Household clients: 4,3 CHP clients: 3,66	15,00	0,35	-

/BdE 06, KWKModG, EEX 07/

Respective results of the profitability analysis are illustrated in the following figures. The effects of price changes of electricity and gas are considered in sensitivity analyses subsequently.

Annual costs

The annual costs of the energy supply shown in **Figure 7-13** are split up into asset, variable, and consumption costs. The example illustrates the results for the CHP-electricity alternative called the 'User-model'. For the "User-model" annual costs of all CHP alternatives are below the annual costs of the corresponding reference cases. The asset and variable costs are greater compared to the CHP systems, which in turn are more expensive than heating boilers. This is compensated, however, by significantly lower variable costs. The annual costs of the CHP systems are in the range of 5,2 and 15,4 % below the annual costs of the reference systems.

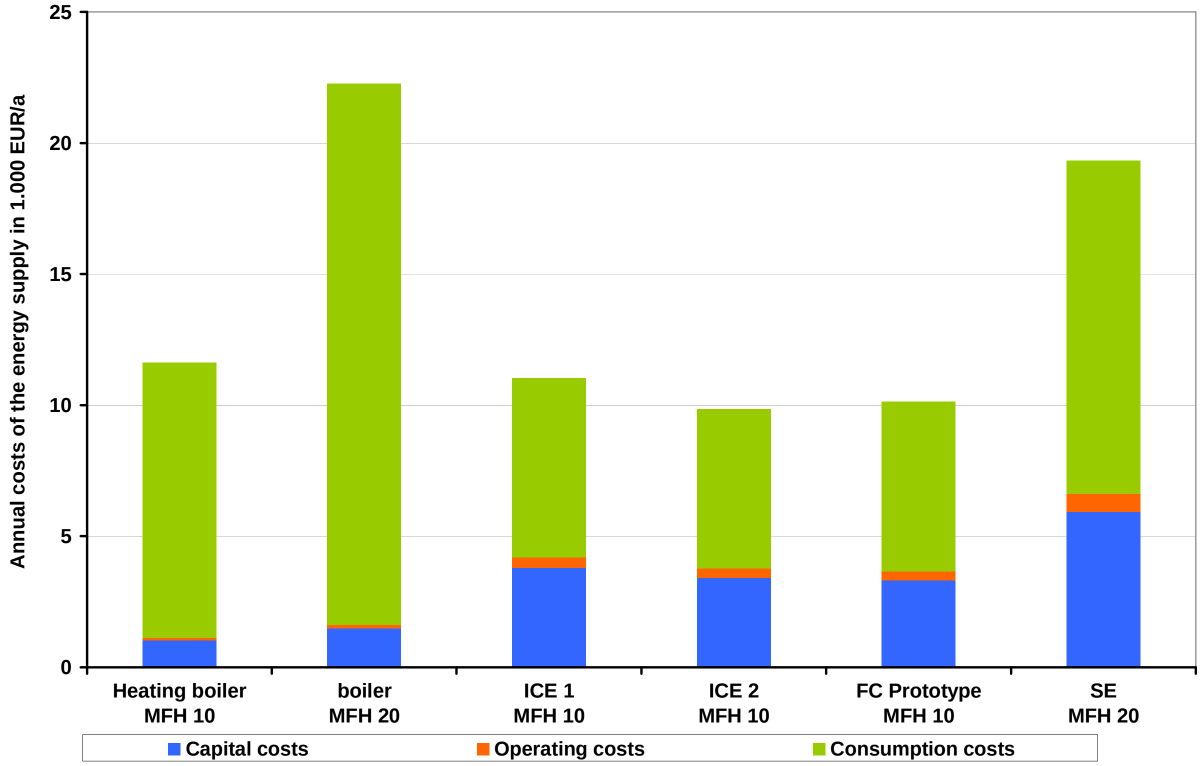

Figure 7-13: Annual costs of the energy supply of the reference and CHP-alternative (‚User'-model)

To account for the size of the residence, the annual costs are related to (divided by) the effective area of a multifamily residence, resulting in comparable specific annual costs as shown in **Figure 7-14**. The cheapest alternatives on a specific annual cost basis are the CHP systems of ICE 2 and SE, which cost around 13,5 €/(m^2a). The other CHP systems cost between 14 (FC Prototype) and 15,3 €/(m^2a) (ICE 1). The reference alternatives are 15,5 (MFH 20) and 16,1 €/(m^2a) (MFH 10),which are more expensive than the CHP alternatives.

Since the profitability analysis always considers the costs of the energy supply for electricity and heat, the selection of the CHP-electricity alternative needs to be considered. In the "User model", CHP-produced electricity is used to the extent available for domestic consumption. The excess electricity is fed into the grid and subsequently sold back to the utility. Domestic electricity demand beyond the one provided by the CHP system is met by the grid.

