Performance Assessment of Residential Cogeneration Systems in Switzerland

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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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 (OECD) to implement an international energy programme. A basic aim of the IEA is to foster co-operation among the twenty-four IEA participating countries and to increase energy security through energy conservation, development of alternative energy sources and energy research, development and demonstration (RD&D).

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 ECBCS - Energy Conservation for Building and Community Systems Programme, 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 commercialisation. The objectives of collaborative work within the ECBCS R&D programme are directly derived from the on-going energy and environmental challenges facing IEA countries in the area of construction, energy market and research. 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;
- integration of building energy measures and tools to changes in lifestyles, work environment alternatives, and business environment.

The Executive Committee

Overall control of the programme 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 (*)):

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: Multi Zone 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 Tool-kit 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 (*)

(*) - Completed

Annex 42

The objectives of Annex 42 are 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 is being accomplished by developing and incorporating models of cogeneration devices and associated plant components within existing whole-building simulation programs. Emphasis is placed upon fuel cell cogeneration systems and the Annex considers technologies suitable for use in new and existing single and low-rise-multi-family residential dwellings. The models are being developed at a time resolution that is appropriate for whole-building simulation.

To accomplish these objectives Annex 42 is conducting research and development in 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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Viktor Dorer
Subtask C Leader

CONTENT

1 SUMMARY

A performance assessment study has been made for a number of micro combined heat and power generation (MCHP) systems in residential buildings in Switzerland. This study is part of Subtask C of the IEA/ECBCS Annex 42 “FC+COGEN-SIM The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems”.

The performance in terms of non-renewable primary energy (NRPE) demand and of CO_2-equivalent (CO_2-eq) emissions was analysed for different cogenerations technologies, namely natural gas fuelled solid oxide (SOFC) and polymer electrolyte membrane fuel cells (PEMFC), Stirling (SE) and internal combustion engines (ICE), and compared to a reference system which is a gas boiler and electricity supply from the grid. A ground source heat pump system was also analysed for comparison. Prototype and commercially available residential cogeneration units were considered, using measured performance data and assumed data (extrapolated from measured data).

The cogeneration units were integrated in single-family houses (SFH) and multi-family houses (MFH) of three energy standards (Swiss average, target values in present building code of the Swiss Engineers and Architects Association (SIA target), and Passive House (PH) standard). Three different electricity generation mixes were considered: average European according UCTE (Union for the Co-ordination of Transmission of Electricity); Swiss; and combined cycle power plant (CCPP). The simulations were conducted for one Swiss location (Zurich) using the whole-building simulation tool TRNSYS, and using the standard domestic hot water and electric demand profiles specified within this Annex. For the cogeneration systems, detailed dynamic component models and calibration data developed within Annex 42 were used (Beausoleil-Morrison 2007) in cases where enough detailed performance data of the residential cogeneration device were available. For the other cases simplified performance map models had to be employed, calibrated with results from laboratory experiments, conducted within Annex 42 with prototype or commercially available micro cogeneration units, calibrated with manufacturer data, or with assumed performance data. Thus, for the latter cases, the dynamic effects of start-up and shut-down were not considered.

Compared to the gas boiler/grid electricity reference system, NRPE reductions were achieved with most MCHP systems, with reductions up to 34% for the UCTE mix. Such large reductions were primarily an effect of the surplus electricity generation, which was considered as a bonus and thus was subtracted from the primary energy demand value associated with the delivered energy to the house. But also systems with no surplus electricity generation offered reductions >10%. However, for the Swiss and the CCPP mixes, the largest NRPE reductions resulted for the ground coupled heat pump systems (up to 29%). The maximum reduction with a MCHP system was 14%.

The comparison in terms of CO_2-eq emission was, as expected, strongly dependant on the grid electricity emission factor. Most MCHP systems offered reductions for the UCTE electricity mix, up to 23%. However, maximum reductions resulted for the heat pump system (24%). For the Swiss mix, only the heat pump system lead to emission reductions, all the MCHP system resulted in higher emissions. For the CCPP mix, maximum reductions were again achieved by far with the heat pump systems (up to 29%). The maximum reduction with a cogeneration system was achieved with the SOFC system in the SFH (12%).

SOFC systems were also analyzed in combination with solar thermal collectors. Not surprisingly, the integration of solar collectors always lowers the NRPE demand. Hence, for the combination of cogeneration and solar thermal system higher reductions can be achieved as with either system individually (solar or cogeneration system). In general, higher reductions result for SFH buildings.

Concerning part load operation and thus dimensioning, the analysis showed that the selected SOFC unit was too small for the MFH Swiss average and SIA buildings, and that the PEMFC and SE unit thermal capacities actually were too large even for the MFH buildings. Especially for the SE system, only in the Swiss average MFH building, a reasonable number of equivalent full load operating hours could be achieved. Also the ICE

unit's thermal capacity was too large for SFH buildings of today's energy standard. This clearly showed that besides the efficiencies of the MCHP unit, the correct sizing is of paramount importance.

This was demonstrated for one type of MHF building. The size of the SOFC and PEMFC unit was varied by scaling the capacity of the original fuel cell unit up and down, and the cases were analyzed in terms of NRPE demand. The optimal ratio of thermal output of the fuel cell unit to building heat demand was dependant on the electricity mix and the characteristics of the electric efficiency curve of the fuel cell unit. The results show that for maximum primary energy performance the annual heat output of any cogeneration unit should be dimensioned to about 80 % to 90 % of the annual building heat demand.

In general, the influence of the storage size on the NRPE demand was small, but the parameters selected for the control of storage tank temperature had quite an important impact on primary energy demand of the system, as narrower temperature bands requested more heat from the auxiliary burner and thus reduced the power and heat output of the MCHP unit.

The current study has focused on the performance assessment of current prototype and commercially available residential cogeneration systems. The used performance data is based on manufacturer declaration or on measurements conducted within Subtask B of IEA Annex 42. In case of the SOFC unit, a small improvement of the actual measured electrical efficiency has been assumed in order to reflect the ongoing short term development in this technology. The results of this study provide only a present-day picture of the development of residential cogeneration systems, and do not reflect the full long term potential of the technologies.

Further investigations into the future potential of residential cogeneration technologies are recommended, including also clustering of buildings and conducting a thorough comparison with a more comprehensive range of efficient and renewable energy technologies. Further work should more rigorously consider warm-up/cool-down effects of the generation units. For design and dimensioning, and for optimization, appropriate methods ought to be further developed and applied.

2 INTRODUCTION

2.1 Motivation

Reducing greenhouse gas emissions in the building sector to a sustainable level will require tremendous efforts to improve both energy performance and the share of energy produced by renewable sources (Koschenz et al.). It is widely accepted which demand side measures are important (including improvement of fenestration, thermal insulation, ventilation heat recovery and air tightness in the building envelope). However, wide-ranging options exist on the supply side for the combined provision of home electricity and heat and the integration of renewable energies (Fig. 1).

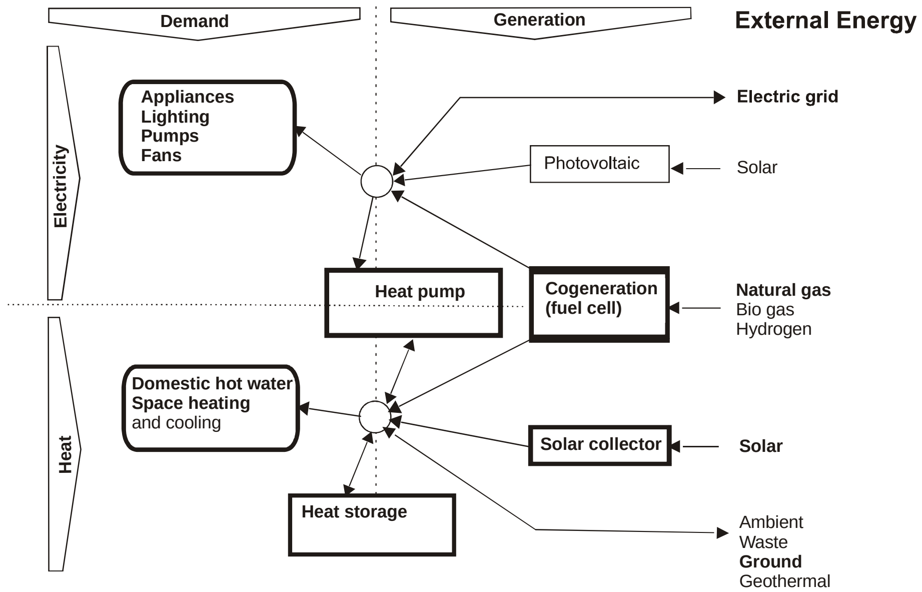

Fig. 1 Options of electricity and heat demand and generation for typical home energy systems with the respective energy management (depicted as circles). Energy resources and systems considered in this study are depicted in bold

One option is cogeneration (combined heat and power generation), where oil and gas boilers are replaced by building-integrated micro-cogeneration units. The "waste" heat from electricity production is thereby fully utilised for space and domestic hot water heating. Micro-cogeneration systems with internal combustion engines and Stirling engines are available on the market. Though still not ready for market entry, fuel cell systems are a focus of interest due to their potential for high electrical efficiency, low emissions and low noise.