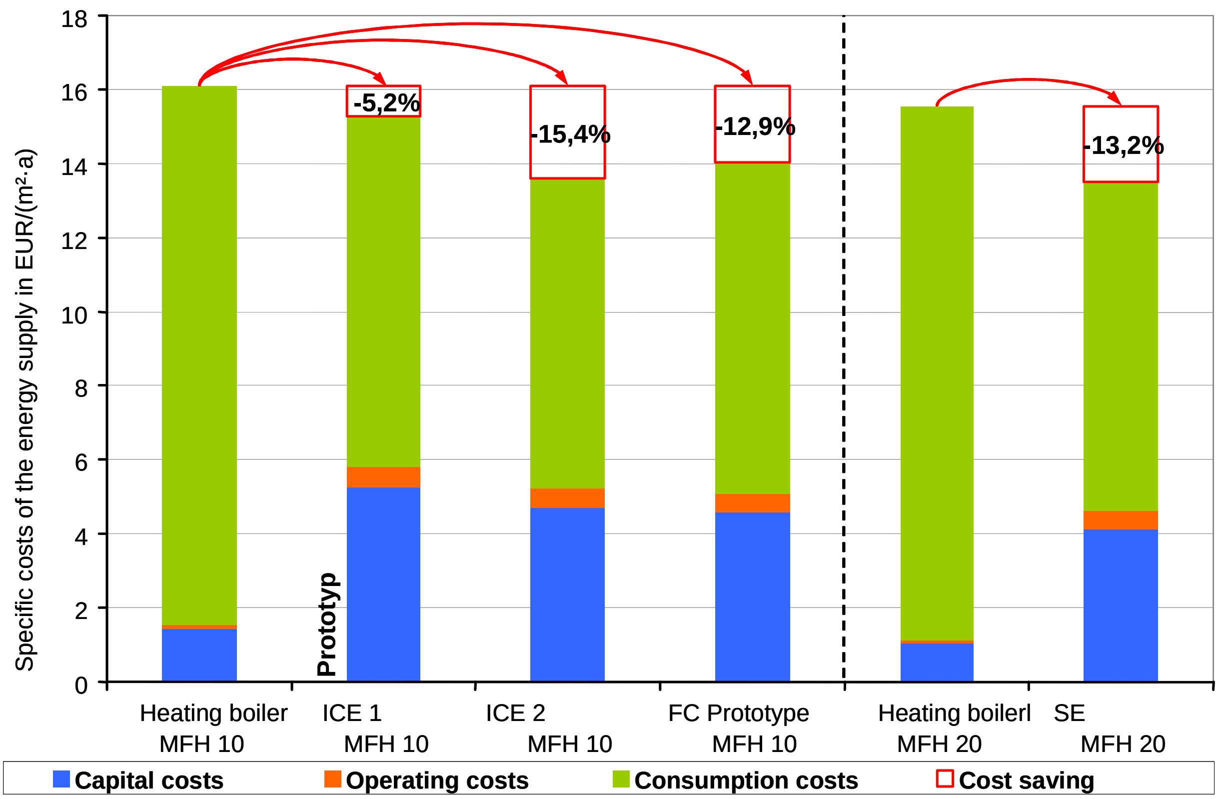

Figure 7-14: Specific annual costs of the energy supply of the reference and CHP-alternative (‚User'-model)

The general electricity model implies that only the collectively used energy in a given multi-family house, such as e.g. the light in the hallway, is supplied by the CHP device. In contrast, in the complete feed-in model the CHP produced electricity is entirely fed into the grid and then sold back to the utility. **Table 7-19** lists the absolute and specific annual costs of the conventional heating boiler/electricity supply alternative and the CHP systems. The energy supply with CHP systems is only cheaper than the conventional alternative if the majority of the generated CHP electricity can be used directly. This is only possible with the "User-model". The energy supply costs of the CHP systems in the 'General electricity' model are between 0 and 9,3 % higher than the conventional alternatives, and are between 1,9 and 11,2 % more expensive than conventional alternatives with the 'Complete feed-in'-model.

The breakdown by percentage of the investment and assembly costs of the reference and CHP alternatives is shown in the 'User model' in **Figure 7-15** the primary (left-hand) axis. Considering the conventional alternatives, the heating boiler dominates the investment costs with 69 and 75 % for the MFH20 and MFH10 cases respectively. The CHP alternatives investment costs are between 56 and 64 % of the total. The second largest portion of the CHP alternative investment is the peak boiler investment, which ranges from 12 to 18 % of the total investment. The remaining 23 to 25 % of the investments go to the other components of the CHP system, e.g., the storage facility and connections. The absolute investment and assembly costs of the reference and CHP alternatives are illustrated in Figure 7-15 on the secondary (right-hand) axis (pale areas).

Table 7-19: Absolute and specific annual costs of the energy supply

		Supply system	Capital costs €	Capital costs €/m²	Operating costs €	Operating costs €/m²	Consumption costs €	Consumption costs €/m²	Total €	Total €/m²
		Boiler MFH 10	**1.032**	**1,43**	**92**	**0,1**	**10.505**	**14,5**	**11.628**	**16,1**
		Boiler MFH 20	**1.482**	**1,03**	**127**	**0,1**	**20.661**	**14,4**	**22.271**	**15,5**
CHP-electricity-alternative	User	**ICE 1**	**3.310**	**4,6**	**354**	**0,5**	**6.465**	**8,9**	**10.129**	**14,0**
		ICE 2	**3.409**	**4,7**	**367**	**0,5**	**6.064**	**8,4**	**9.840**	**13,6**
		FC prototype	**3.786**	**5,2**	**413**	**0,6**	**6.829**	**9,4**	**11.029**	**15,3**
		SE	**5.931**	**4,1**	**685**	**0,5**	**12.717**	**8,9**	**19.333**	**13,5**
	General elec-	**ICE 1**	**3.244**	**4,5**	**352**	**0,5**	**8.393**	**11,6**	**11.989**	**16,6**
		ICE 2	**3.343**	**4,6**	**365**	**0,5**	**7.996**	**11,1**	**11.704**	**16,2**
		FC prototype	**3.721**	**5,1**	**411**	**0,6**	**8.661**	**12,0**	**12.793**	**17,7**
		SE	**5.800**	**4,0**	**681**	**0,5**	**15.582**	**10,9**	**22.062**	**15,4**
	Complete	**ICE 1**	**3.244**	**4,5**	**352**	**0,5**	**8.599**	**11,9**	**12.195**	**16,9**
		ICE 2	**3.343**	**4,6**	**365**	**0,5**	**8.202**	**11,3**	**11.910**	**16,5**
		FC prototype	**3.721**	**5,1**	**411**	**0,6**	**8.856**	**12,3**	**12.988**	**18,0**
		SE	**5.800**	**4,0**	**681**	**0,5**	**15.891**	**11,1**	**22.372**	**15,6**

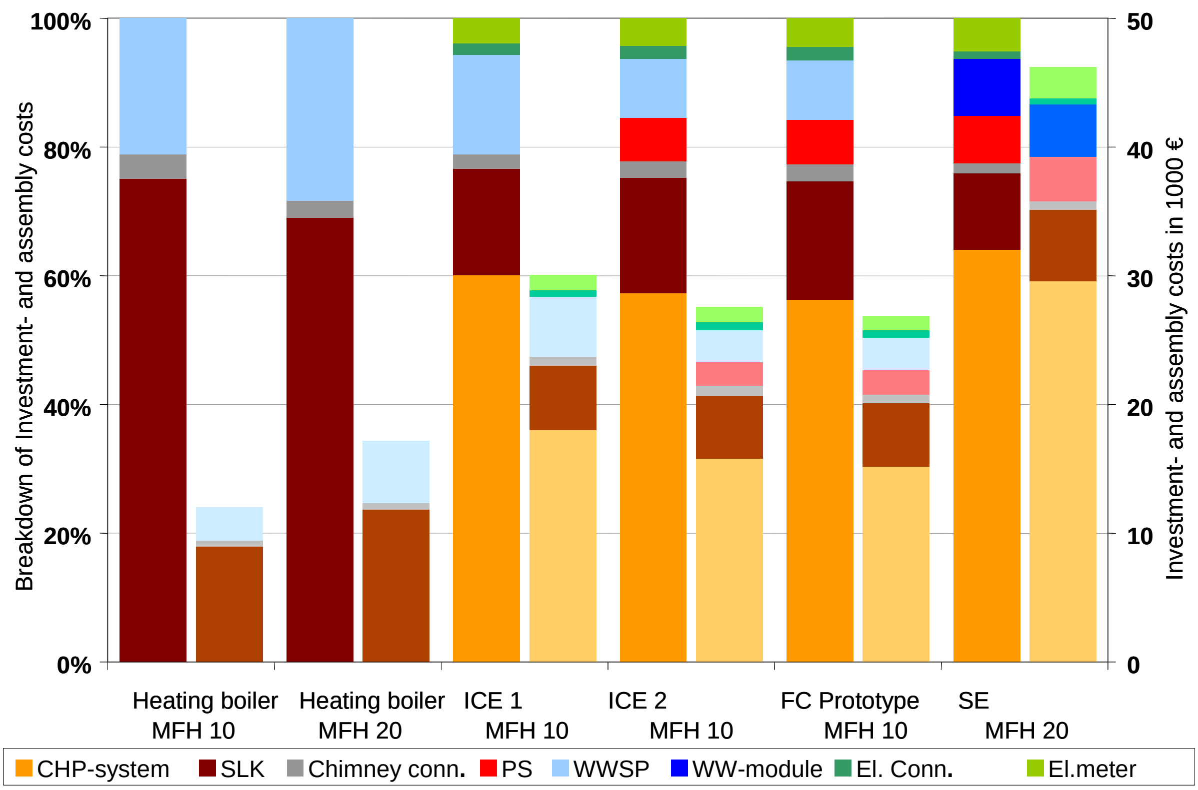

Figure 7-15: Percentaged breakdown (primary axis) and absolute values (secondary axis) of the investment and assembly costs of the reference- and CHP alternative (‚User' model)

Actual costs of energy

The profitability results presented above can be clarified through use of actual costs of energy analyses such as that presented in **Figure 7-16**. Actual costs of electricity (light blue) and heat (light green) of the CHP systems are presented in comparison to the actual costs of the conventional alternative with electricity supply (blue) and heat generation by boiler (green). The cost allocation of the CHP systems was conducted by means of the efficiency method (see /Arn 07/). At first glance, the actual costs of CHP systems are 3,9 to 19,9 % below the actual costs of the separate conventional supply, which suggests economical operation of the CHP systems. But these analyses assumed that the generated electricity from the CHP systems substitutes most of the electricity supply from the grid. If the actual costs for CHP electricity generation of 15,8 to 18,9 ct/kWh are not compared with the mixed price for electricity supply of 19,6 ct/kWh on average ('User-model'), but otherwise compared to the CHP feed-in tariff of 10,08 ct/kWh (see

Table 7-18) ('Feed-in-model'), an economical operation is difficult to achieve.