Various fuels may be considered in conjunction with each technology. Internal combustion engines mostly run on petrol (gasoline) or natural gas. Stirling engines accommodate a wide range of thermal energy sources, ranging from fossil fuels to biomass and waste heat. Fuel cells normally run on hydrogen, but can also be used with natural gas or other fuels by external or internal reforming.

Micro-cogeneration fuel cell systems face a highly competitive environment that encompasses traditional heating systems such as condensing gas boilers or heat pumps and renewable energies - solar thermal and photovoltaic systems and biomass heating systems.

2.2 Purpose and objectives of this report

The general purpose of this Annex 42 Subtask C performance assessment study is to analyze the performance of selected cogeneration system cases in terms of their energy and emissions, for the Swiss building stock, and for sustainable low-energy building concepts. The interaction of the cogeneration unit with the other components of the cogeneration systems (e.g. water storage), and with other energy supply components such as heat pumps, or with solar renewable energy systems (solar thermal collector), is analysed by computer simulations, using the models developed in Annex 42, and evaluated in terms of selected criteria, namely primary energy demand and CO_2 emissions. Different types of residential buildings featuring standard Annex 42 hot water and electricity demand load profiles are considered, and compared with reference systems comprising traditional energy supply systems. Based on these results, conclusions in terms of cogeneration systems and cogeneration unit sizing, storage configurations and control strategies are derived. Partially, this work can be seen as an extension of the Swiss *novatlantis* study (Dorer, Weber 2004) (Dorer et al. 2005), conducted prior to Annex 42.

While the study focuses mainly on conditions in Switzerland, many of the results and conclusions equally apply to a more general context.

In short, the objectives of this performance assessment study are to:

- quantify the performance of selected cogeneration systems in terms of energy and emissions, and compare to conventional systems
- determine and show sensitivities and identify the most influential parameters
- evaluate control strategies and methods
- document the successful elements of individual cogeneration configurations
- identify promising application fields for cogeneration systems
- demonstrate application potential of models and building simulation tools developed

This is achieved through:

- applying the generic framework for residential cogeneration performance assessment, as defined in this Annex
- using the cogeneration system models developed in this Annex.

2.3 Scope

The performance assessment task concentrates on decentralized, building-integrated energy supplies in the residential sector. The focus is on the performance of cogeneration systems in their interaction with the building (or a cluster of buildings connected via a local district heating network) and occupant loads in terms of control and energy management.

The supply chain from primary energy to delivered energy is considered in terms of primary energy factors and in terms of emission factors, (see Table 4).

This performance assessment study does 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 plant).

Also not within the scope of this study is an in depth technological analysis and assessment of the different products e.g. in respect to installation, start-up and shut-down procedures, operation and maintenance. It is also outside the scope of this work to optimize individual components and the respective control within a cogeneration device.

This study specifically avoided addressing criteria for economic viability because most cogeneration units analyzed are currently at the prototype and early deployment stages, and so, the eventual costs of these units were hard to predict. The technologies' economic viability is very dependent upon the cost of fuel (gas and electricity), which is currently in a state of flux in Switzerland and elsewhere in Europe. Fuel price increases may make technologies such as micro-power more attractive, but for example the electricity/gas price differential is also crucial. Only with demonstrable environmental benefits from new domestic energy technologies also economic arguments are relevant when considering the installation of such systems in residential buildings.

Therefore, also dynamic energy prices are not considered in the performance assessment of control strategies and algorithms, and also the development and assessment of dynamic price strategies and policies is out of scope of this study.

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 into 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). This methodology was developed within Annex 42 and is described in (Dorer, Weber 2007), and the relevant elements are summarised within this report.

2.5 Target audiences

This report is aimed at the following readership:

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

2.6 Introduction to the content of the report

Sections 2 and 4 give definitions, particularly with respect to energy, and describe performance assessment procedures used in this study. Section 5 outlines the performance criteria used. Section 6 to 8 describe the different elements of the cases studied. Section 6 describes the buildings analyzed and the external factors applied (emission factors, climate etc.), in section 7 the individual components of the cogeneration and the reference systems are specified, and section 8 describes the cogeneration and the reference systems modelled, including also the energy management and systems control. Section 9 gives an overview of all cases and configurations analyzed. The results of the simulations are given in section 10, and section 11 comprises conclusions and an outlook.

3 NOMENCLATURE AND SYMBOLS

The nomenclature used in the study is outlined in this chapter, including the list of symbols and indices. The nomenclature follows the standards set in the Annex 42 Performance assessment methodology report (Dorer, Weber 2007).

3.1 Terminology

Term	Description
Case	A specific installation with its data set in terms of environment, building, demand profiles and cogeneration system. A case can have several configurations.
Configuration	A specific data set for an individual case in terms of cogeneration system and of components size/dimensions, and of the control strategy and algorithms used.
Cogeneration (cogen)	Combined generation of heat and electricity.
Cogeneration device (cogen unit)	The cogeneration plant or appliance, as provided by the manufacturer.
Cogeneration system (cogen system)	The system providing heat and electricity. This includes the cogeneration device and further components such as storage, external pumps, auxiliary heater, and other supply components such as solar collector, heat pump etc.
Criterion (objective)	Parameter used in the assessment as a measure of the performance of the system analyzed. In optimizations, the optimized parameter(s) is named objective.
Empirical evaluation	Comparison between measured data from laboratory or demonstration buildings and results from simulations.
Performance assessment (PA)	Assessment of the performance of the system under investigation in regard to the selected performance criteria, by simulation.

3.2 Abbreviations and indices

Energy terms, symbols and indices see § 3.3

Abbr./index	Description
Bsim	Building Simulation (with the building and system simulation tools used within A42)
CC	Combined cycle (gas and steam)
CCPP	Combined cycle (gas and steam) power plant
CGU	Cogeneration device (cogen unit)
CHP	Combined heat and power (= cogeneration)
CO2	Carbon dioxide
DE	Delivered energy
DHW	Domestic hot water
El	Electric, electricity
El-Grid	Electricity supplied from the grid
El-NetGrid	Net amount of electricity exported to grid, or net amount of electricity delivered from grid
ERFA	Energy reference floor area
Fuel	Delivered fuel
FC	Fuel cell system or building equipped with fuel cell system
FCU	Fuel cell device (fuel cell unit)
GB	Gas boiler, gas boiler system
GHG	Green house gases
GWP	Global warming potential
H2	Hydrogen
HD	Heat from/to district heat network
ICE	Internal combustion engine
LHV	Lower heating value
MCHP	Micro cogeneration (micro combined heat and power)
MFH	Multi-family house
MOO	Multi-objective optimisation
NG	Natural gas
NRE	Non-renewable energy
NRPE	Non-renewable primary energy
PA	Performance assessment
PEMFC	Polymer electrolyte membrane fuel cell (or proton exchange membrane fuel cell)
PV	Photovoltaic
RE	Renewable energy
SC	Solar collector
SFH	Single-family house
SE	Stirling engine
SH	Space heating
SOFC	Solid oxide fuel cell
TBD	To be defined
Th	Thermal
UCTE	Union for the Co-ordination of Transmission of Electricity, Luxembourg

3.3 Glossary of energy terms

All energies are based on LHV. See also § 4.2 Energy analysis, for further description of energy terms.

No See Fig. 2	Term	Description
1	Energy demand	Energy needed to fulfil the user's requirements for space heating or cooling, for domestic hot water, for ventilation, and for electric lighting and appliances
2	Non-HVAC energy	Part of the energy demand that is covered by "natural" (passive) energy gains (passive solar, natural ventilation, natural ventilation cooling, internal gains, etc.). Losses from the heat/cold distribution system and from the HVAC system (incl. cogen system) may contribute as internal gains.
3	Net energy	Part of the energy demand (for space heating/cooling, domestic hot water and electricity respectively) that is covered by the HVAC system (including RE systems).
4	Delivered energy *Equally valid terms, but not used here:* *- Final energy* *- End energy*	Energy, represented separately for each energy carrier (fuel, electricity, heat/cold, incl. auxiliary energy), that is entering the individual building envelope (the system boundary) in order to be used by the heating, cooling, mechanical ventilation, hot water, lighting systems and appliances. This may be expressed in energy units or in units of the energy ware (kg, m^3, kWh, etc.). Locally generated solar and ambient energies are not considered as delivered energy, but are accounted for by a separate contribution (5) to cover the net energy demand. However, delivered energy may include heat or electricity produced from renewable sources elsewhere, like electricity from a PV plant, or heat from a plant fired by sustainable grown wood (see 8). Fuel from renewable energy sources (e.g. hydrogen or wood) is taken into account in (5) Renewable energy.
5	Renewable energy	Renewable energy generated on the building premises (e.g. electricity by PV, or heat by solar thermal system or from stove fired by wood).
6	Exported energy	Energy (heat/cold or electricity) generated on the premises and exported to the market; this can include part of renewable energy (5). Note: This option of exporting RE it is not evident in Fig. 2.
7	Primary energy	Represents the energy usage associated with the delivered energy which is embodied in natural resources (e.g. coal, crude oil, natural gas, sunlight, uranium) and which has not yet undergone any anthropogenic conversion or transformation ("well to building" path). Primary energy is subdivided in renewable / non renewable or in fossil / non-fossil PE.