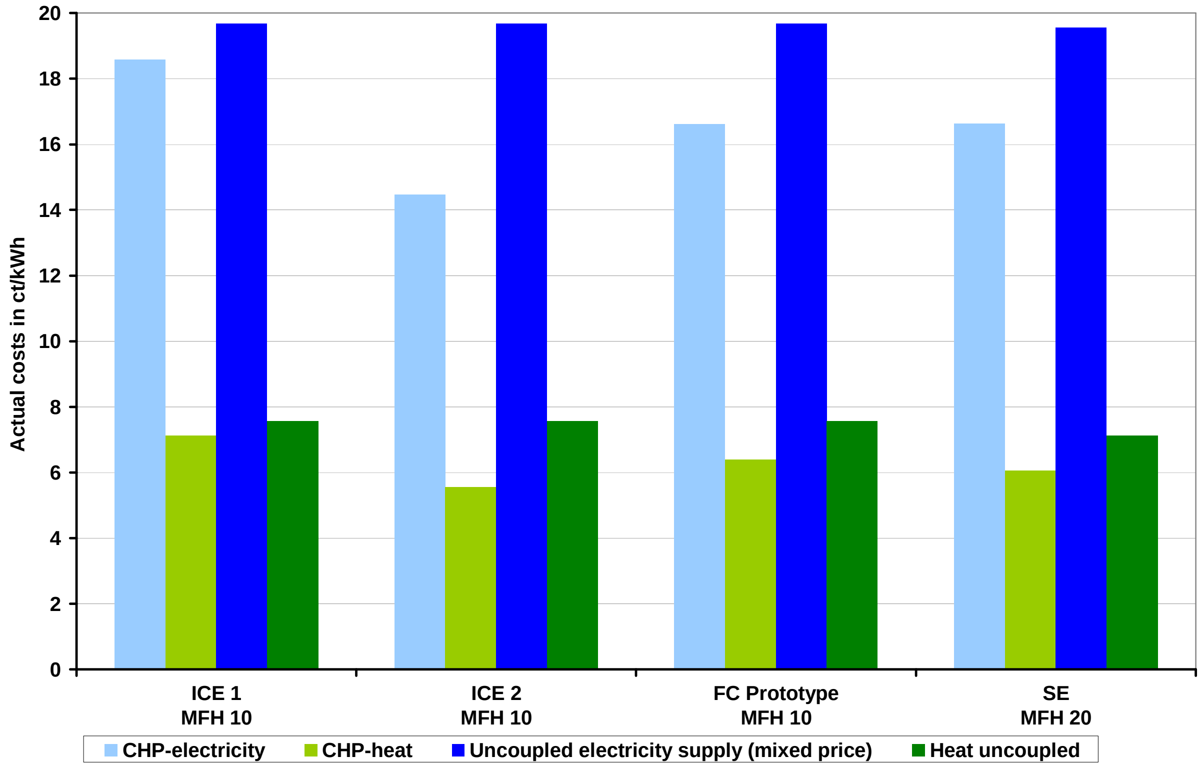

Figure 7-16: Actual costs of energy of the CHP alternatives in comparison with the reference

Amortisation

A quick estimate of the profitability of CHP systems is provided by means of the payback period. **Figure 7-17** shows the standardised net present value (net present value divided by net present value at the beginning of the useful life) and the expected useful life of a CHP system of 15 years (/VDI 2067-1/). The zero crossing indicates the payback period of these CHP systems, which is between 7,6 and 10,8 years. These analyses are presented for CHP systems considering the 'User-model.' Neither the 'General electricity' nor the 'Complete feed-in' model cases reach a zero amortisation before the end of the CHP system useful life.

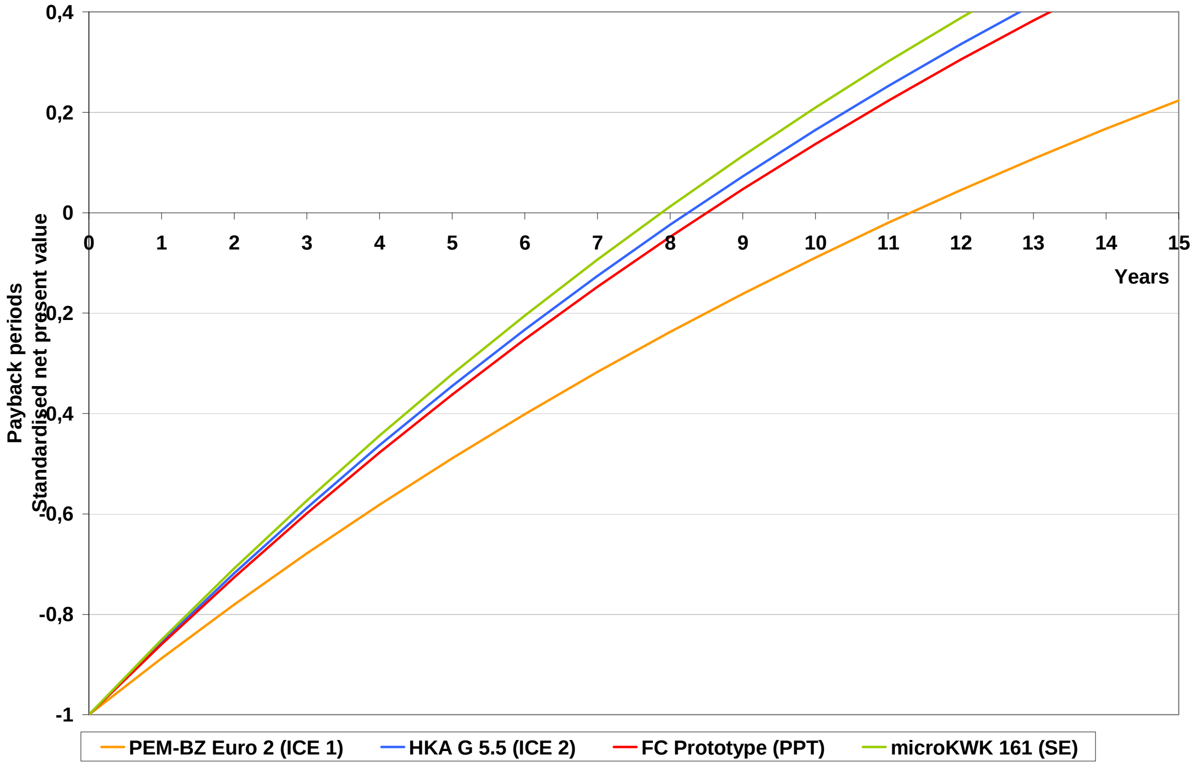

Figure 7-17: Payback periods of CHP-systems on the basis of standardised net present value (‚User' model, reference ‚Stock')

Sensitivity of electricity and gas price development

The previous analyses are based on the assumption that energy prices remain constant. Recent history shows that energy prices are likely to increase in the long term. This is shown by the price monitoring data of the Federal Statistical Office as shown in **Figure 7-18**.

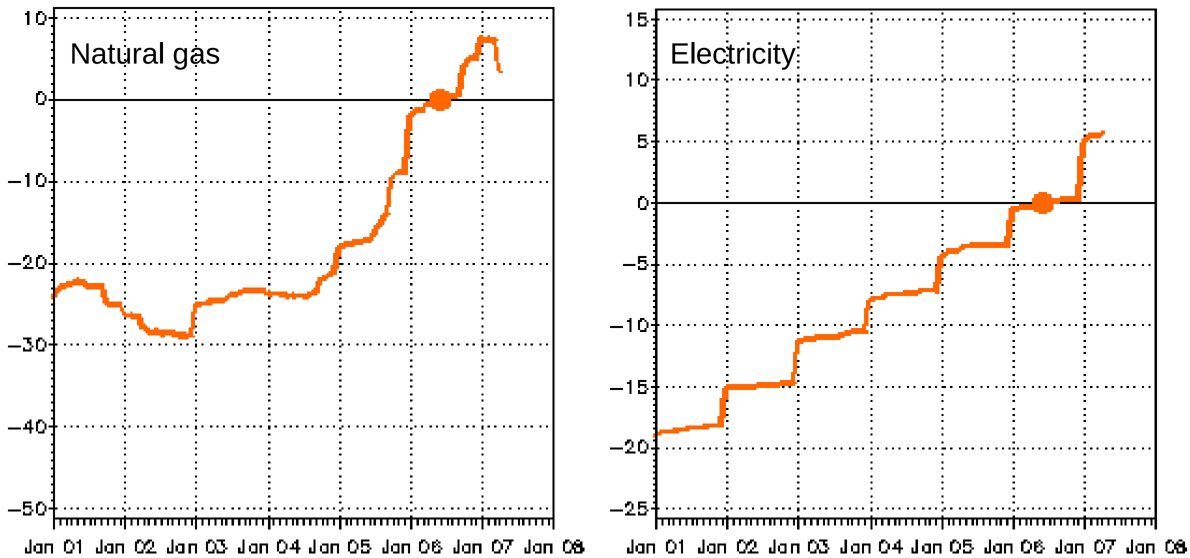

Figure 7-18: Gas and electricity price trends from 2001 until 2007 (Price changes in percent compared to June 2006) /Destatis 07/

The effects of electricity and gas price changes for the operation of CHP-systems are different. **Figure 7-19** illustrates the payback periods of four CHP-systems in the 'User' model depending on electricity and gas price alterations. The reference alternative for separate energy supply is the combination 'Stock'. The intersection without price alterations describes the basic case (rear corner of the 3D-area). Here, the payback periods of the CHP-systems are between 7,8 and 11 years. Further sampling points are annual price increases of respectively 2,6 and 10 %. It becomes clear that the operation of CHP-systems benefits from energy price increases, even though with varying intensity. Considering for instance the 3D graphics of FC Prototype in Figure 7-19 (left, bottom), the payback period drops from 8,3 years to 7,5 years (based on the basic case) at a gas price rise of 10 %/a. For an electricity price rise of 10 %/a the payback period drops to 6,4 years. If both price increases happen, the payback period is reduced to 6,1 years.