No	Term	Description
8	Primary energy equivalence for locally generated renewable energy	Represents savings in non-renewable PE and in GHG emissions due to the on-site generated renewable energy (electric or thermal energy provided on site by PV, solar collectors, wood stoves, etc.). The same conversion from PE to DE as for (7) to (4) must be considered. Electric/thermal energy provided by power plants fuelled by renewable sources (solar, geothermal, hydro, wind, photovoltaic, biomass fuelled station etc.) is accounted for as renewable PE in (7) and reflected in the respective primary energy factors or emission factors.
9	Primary energy equivalence for exported energy	Represents the primary energy equivalence associated with exported energy, which is subtracted from (7) to calculate the (net) primary energy use

For additional information on how the different energies were applied and handled in this PA study, see § 4.2.1 and also Fig. 4.

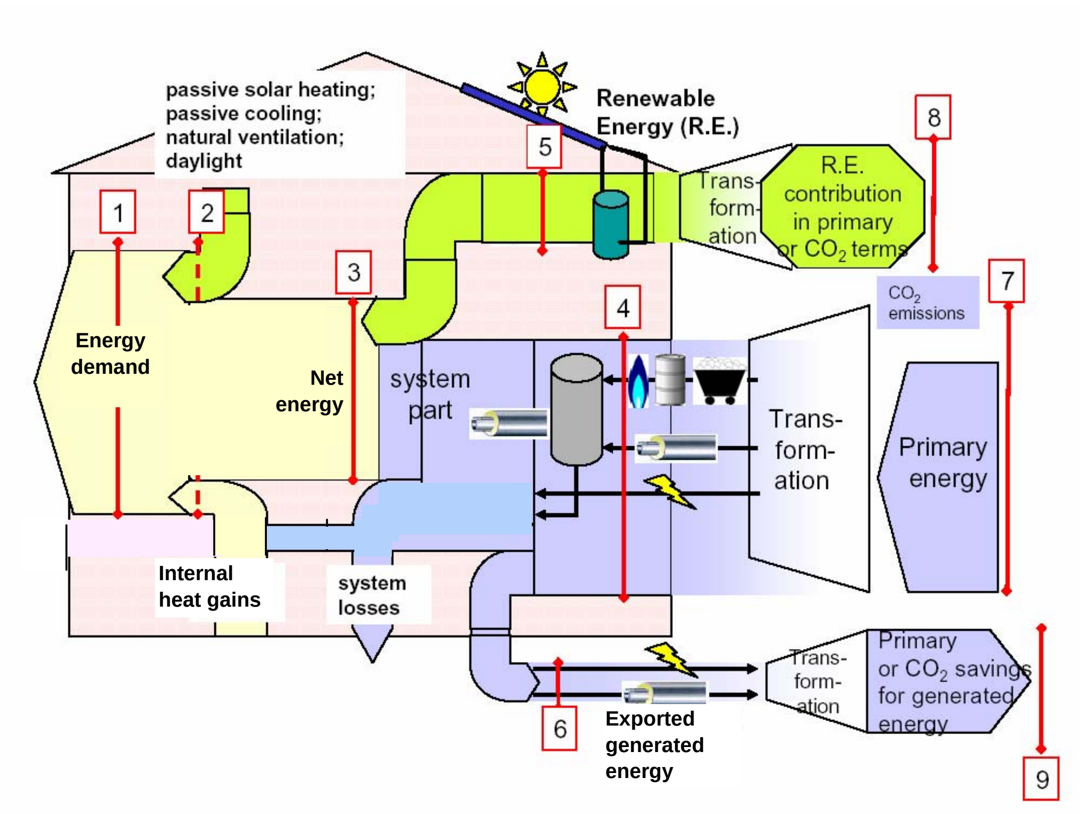

Fig. 2 Energy conversion processes and energy terms, as exemplified by residential building supply (Source: CEN/BT WG 173 EPBD N 68)

(1) Energy demand
(2) Non-HVAC energy
(3) Net energy
(4) Delivered energy
(5) Renewable energy
(6) Exported energy
(7) Primary energy
(8) Primary energy equivalence for locally generated renewable energy
(9) Primary energy equivalence for exported energy

Symbols for energy parameters and related factors

Below, symbols for energy value parameters related to a one year period are given. The same symbols may be applied to other simulation periods.

Parameters starting with a capital letter refer to amounts of energy, parameters starting in lower case represent energy amounts per reference area (annual energy values in MJ/a or $MJ/m^2/a$).

The energy values are valid for the selected simulation period, normally one year (annual energy values in MJ/a or MJ/m2/a).

Energy values are based on LHV. Electricity input and output as used (normally AC, as electricity from and to grid). See also § 4.2 for further description of energy terms.

Symbols	Description	Unit
BE	Non-HVAC energy, often related to the building design (Energy type No 2 in Fig. 2)	MJ
DE	Delivered energy (No 4)	MJ
NE	Net energy (No 3)	MJ
OE	Energy output of cogen unit or reference energy system	MJ
PE	Primary energy (No 7)	MJ
RE	Renewable energy generated on the building premises (No 5)	MJ
XE	Exported energy (No 6)	MJ
Fl	Loss factor	-
Pef	Primary energy factor (ratio of primary energy to delivered energy)	-
nrpef	Non-renewable primary energy factor (ratio of primary energy to delivered energy)	-
η	Energy performance factor of system: ratio net energy output to consumed delivered energies (η_{DE}) or to the primary energies respectively (η_{PE})	-

Indices

Build	Building
DE	Delivered energy
DHW	Domestic hot water
El	Electricity
El-Grid	Electricity from grid
El-Back	Electricity delivered back into the grid
El-NetGrid	Net amount of electricity exported to grid or delivered from grid
El-CGU	Electric energy output of cogen unit
Fuel	Fuel
H	Heat
HD	District heat
NRE	Non-renewable
NRPE	Non-renewable primary energy
NG	Natural gas from grid
PE	Primary energy
SH	Space heating
SC	Space cooling
Th	Thermal
Th-Build	Thermal energy demand of building (SH and DHW)
Th-CGU	Thermal energy output of cogen unit

Examples

pE_{NRE}	Non-renewable primary energy usage per energy reference floor area of building	MJ/m^2
$PE_{El\text{-}Grid}$	Primary energy usage for electricity from grid	MJ
NE_{El}	Net electricity demand	MJ
$XE_{El\text{-}NetGrid}$	Net amount of electricity exported to the grid (total exported minus re-delivered)	MJ
OE_{Th}	Thermal energy output of cogen unit	MJ
$nrpef_{NG}$	Non-renewable primary energy factor (primary energy to delivered energy) for natural gas	-
η	Energy performance factor	-
η_{PE}	Primary energy performance factor	-
η_{NRPE}	Non-renewable primary energy performance factor	-

3.3.1 Energy terms for electricity

Fig. 3 illustrates the definition of the energy terms for electricity, considering specifically the situation of the indirect use of the energies, namely energy exported to the grid and re- delivered (re- imported) from the grid.

Electricity from/to grid

see Fig. 3:

$$XE_{El-NetGrid} = \begin{cases} XE_{El-Grid} - DE_{El-Grid} & if \quad XE_{El-Grid} > DE_{El-Grid} \\ 0 & if \quad XE_{El-Grid} \le DE_{El-Grid} \end{cases}$$

and

$$DE_{El-NetGrid} = \begin{cases} DE_{El-Grid} - XE_{El-Grid} & if \quad DE_{El-Grid} > XE_{El-Grid} \\ 0 & if \quad DE_{El-Grid} \le XE_{El-Grid} \end{cases}$$

Grid loss factor

For electricity produced locally, delivered into the grid and consumed later on again from the grid, a grid loss factor $fl_{El\text{-}Grid}$ of 10% ($fl_{El\text{-}Grid}$ = 0.1) was considered. Thus (see again Fig. 3),

$$XE_{El-Grid} = \frac{OE_{El-Grid}}{(1 + fl_{El-Grid})}$$

Thus, basically the availability of net-metering is assumed whenever considering the feed-back of locally generated electricity. However, as outlined above, for the performance assessment, for electricity delivered back into the grid, and later on used again, this grid loss factor is applied.