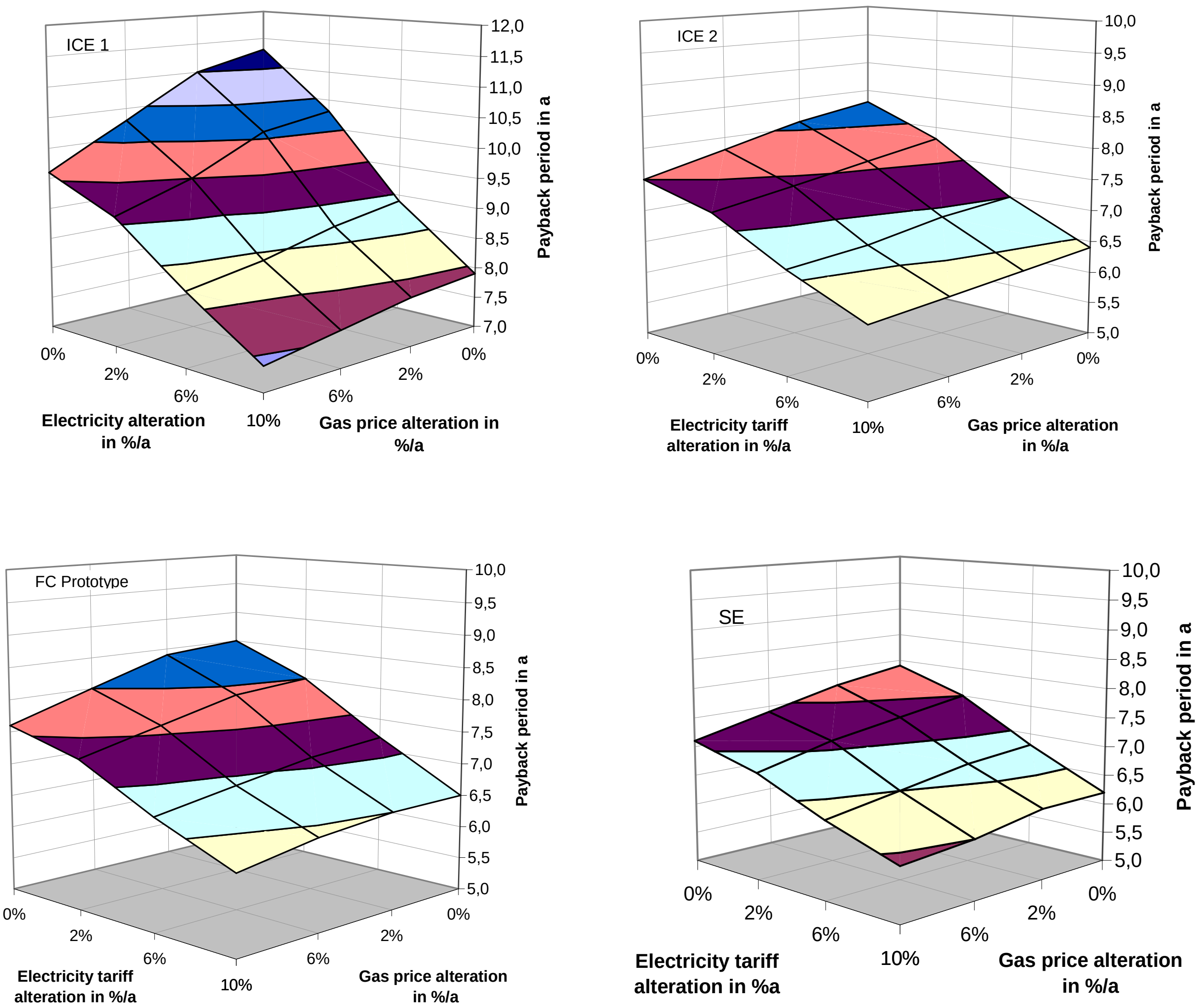

Figure 7-19: Sensitivity of payback periods with varying electricity and gas price changes (‚User' model, reference 'Stock')

The different effects of electricity and gas price alterations can be explained as follows:

The gas price increases affect the CHP systems production of both electricity and heat. But, in comparison with the reference alternative ‘Stock’ it is a more efficient way of using gas energy to produce electricity and heat resulting in a positive reduction in the payback period for CHP systems.

When the price of electricity increases, the more expensive electricity supply from the grid can be substituted with the operation of the CHP systems, which results in a reduction in the payback period of the CHP systems.