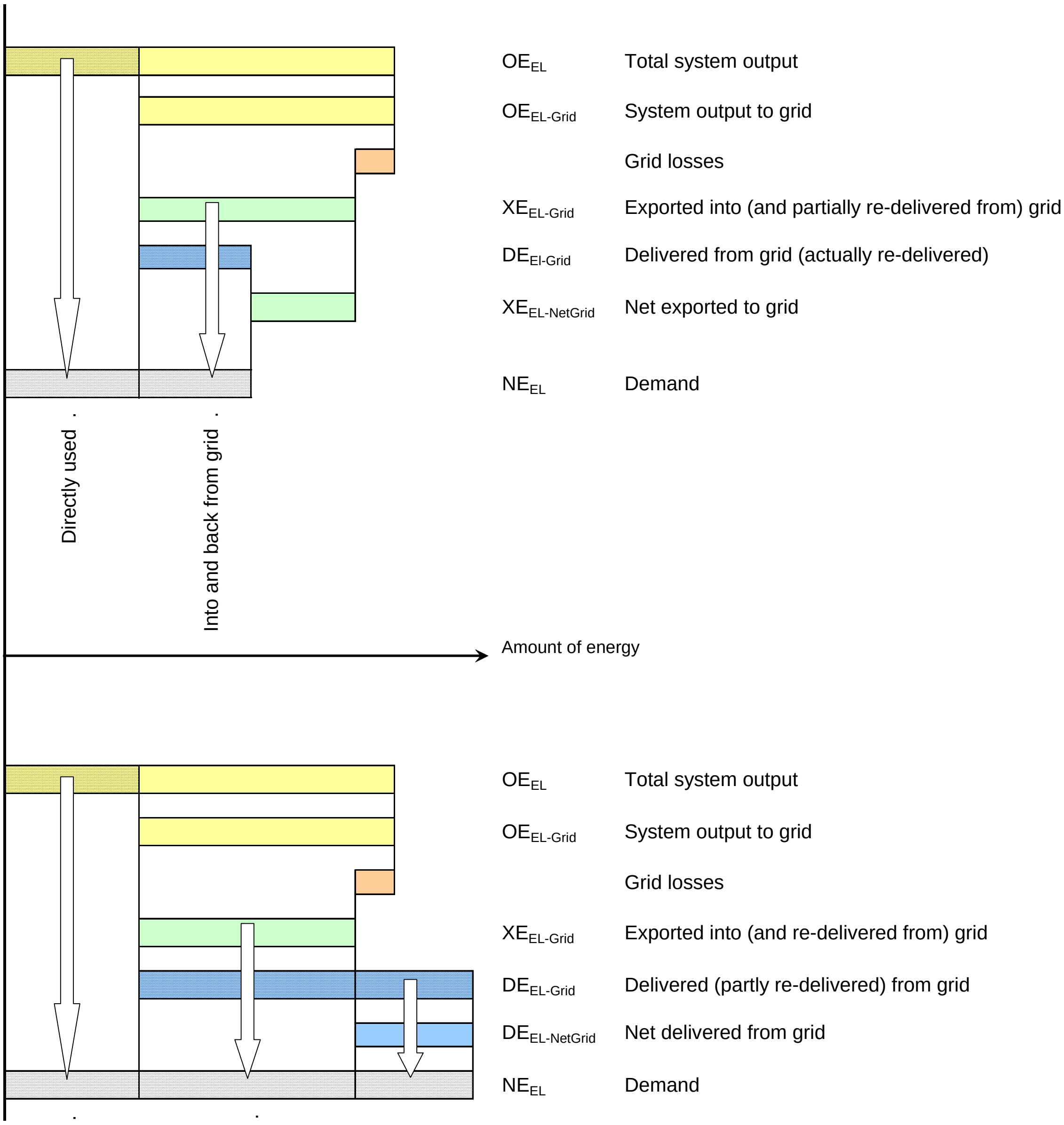

Fig. 3 Energy terms for electricity

4 PERFORMANCE ASSESSMENT PROCEDURE

4.1.1 Types of performance assessments

The following analysis types were applied within this Subtask C study:

- Energy analysis
- CO_2 emission analysis

4.1.2 Performance assessment procedure

The energy analysis involved the following steps :

1) Building simulation analysis produced values for energy demand and, by simulation of the building integrated generation systems, the demand for delivered energy for the building.
2) Primary energy consumption was derived in a post-processing analysis, based on the calculated value for the demand of delivered energy.
3) From these energy values, further figures such as overall efficiencies, energy performance factors etc. were derived.
4) Further post-processing to calculate emissions based on the energy demand values.

These individual steps are detailed in the following chapters.

4.1.3 Building simulation code

The analysis was undertaken with the transient multi-zone building and plant simulation code TRNSYS (TRNSYS 16.1). Details of the components and the respective models used and model parameters considered, are given in the Appendix to this report.

4.1.4 Evaluation period and time step

Unless otherwise stated, the evaluation period was one year (Jan to Dec), see also the section on boundary conditions. The standard simulation time step was 15 min. However, some components used smaller internal time steps.

4.2 Energy analysis

4.2.1 Energies considered

Three types of energy were considered for the assessment of the energy consumption:

- Net energy demand (energy used by the HVAC, the cogeneration and the RE systems to cover the demands for space heating, for domestic hot water, and for electricity)
- Delivered energy (energy delivered to the building as fuel, heat or electricity)
- Primary energy
  - Renewable energy / non-renewable primary energy (NRPE)
  - Fossil energy / non-fossil energy

  Total primary energy demand values are differentiated into primary energy demand for delivered grid electricity and for the fuel.

From the environmental standpoint, fossil and/or non-renewable energies have to be considered. Fossil energy is related to the emission criteria. The aspect “renewable/non-renewable” focuses mainly on hydro vs.

nuclear power generation, and on the use of solar heat or electricity.

4.2.2 Reference and units for energy values

In this Subtask C analysis, delivered and primary energies are related to the energy reference floor area (ERFA) of the building. The energy values are thus expressed in MJ/m^2, or $MJ/m^2/a$ for annual period.

The energy reference floor area is based on external dimensions and considers all (also indirectly) heated spaces of the building.

4.2.3 Control volumes and types of energy balances for the energy analysis

In performance evaluations, the following types of boundaries or control volumes and types of balance analysis can be applied (see Fig. 4)

a) analysis of the cogen device in terms of power-oriented assessments
b) analysis of building energy supply system (cogen device and other HVAC components) in terms of net power
c) analysis of the building in terms of delivered energy (electricity and fuel), based on the net energy demand for space heating (cooling), domestic hot water, and electric demand, for the whole simulation period.
d) analysis of the building including grid related factors (building plus supply structure) in terms of primary energy, for the whole simulation period (normally one year).

This study focuses mainly on analysis types (c) and (d) (delivered and related primary energy demand). However, analysis type (b) was also applied, e.g. for the analysis of different control algorithms or of the size of components.

Ambient energies and energy conversions from primary to delivered energy are considered by factors in the simulation or in the post processing of the simulation results.

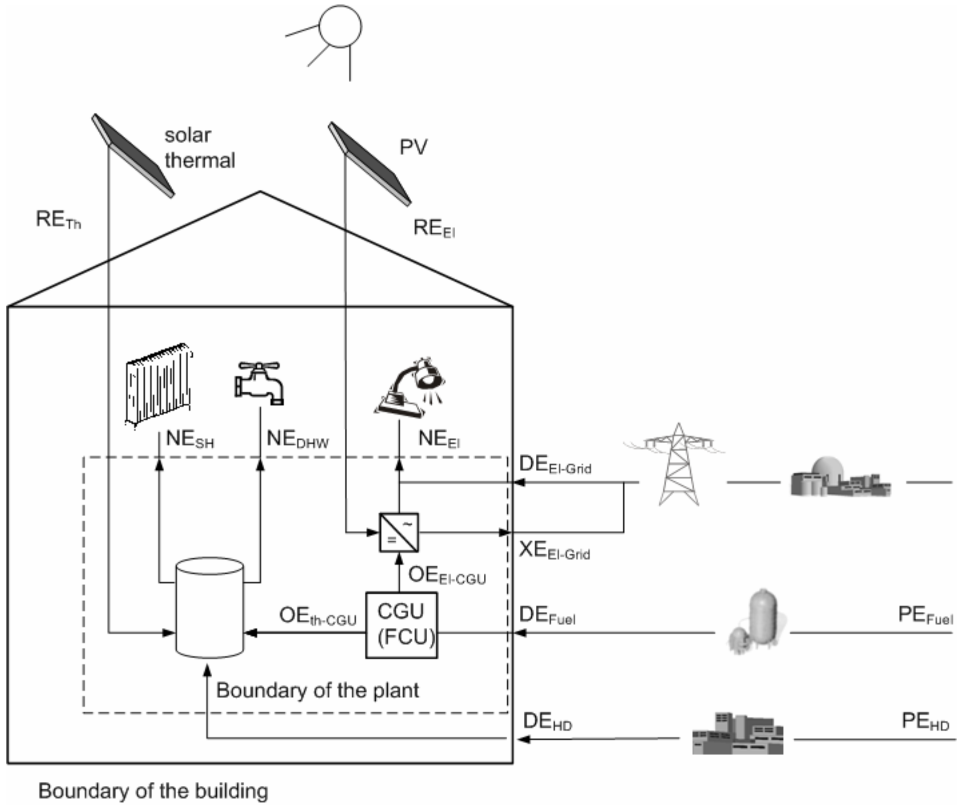

Fig. 4 Control volumes and related energies

4.2.4 Amendments to energy definitions

Net energy demand for space heating and for domestic hot water

The net energy demand for space heating is Q_h according (ISO 13790), in our terms called the (annual) net energy for space heating NE_{SH} (nE_{SH} per reference floor area).

Electricity demand for heat distribution and distribution heat losses

The electricity demand of the pumps for the heat distribution within the building analyzed is assumed to be quite similar for both the cogeneration and the reference systems. As the focus in this study is the comparison of the performance of the cogeneration unit with the reference systems, this electricity demand was not considered. This has be taken into account when an overall assessment of energy conversion and the heat distribution system is made. Heat losses for space heating distribution are also not considered. For domestic hot water, it is assumed that the heat demand equals the net energy for hot water (no distribution losses assumed).

Parasitic losses of the cogeneration system

A part of the parasitic losses of the cogen system (radiative and convective skin losses incl. venting of heat from individual cogen system components for cooling purposes) may contribute to the internal heat gains of the building and thus reduce heating load or increase cooling load. In this study, these gains are not considered as the systems are assumed to be located in unheated rooms. Thus, the useful amount of the parasitic heat loss is not considered neither as an increase of the thermal output of the cogen device ($OE_{th\text{-}FCU,\ CGU}$) nor as an increase of the thermal efficiency of the system.

Combined hot water storage for cogen and solar system

In this case the net energy output of the system "cogen device and storage" includes already the contributions from the RE system (Energy type 5 in Fig. 2). The system is evaluated by energy ratios as NE to DE or to PE. System efficiency evaluations focus on non-renewable energies or emissions. In addition, the percentage of NE supplied by the renewable energy system is used as another parameter in comparing different systems.

Electricity demand

It is assumed that the electricity demand equals the net electricity (no distribution losses within the building assumed).

4.2.5 Primary energy definitions

Allocation of primary energy consumption and emissions to generated electricity and to generated heat

Generally, several types of allocation methods can be used in performance assessments, such as (see Annex 42 Performance assessment methodology report (Dorer, Weber 2007)):

a) Equivalent consideration of heat and electricity
b) Bonus or credit methods
c) Exergetic allocation

Method a) was used in this study.

Non-renewable / renewable energies

For hybrid systems which use non-renewable and renewable energies (such as the a natural gas driven co-generation system combined with a solar thermal system analysed in this study), one has to distinguish between energy performance factors for non-renewable and factors for renewable energies. The reason for this is related to the problem of the definition of the basis for primary renewable energy. An example may illustrate this:

For a PV panel with an electric efficiency of 12.5% (solar irradiation input to electric output), the primary energy factor *pef* is 8. Hence, any hybrid system with PV will have a very low primary energy performance factor, unless only the non-renewable primary energy factor is considered. The PV system contributes to the coverage of the electric demand without any increase of delivered non-renewable energy. Thus the non-renewable energy performance factor is higher than the one of the system without PV.

5 PERFORMANCE CRITERIA

5.1 Energy performance criteria

5.1.1 NRPE demand

The performance criterion for the primary energy demand applied in this study is the non-renewable primary energy demand per reference floor area (pE_{NRPE}), as used during the simulation period by

a) the cogen system
b) the production chain for fuel (emission factors see Table 4)
c) the production chain for grid electricity (depending on the electricity generation mix) (Table 4)

5.1.2 Energy performance factors

General

In order to evaluate how efficiently the energy is utilized by the building and its cogeneration system to cover the annual electricity and net heat demands, dimensionless energy performance factors η_{DE} and η_{PE} are defined. Where η_{DE} is the ratio of the net energy demand of the building to delivered energy and η_{PE} to primary energy respectively.

Energy quality: In the energy performance factors given below, electric and heat energy values are added together. However, due to the different energy quality (exergy) levels, this approach is of course questionable on the level of delivered energies. Therefore, the evaluation was made, as far as possible, on the level of primary energies (η_{PE}).

The energy performance factor by itself is not a measure of the effectiveness of a MCHP unit, but a measure of how effectively the building's demand is covered by the energy system, consisting of MCHP system and other energy converters, and the external supply (see Fig. 4). The energy performance factors are defined for the comparison of different cogeneration systems and of reference systems, such as conventional (i.e. separate) heat and power generation, which produce the same amount of heat and power, or cover the same energy demands.

Consideration of net electricity supplied back to grid

Another item that needs to be defined is how the part of the locally generated electricity is accounted for, which is net supplied back into the grid ($XE_{El\text{-}NetGrid}$), and which primary energy factors are to be applied.

There are two ways of considering $XE_{El\text{-}NetGri}$. Method a) was applied in this study:

a) Additional demand: the net amount of electricity delivered back into the grid is treated as an additional demand, which is covered by the cogeneration system.

b) Substitution principle: it is assumed that the net amount of electricity produced locally and delivered back into grid substitutes or displaces the same amount of electricity produced according to the considered electricity mix of the grid.

Both methods have advantages and disadvantages, (see Annex 42 Performance assessment methodology report (Dorer, Weber 2007)). Method a) relates the energy input to the energy demand of the building plus any surplus electricity generated, while method b) relates the energy input to the energy demand of the building only, and any surplus electricity generated locally is accounted for by a reduction of the energy input. In the extreme case that neither heat or electricity is locally used, and all electricity is exported (cogen unit acts as micro power plant), with method a) the performance factor η_{PE} is identical to the electric efficiency of the cogeneration unit, whilst the factor becomes zero with method b). On the other hand, with method b), performance factors $\eta_{PE} > 1.0$ may result for cases where electricity is exported and a high $pef_{El\text{-}Grid}$ applies.

Primary energy performance factors

According to method a), the primary energy performance factor is defined as

$$\eta_{PE} = \frac{NE_{El} + NE_{SH} + NE_{SC} + NE_{DHW} + XE_{El-NetGrid}}{PE_{El-NetGrid} + PE_{Fuel} + PE_{HD}}$$

using annual net energy consumption *NE*, in conjunction with indices for electricity (*El*), space heating (*SH*), domestic hot water (*DHW*), the net amount of electricity delivered to grid (XE) (*El-NetGrid*); and the primary energy demand for the net amount of electricity consumed from the grid, for the fuel (*Fuel*) and for district heat (*HD*) (see also § 3.3 and especially Fig. 3).

Note 1: For a specific case, either $PE_{El-NetGrid}$ *(and* $DE_{El-NetGrid}$*) or* $XE_{El-NetGrid}$ is equal to zero, see definitions in § 3.3.1.

Note 2: In comparing the net energy to the delivered energy, the amount of on-site produced renewable energy will bias the energy performance factors. A very efficient system without on-site produced renewable energy may have a lower performance factor than a not so efficient system with on-site produced renewable energy. A possible solution for this is to exclude the on-site produced renewable energy from the performance factor and to define the performance factor as DE/PE.

The primary energy can also be expressed in terms of delivered energy multiplied by the primary energy factor *pef* (ratio primary energy to delivered energy). For constant or averaged primary energy factors *pef*, this is

$$\eta_{PE} = \frac{NE_{El} + NE_{SH} + NE_{SC} + NE_{DHW} + XE_{El-NetGrid}}{pef_{El-Grid} \cdot DE_{El-NetGrid} + pef_{Fuel} \cdot DE_{Fuel} + pef_{HD} \cdot DE_{HD}}$$

If the primary energy factors *pef* are considered time dependent, then the primary energy demand must be calculated within the simulation.

The performance factor can also be derived from energy reference area related energy values, e.g.

$$\eta_{PE} = \frac{nE_{El} + nE_{SH} + nE_{SC} + nE_{DHW} + xE_{El-NetGrid}}{pE_{El-NetGrid} + pE_{Fuel} + pE_{HD}}$$

Similar factors can be defined for the use of non-renewable or fossil primary energy. For non-renewable energy the non-renewable primary energy performance factor is

$$\eta_{NRPE} = \frac{nE_{El} + nE_{SH} + nE_{SC} + nE_{DHW} + xE_{El-NetGrid}}{pE_{NRE,El-NetGrid} + pE_{NRE,Fuel} + pE_{NRE,HD}}$$

5.2 Emissions analysis

The performance criterion regarding emissions was the amount of CO_2 equivalents emitted during the simulation period by

d) the cogen system
e) the production chain for fuel (emission factors see Table 4)
f) the production chain for grid electricity (depending on the electricity generation mix) (Table 4).

CO_2 equivalents (CO_2-eq) are a metric measure used to compare the emissions from various greenhouse gases (GHG) based upon their global warming potential (GWP). The global warming potential (GWP) is a factor describing the radiative forcing impact (degree of harm to the atmosphere) of one unit of a given GHG, as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years), relative to one unit of CO_2. The GWP provides a construct for converting emissions of various gases into a common measure, which allows climate analysts to aggregate the radiative impacts of various greenhouse gases into a uniform measure denominated in carbon or carbon dioxide equivalents. The CO_2 equivalent for a gas is derived by multiplying the mass of the gas by the associated GWP. The table below compares the GWPs published in the Second and Third Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC 2001).