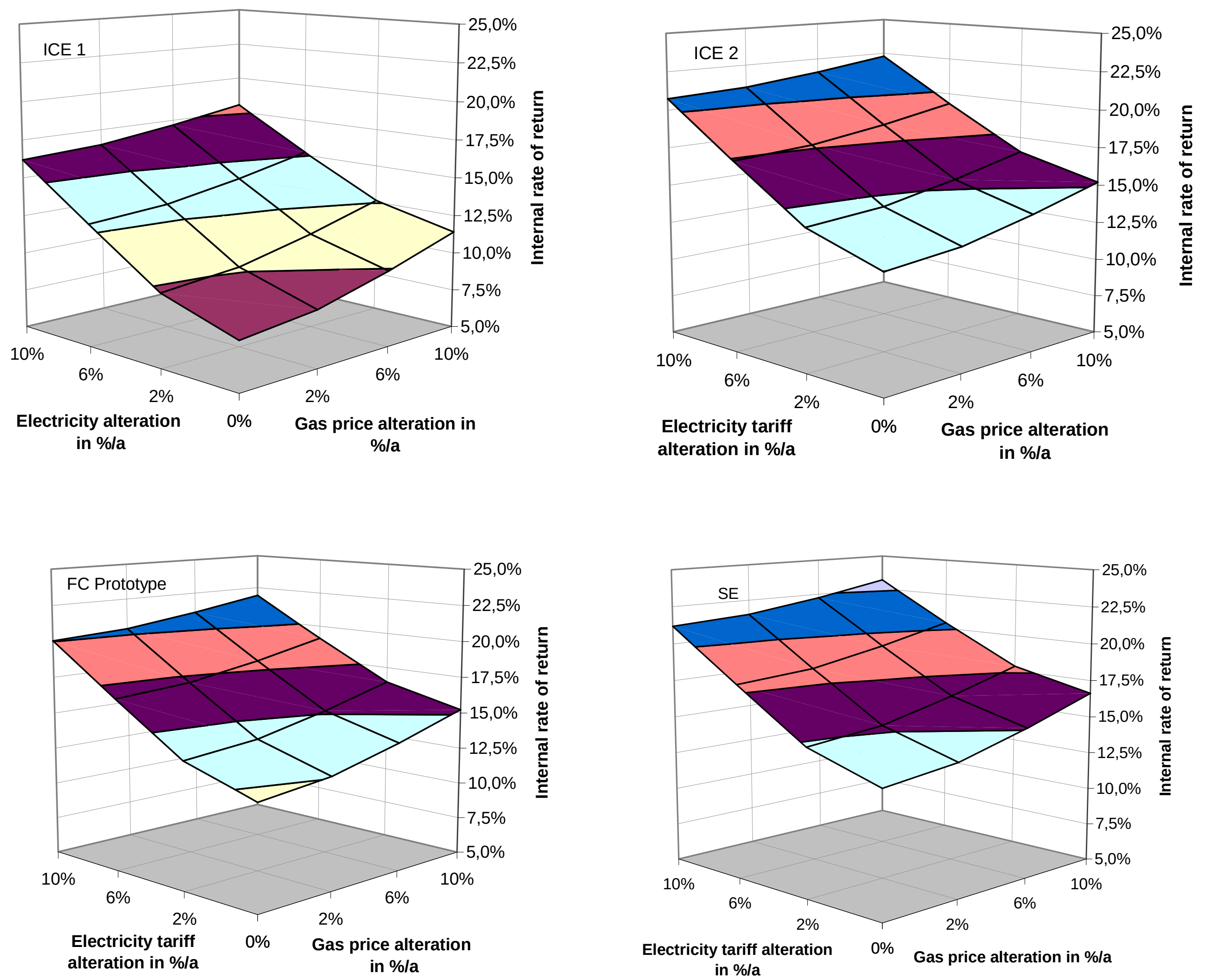

Figure 7-20: Sensitivity of the internal rate of return of various electricity and gas price alterations (‚User’ model, reference ‚Stock’)

Figure 7-20 shows the internal rate of return (IRR) of the four CHP systems in the ‘User’ model as it depends upon electricity and gas price variations (using the reference ‘Stock’). The basic case without price variations is at the front corner of the 3D plots. The internal rate of return values are in the range of 8,5 and 13,4 % and increase to 18,4 and 23,4 % for the case when annual energy prices increase at 10 %/a. The basic correlations of the effects of electricity and gas price increases as described in the payback period section are also true for internal rate of return.

Table 7-20: Payback periods and IRRs of the CHP-systems depending on CHP-electricity-alternatives and reference systems

	CHP- system	Reference alternatives			
		EW and stock		BVT	
		t_{amort} in a	IRR in %	t_{amort} in a	IRR in %
User	ICE 1	8,3/6,1	12,4/22,3	10,3/7,0	9,4/19,2
	ICE 2	8,1/6,0	12,8/22,7	9,9/6,8	9,9/19,7
	FC Prototype	11,0/7,3	8,5/18,4	14,3/8,5	5,5/15,4
	SE	7,8/5,8	13,4/23,4	9,8/6,8	10,1/20,0
General electricity	ICE 1	-/13,3	<0/7,1	-/-	<0/0,9
	ICE 2	-/12,5	<0/8,0	-/-	<0/2,3
	FC Prototype	-/-	<0/3,7	-/-	<0/<0
	SE	-/10,7	<0/10,7	-/15,0	<0/5,0
Complete feed-in	ICE 1	-/-	<0/4,4	-/-	<0/<0
	ICE 2	-/14,5	<0/5,5	-/-	<0/<0
	FC Prototype	-/-	<0/1,0	-/-	<0/<0
	SE	-/12,0	<0/8,7	-/-	<0/2,2

1. Value.. basic case / 2. value.. 10 %/a price increase

Considering the ‘Complete feed-in’ or ‘General electricity’ models with the current feed-in tariff, there are almost no economically favourable results for the payback period and the IRR. **Table 7-20** shows the payback periods and IRRs of the CHP systems as a function of the CHP-electricity alternative and the reference system. The reference alternatives ‘EW’ and ‘Stock’ can be considered together as they possess the same heat generation reference. There are only few payback periods that are shorter than the useful life when there is an annual price increase of 10 %/a for both gas and electricity.

Sensitivity of the profitability to investment costs and the feed-in tariff

Operation of the CHP system alternatives in the ‘Complete feed-in’ model cannot be made profitable under current circumstances of price (investment costs) and feed-in tariff. However, reductions in the investment cost of CHP systems may make them profitable in the ‘Complete feed-in’ model. The degree to which the investment costs of respective CHP systems need to be reduced must be identified so that the amortisation lies within the useful life time of 15 years and an IRR of at least 5 % can be achieved. The left column of **Table 7-21** lists, in percentage terms, the required reductions in investment costs that are required of each of the CHP systems. An economical operation would be possible even in the ‘Complete feed-in’ model if the investment costs of the CHP systems were 10 to 44 % lower.

The second parameter of interest in this sensitivity analysis is the amount of money one garners from provision of CHP electricity to the grid (‘feed-in’). Since policies desire the efficiency increases and CO_2-reductions that can be garnered by use of CHP, they should be designed to maximize the amount of cogenerated electricity independent of the feed-in tariff value. Note that the effects of the feed-in tariff are negligible if most (or all) of the CHP electricity is used in the building itself with supplemental electricity provided by the utility grid. What remains to be identified is the value of the feed-in tariff (usual price, avoided grid use and CHP-bonus) that makes the simpler ‘Complete feed-in’ model possible (that is profitable). Therefore, the sensitivity of the CHP system profitability to the feed-in tariff was considered and is provided in the right column of Table 7-21. The values indicate the break-even point of the economical operation of each of the CHP systems in the ‘Complete feed-in’ model. If the feed-in tariffs for the CHP systems were between 11,8 to 19,4 ct/kWh_{el}, an economical operation of the ‘Complete feed-in’ model would be possible.