Table 1 GWP factors for GHG according to Kyoto protocol (IPCC 2001)

Gas	**Formula**	**Relative GWP / CO_2 (100 years)**
Carbon dioxide	CO_2	1
Methane	CH_4	23
Nitrous dioxide (protoxyde)	N_2O	298
Perfluorocarbons	C_nF_{2n+2}	6 500 to 8 700
Hydrofluorocarbons	$C_nH_mF_p$	140 to 11 700
Sulfur hexafluoride	SF_6	23 900

5.3 Technological analysis

There is a wide range of possible topics for technological evaluations and assessments, such as efficiency issues, operation cycles, number of shut-downs, reliability issue and electric power quality.

However, this Subtask C study focuses on criteria that have a relation to, or an impact on, the energy and emission performance criteria set out above, such a s the number of equivalent full load operation hours or demand coverage.

The influence on energy use and emissions of the following technical issues were partially considered:

- length of start-up / shut down cycle, considering the transient behaviour of the system
- temperature levels of heat supplied to space heating and DHW system, and respective limitations for heat supply temperatures
- flow rates in water heat exchange system

6 BUILDINGS, LOADS AND EXTERNAL FACTORS

6.1 Buildings

6.1.1 Building types

Two building types were considered:

a) SFH Single-family house
b) MFH Multi-family house with 4 dwellings

6.1.2 Building energy demand levels

Three energy demand levels, identical for the SFH and MFH building types, were considered:

a) Swiss average Energy level based on the average for the Swiss building stock
b) SIA target Target energy level for new buildings stated in the Swiss building energy standard (SIA 380/1)
c) PH Energy level compliant with the Passive House standard, defined by the German Passive House Institute (Feist 2002)

The Passive House standard requires a space heating demand of less than 54 MJ/m2/a (15 kWh/m2/a) per net useable floor area (equivalent to 81 % of the energy reference floor area for the SFH and 86 % for the MFH building type), and a total demand for non-renewable primary energy of less than 432 MJ/m2/a (120 kWh/m2/a). In the standard, primary to end energy ratios of 2.97 for electricity and 1.07 for natural gas are assumed.
In the evaluations, the values of the net energy demand for space heating used were derived from the results of the dynamic building and systems simulations. The values are given in Table 2 .

Table 2 Energy demands per m^2 energy reference floor area derived from simulations, heat transfer coefficients (U-values) of exterior walls and glazing, and solar heat gain coefficient (G-value) of glazing of the different building types

Building energy demand level	Swiss average		SIA target		PH	
Building type	SFH	MFH	SFH	MFH	SFH	MFH
Space heat demand (MJ/m^2/a)	516	518	172	154	66	47
Electricity demand (MJ/m^2/a)	51	68	54	67	47	64
U-value exterior walls (W/m^2/K)	0.7	1.1	0.2	0.3	0.15	0.16
U-value roof (W/m^2/K)	0.35	0.58	0.16	0.2	0.11	0.15
U-value glazing (W/m^2/K)	2.8	2.8	1.4	1.4	0.7	0.7
G-value glazing (-)	0.76	0.76	0.59	0.59	0.59	0.59

Building construction type

The construction type of a building (heavy / lightweight construction) has an influence on the transient room temperatures and thus on the heating or cooling loads. This was considered in the definition of building types, however building mass was not a parameter to be evaluated separately.

6.1.3 Building geometry

The geometric layout of the MFH is basically a multiplication of the SFH type building geometry (Fig. 5). All dwellings have the same useable floor area (188.8 m^2). The thermal properties of the building envelope (insulation and glazing), and the building equipment and appliances are adapted to the different energy demand levels of the buildings (Table 2). The energy reference floor area is the sum of the floor areas of all heated or air conditioned rooms, based on the outer dimensions of the building including the exterior walls. Therefore the values for the energy reference floor area for space heating differ slightly for the different building types due to the varying insulation and wall thicknesses.

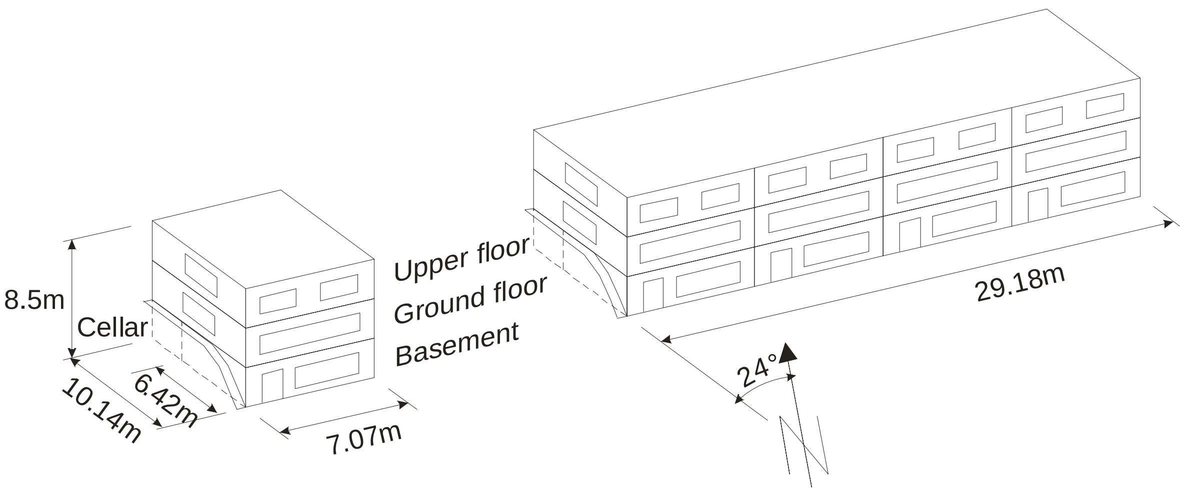

Fig. 5 Geometry and orientation of SFH building (left) and MFH building (right).

6.1.4 Building distribution system for space heating and cooling; ventilation system

The heat distribution and the ventilation for the individual building types are given in Table 3. The ventilation rates were kept constant throughout the simulation period, also for the cases with natural ventilation.

Table 3 Heat distribution and ventilation for the individual building types

Building type (Acronym)	Heat distribution	Ventilation
Swiss average (“Swiss av.”)	Water-based radiators/convectors (27% radiative)	Natural ventilation by window airing (2.1 m^3/h/m^2)
SIA 380/1 target value (“SIA target” or “SIA”)	Floor heating, similar to concrete core cooling/heating	Natural ventilation by window airing (0.7 m^3/h/m^2)
Passive house (“PH”)	Floor heating, similar to concrete core cooling/heating	Mechanical balanced ventilation with heat recovery, (heat recovery efficiency: 68 %) (120 m^3/h per dwelling) 0.1 h^{-1} infiltration in zones with external doors

6.1.5 Internal and external heat gains

100% of the heat from electrical appliances, lighting and occupants was assumed to contribute to the internal load. These gains were distributed to the individual rooms using a fixed distribution scheme, considering also results of the earlier study (Dorer et al. 2005), where electricity demand for artificial lighting was calculated considering the availability of daylight. External loads were calculated by the TRNSYS building model. 60 to 80% solar protection was applied with due consideration to the daylighting requirements. Excessive indoor air temperatures in summer were reduced by increased natural ventilation.

6.1.6 Space heating loads

The basic link between building and the cogeneration system is given by the time dependant heating load of the building. As within IEA Annex 42, the influence of the building design on passive gains (solar, daylighting, use internal gains) was not a topic of investigation, the net heating demand is the decisive parameter, determined by the dynamic building model within the actual simulation. This allowed us to fully consider the interaction between building, HVAC and cogeneration system, heat distribution system and the time varying boundary conditions. In the simulation, the loads were determined using the TRNSYS multi-zone building model Type 56.
The supply temperature for the heating system was controlled according the outside air temperature dependant heating curve. In addition, the radiator system has room thermostatic valves with a 1K proportional band.

6.2 Occupancy related loads

6.2.1 DHW demand profiles

<u>Data for SFH</u>

The standard DHW consumption profiles provided by the Annex 42 were used for the simulations. The Annex 42 consumption profiles have been produced at 1 minute, 5 minute and 15 minute intervals. All the demand profiles are given for the whole building. The profile data originate from IEA SHC Task 26. Details are given in the Annex 42 Subtask A report (Knight et al. 2007). The 15 min data are used in this study.

The volume of DHW provided in the profiles assumes a supply temperature of 45°C and a cold feed water temperature of 10°C. This means that on average each 100 litres from the profile data would correspond to about 70 litres of DHW drawn from a storage tank at 55 – 60°C.
If DHW water is stored and supplied at a different temperature in a particular situation to be modelled then the volume of DHW provided in the profiles was altered by using the following correction:

$$actual\_volume = \frac{35}{(stored\_water\_temperature - cold\_feed\_temperature)} \cdot profile\_volume$$

This correction was made in each simulation time step.

The following three standard demand levels provided by Annex 42 Subtask A were used:

1. low demand 100 litres per day
2. moderate demand 200 litres per day
3. high demand 300 litres per day

Data of the moderate demand are used in the simulations unless otherwise stated in the results.

<u>Data for MFH</u>

For MFH, in contrast to the approach made for electric demands (superposition of SFH demands), directly the IEA SHC Task 26 profiles for higher demands (800 litres per day) were used (IEA Task 26 2001), (Jordan & Vajen 2001).

For the MFH analysed, a 4 family house with 12 persons, only one load profile type (moderate demand, corresponding to 200 litres per dwelling) is considered.

The same temperature/volume correction as outlined above for the for SFH is applied.

6.2.2 *Electricity demand profiles*

The European domestic electrical energy consumption data profiles, as provided by Annex 42 (Knight et al., 2007), were used. Out of these data sets, namely the three sets of actual annual load profiles from three homes, typical for low/medium/high electric energy consumption, as provided by Annex 42 (Kreutzer & Knight 2006), were used.

The data provided are total electricity demand values, including the demand of

- HVAC components (pumps, fan, control)
- appliances (refrigerator, stand by loads of electronics)
- occupant related additional loads (lighting, household appliances, IT devices)

but not including any demand for electric heating (SH or DHW).

The time resolution of each profile is 5 minutes and the unit is Watts (W).

Data for MFH

The electric load profile for MFH was produced by superposition of several SFH profiles. The assumed MFH is a 4 family house with 12 persons. The superposition was as follows:

1. Superposition of 1 low demand, 2 medium demand and 1 high demand profile.
2. All the profiles were firstly shifted such that they all start on a Monday, in order to synchronize the weekdays.
3. One of the medium demand profile was shifted an additional week minus 1 hour. With this shift the weekdays are still synchronized but the peak demands do not exactly correspond.

6.2.3 *Synchronisation of DHW and electric loads*

Coherence between occupancy related DHW and electric loads in regard to weekday was established by shifting the profiles such that all the profiles start on a Monday. However, disaccords between the two load profiles in regards to absence (e.g. vacation times) may still exist.

6.3 External factors

6.3.1 *Outdoor climate*

Statistically processed meteorological data, measured over a period of 10 years, of the meteo station Basel-Binningen (Switzerland) were used, as so called DRY data file (Design reference year). The file was generated using (METEONORM 4.0.).

6.3.2 *External energy supply (delivered energy)*

Energy sources

The following types of external energy are considered in this study:

- Fuel: Natural gas
- Electricity: Grid electricity with different generation mix and with feedback possibility
- Renewable / ambient energies: Solar thermal energy and energy from ground

Natural gas

The average values for import gas by Swissgas are considered for the natural gas properties (ecoinvent 2004):

Lower heating value (LHV): 36.5 MJ/m^3
Higher heating value (HHV): 40.2 MJ/m^3

The composition for natural gas was assumed as [% weight]:

- Methane CH_4 89.12 %
- Ethan C_2H_6 3.93 %
- Nitrogen N_2 2.62 %
- Carbon dioxide CO_2 1.35 %
- Propane C_3H_8 1.44 %
- Other -- 1.18 %

The primary energy factor and CO_2-equivalent emission rates used for natural gas are taken from (ecoinvent 2006) and shown in Table 4.

Grid electricity

For grid electricity, the NRPE demand and the respective CO_2-equivalent emission rates depend on the electricity mix. Three electricity mixes were considered:

a) European average according to the statistics issued by the (UCTE)
b) Swiss average (Switzerland incl. import)
c) an energy ratio for a state-of-the-art gas & steam combined cycle power plant (CCPP).

The primary energy factors (pef) and emission rates used for the different electricity mixes are taken from (ecoinvent 2006) and shown in Table 4. They include a factor for the distribution of primary energy to the electric power plant plus a factor assuming 11.7% distribution losses in the electric grid (including high and low voltage distribution losses). A low voltage grid loss of 10% was applied for home-generated electricity delivered into and re-supplied from the grid.

Table 4 Energy factors (primary to delivered energy ratios) and CO_2 – equivalent emission factors Sources: (ecoinvent v1.3 2006) and (IPCC 2001 GWP 100a)

	Electricity mix for low-voltage electricity supply			Natural gas supply
	UCTE/ECOINVENT	Swiss average incl. import	CC power plant	As typical for Switzerland
PE factor *pef* (based on LHV) [MJ primary / MJ delivered energy]				
Renewable energy	0.281	0.611	0.0040	0.0021
Non-renewable energy	3.26	2.29	2.29	1.19
$CO_{2-Equiv}$ factor [kg/MJ delivered energy] [kg $CO_{2-Equiv}$/MJ end energy]	0.149	0.0396	0.129	0.0112
$CO_{2\text{-}Equiv}$ factor, including combustion IPCC 2001 GWP 100a [kg $CO_{2\text{-}Equiv}$/MJ end energy]				0.0672

The Swiss mix is mainly based on nuclear and hydro power (Swiss Energy, 2006). Therefore, the CO_2 emission factor as well as the non-renewable energy factor are low, as hydro power is generally considered a renewable energy.

Of all the possible electricity mixes, the combined cycle power plant (CCPP) mix is best suited as a reference, as it is related to an electricity generation which is based on the same fuel as the cogeneration systems analyzed (mostly natural gas), it is clearly identifiable by its technical processes and it may be seen as another innovative substitution technology. For the CCPP, an electrical efficiency of 58% (in relation to the LHV of NG fuel; this is the value used by the Swiss Federal Office of Energy for a state-of-the-art CCPP), a factor of 1.19 for primary energy to plant input according to the PE factor of natural gas and an electricity grid distribution loss of 11.7% of the delivered electricity were assumed.

In this study, unless otherwise stated, results are based on the UCTE electricity mix.

7 DESCRIPTION AND CHARACTERISTICS OF SYSTEM COMPONENTS

7.1 Modelling in TRNSYS

The systems were modelled using:

- Detailed mathematical models of the cogeneration components, developed and calibrated within IEA Annex 42 (Beausoleil-Morrison, Kelly, (eds). 2007), (Beausoleil-Morrison (ed). 2007)
- Performance map based models for the cogeneration units, were no calibrated data for the IEA Annex 42 models were available
- Non-standard TRNSYS model for the reference gas boiler
- Available non-standard TRNSYS model for ground coupled heat pump system
- Standard TRNSYS model of stratified and mixed storages
- Standard TRNSYS model of the solar collector
- Non-standard TRNSYS model for the energy manager and controller adapted to the individual cases
- TRNSYS Multi-zone building models with respective heat distribution and ventilation systems
- Standard electric and domestic hot water demand load profiles as specified within Annex 42 (Knight et al. 2007).

Details of the modelling of the individual components (models and respective parameters used) are given below in the description of the individual components, and in the Appendix of this report.

For the modelling of the MCHP devices, detailed dynamic component models and calibration data described in the Annex reports were used in cases where detailed enough performance data of the MCHP device were available. For the other cases simplified performance map models had to be employed, partially calibrated with results from laboratory experiments conducted within Annex 42 (Beausoleil-Morrison 2007), with manufacturer data, or with assumed performance data, extrapolated from existing values. Using the performance map based models led to somewhat too optimistic energy performance results as energies required for heat up and the cool down losses caused by the start/stop cycles were not accounted for. Further investigations need to be done in order to quantify these losses. However, in the cases analyzed, with the use of an appropriate control strategy and energy management, and the integration of buffer storage, the number of start/stop cycles were minimized.

7.2 Micro cogeneration devices

Cogen types and respective devices considered in this study comprise:

- existing prototypes and available commercial devices
- devices/systems to be developed in the future
- synthetic data of a virtual device in terms of power rate, electric and thermal efficiency characteristics (also at part load), temperature levels, etc.

Prototypes and available systems tested in the empiric evaluation cases of Annex 42 were selected with priority. However, also systems with extrapolated performance are considered that (i) are larger or smaller and (ii) more efficient than systems presently available today. However, as mostly only limited data were available for the system selected, it was challenging to establish inputs for an explicit and detailed model such as the Annex 42 model.

7.2.1 Solid oxide fuel cell (SOFC) unit

The considered SOFC unit has a nominal rating of 1kW electric and 2.5 kW thermal power output. The assumed performance characteristics are given in Fig. 6 as electrical and thermal efficiencies (in relation to the LHV of NG fuel) in function of the actual power input of the fuel (LHV) and for three water return flow temperatures (at inlet to SOFC unit). For modelling reasons, the temperature of the return flow (into the SOFC unit) and not the supply temperature (at SOFC outlet) must be specified. A back-up heater (see § 7.3) was assumed to cut in automatically if additional thermal power was needed. The generated electricity was directly used in the house or else delivered back into the electric grid. The electric grid was also used to cover peak demand.

The detailed dynamic Annex 42 model was used for the SOFC unit. Further details of the model capabilities and the model assumptions and limitations see (Beausoleil-Morrison, Kelly, (eds). 2007). Measured data of an actual prototype have been used to calibrate the model parameters. Fig. 7 shows the goodness of fit between efficiencies derived from measured data and those calculated with the model. After the calibration the electrical efficiency has suppositionally been improved (and as a result the model adapts the thermal efficiency accordingly). The resulting model input parameters are given in the Appendix. This assumed improvement of the electrical efficiency is based on industry expectations to be realistically achieved within the next couple of years. The efficiency specified is somewhat smaller than the electrical efficiency of actual large industrial SOFC systems. It seem reasonable for small residential SOFC systems considering that parasitic energy was also accounted for. The characteristics shown in Fig. 6 have been produced using the model with the parameters adjusted as described.