Table 7-21: Required reduction of the CHP-system costs and feed-in tariff respectively for an economical operation in the ‚Complete feed-in’ model

CHP- system	Reduction of the investment costs in %	Feed-in tariff in ct/kWh
ICE 1	28	14,9
ICE 2	19	12,7
FC Prototype	44	19,4
SE	10	11,8

7.6 Summary of the comparison of systems

The comparison of CHP systems as installed in residential co-generation applications to similar facilities with separate, conventional energy supply illustrates that the CHP alternatives have a lower primary energy consumption and CO_2 discharge. The CHP alternatives are only economically viable, however, when the energy supply of the CHP system is completely used in the building (‘User’ model) as shown by reasonable payback periods and internal rates of return.

There are differences amongst the CHP alternatives with regard to the amount and breakdown of the specific primary energy consumption, CO_2 emissions and costs. Table 6-1 shows various factors that affect performance and profitability. Data was evaluated on the basis of the objects MFH 10 and 20. Therefore the results of the comparison of the CHP systems are not directly transferable on other objects (applications), but should be representative of other residential applications of interest. The accuracy and precision of control strategies used by the CHP systems have not been taken into consideration in the current analyses, which could affect the results achieved in practice.

Share of the thermal power on the power load of the building $P_{th,CHP}/P_{building}$

The selected approach to design the building so that the thermal power of the CHP system equals 25 % of the building’s power load well-represents the actual output of the various CHP systems tested, which range from 25,3 % down to 21,5 % of the total building power.

Electrical CHP-demand fraction

The fraction of the total building electrical demand that is met by usable CHP-electricity varies a-mongst the CHP systems tested. The CHP systems tested can cover 55,1 55,6 %, and just under 61 % of the total building electricity demand. Hence, the remaining electricity that must be supplied to the building is lower than the amount of thermal energy that must be separately supplied to the building to meet demand for all of the CHP systems studied herein.

Electrical CHP- production fraction

On the basis of the electrical CHP-production fraction $d_{el,CHP,Prod.,}$ the modulation of CHP-systems is identifiable. Modulating CHP-systems show 91,9 up to 94,8 % since the electricity demand can be covered by CHP-systems by night at least throughout the heating period. Accordingly the CHP feed-in is low. The ICE 2 device shows an $d_{el,CHP,Prod.}$ of 73,2 %. Another supporting criterion is the greater CHP coefficient of this device which is higher in comparison with other CHP-systems. That means that the ICE 2 device generates more electricity with the same heat production.

Thermal CHP fraction

The thermal CHP fraction shows the share of heat generation of the CHP-system in relation to the heat demand of the building. For ICE 2 it is 85,3 %, for ICE 1 78,5 % and 76,6 % for the SE system. The remaining share needs to be covered by the peak boiler which leads to an overall result of greater primary energy consumption and CO_2 discharge.

Primary energy and CO_2-Emissions

The comparison of systems confirms that the implementation of CHP in comparison to the current separate generation of electricity and heat saves primary energy and CO_2-emissions. The results are listed in **Table 7-22** specific primary energy demands, CO_2-emissions and costs for the energy supply of the reference and CHP alternatives.

The primary energy consumption of the considered CHP systems (including peak boiler and storage) lie in the range of 19,1 to 27,9 % below the ‘Stock’ reference alternative with separate energy provision. There is an even greater reduction effect with regard to the CO_2-emissions of the CHP alternatives. The CO_2-emissions of CHP systems are between 21,8 and 31,3 % less than current separate provision of electricity and heat. Even with the reference alternative ‘best available technology’ (BVT), the primary energy consumption of CHP systems is lower by 5,2 to 12,7 % and CO_2-emissions are 5,9 to 13,5 % lower than the highly efficient separate energy supply. The greatest CO_2-reductions of CHP systems can be achieved by comparison to the reference alternative ‘EW’ (up to 40,9 %).

Table 7-22 Specific primary energy consumptions, CO_2-emissions and costs of energy supply of the reference- and CHP alternatives on the basis of 10-family houses

				Supply system	
Reference alternative	**CHP-electricity-model**	Size	Unit	Separate supply: heating boiler / electricity supply	CHP-alternatives
EW	↓	KEA	MWh/(m²·a)	264,2 – 265,5	195,5 – 217,8
		Δ	%	-	18,0 – 26,4
		CO_2	t/(m²·a)	66,8 – 66,9	39,6 – 47,6
		Δ	%	-	29,0 – 40,9
Stock		KEA	MWh/(m²·a)	271,5 – 272,8	196,7 – 220,7
		Δ	%	-	19,1 – 27,9
		CO_2	t/(m²·a)	54,4 – 54,6	37,5 – 42,7
		Δ	%	-	21,8 – 31,3
BVT		KEA	MWh/(m²·a)	217,7 – 219,0	191,1 – 207,6
		Δ	%	-	5,2 – 12,7
		CO_2	t/(m²·a)	41,3 – 41,6	36,0 – 39,1
		Δ	%	-	5,9 – 13,5
	User	k_{ges}	€/(m²·a)	15,5 – 16,1	13,5 – 15,3
		Δ	%	-	5,2 – 15,4
	General electricity	k_{ges}	€/(m²·a)	15,5 – 16,1	15,4 – 17,7
		Δ	%	-	-10,0 – 0,9
	Complete feed-in	k_{ges}	€/(m²·a)	15,5 – 16,1	15,6 – 18,0
		Δ	%	-	-11,7 – -0,5

From the economical point of view the only profitable CHP system use condition are those represented by the ‚User' model. The annual costs of the CHP systems are then between 5,2 and 15,4 % below the annual costs of the 'User' reference alternatives and the simple payback period of the CHP systems ranges from 7,9 to 11,3 years. The profitability of CHP systems increases with rising electricity- and gas prices.

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