A modulation range from 480 W to 1kW electrical power output was assumed. The change of the modulation from one time step to the next was not restricted. This implies a maximum power output change of at least 0.6W/s which is a value probably too high for current prototypes.

The same SOFC unit was assumed to be installed in the SFH as well as in the MFH buildings, see Table 8.

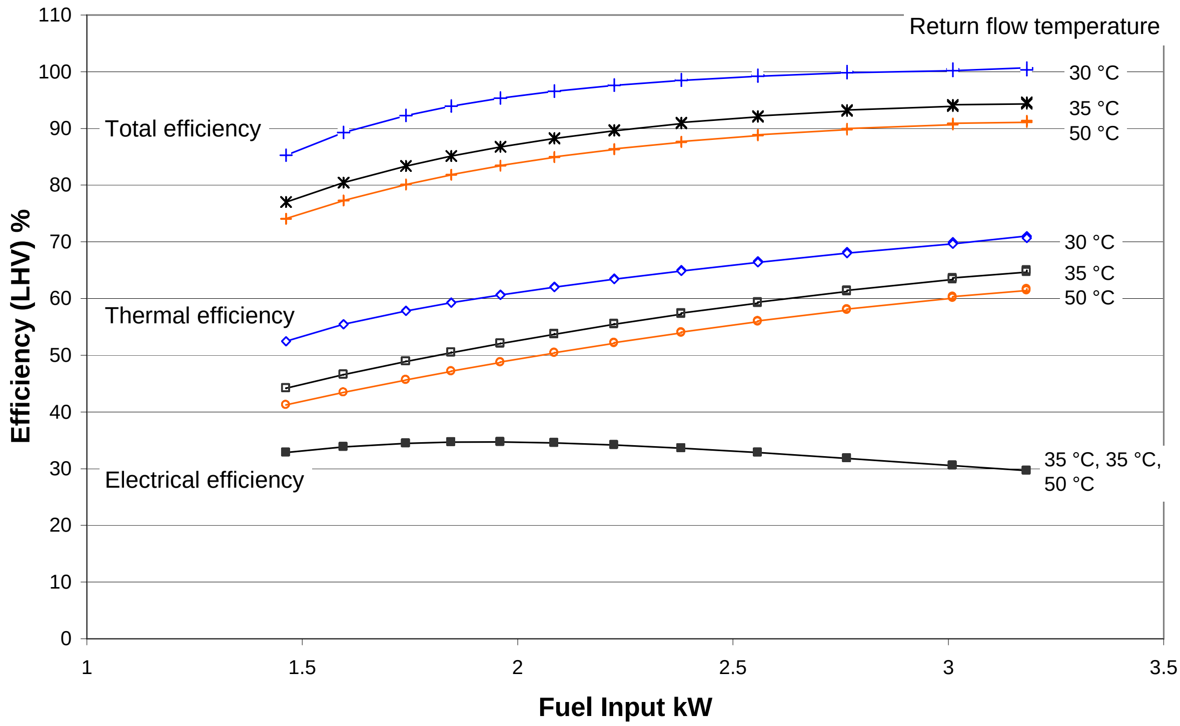

Fig. 6 Electric (AC to grid), thermal and total efficiency performance characteristics of the 1 kWe SOFC unit considered, in relation to the power input of the fuel (lower heating value), for three different levels of return flow temperatures

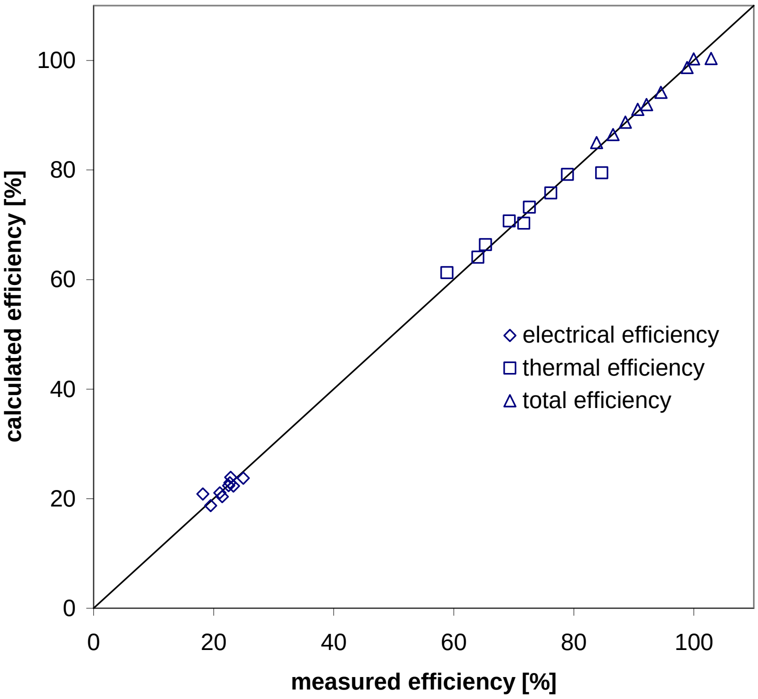

Fig. 7 Goodness of fit between efficiencies derived from measured data and those calculated with the model prior to the assumed improvement of the electrical efficiency

7.2.2 Polymer electrolyte fuel cell (PEMFC) unit

The considered PEMFC has a nominal rating of 4.6 kW electric and 7.0 kW thermal power output. The assumed performance characteristics are given in Fig. 8 as electrical and thermal efficiencies (in relation to the LHV of NG fuel) in function of the modulation ratio (ratio of actual to nominal fuel input), and for three temperature levels at the outlet of the PEMFC (supply temperature). Due to the assumed capacity, the PEMFC is considered to be installed and operated only in MFH. The generated electricity was directly used in the house or else delivered back into the electric grid. The electric grid was also used to cover peak demand. For the specification of the performance characteristics, experimental data of a prototype PEMFC unit, gained within Subtask B of IEA Annex 42 (Beausoleil-Morrison (ed.) 2007), were used. A simple performance map approach has been used to model the PEMFC device.

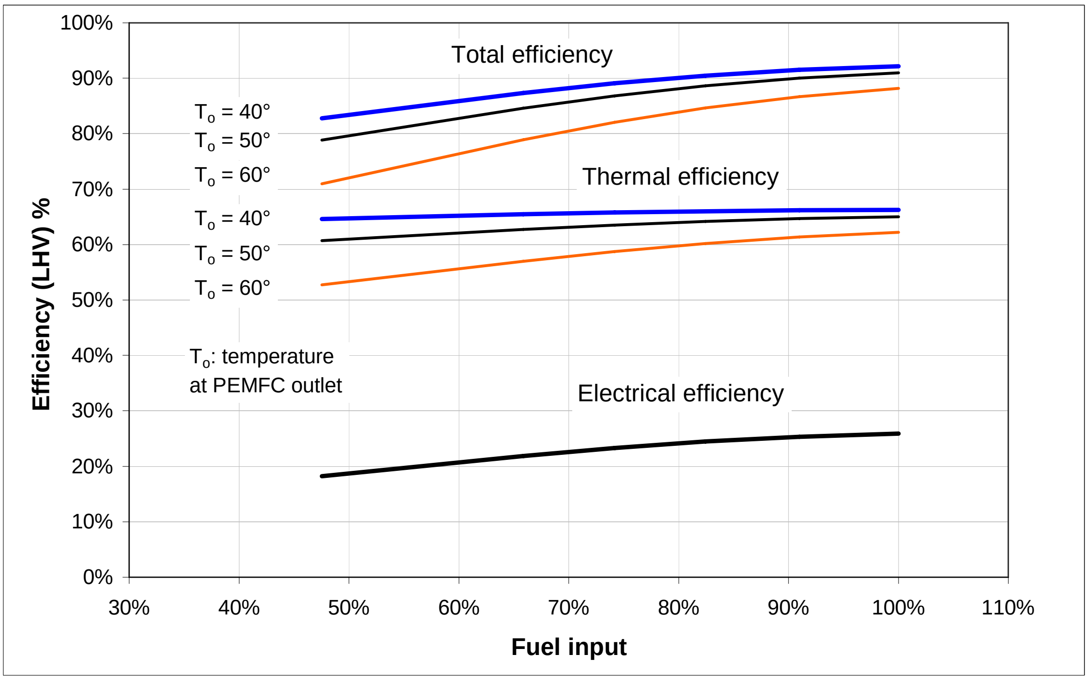

Fig. 8 Electrical (AC to grid), thermal and total efficiency performance characteristics of the 4.6 kWe PEMFC unit considered, in relation to the power input of the fuel (lower heating value), for three different levels of outlet/supply flow temperatures

7.2.3 Stirling Engine (SE) units

Two different types of SE units with different power levels are considered:

1. For SFH: SE unit with 0.75 kW nominal electric output
2. For MFH: SE unit with 9.50 kW nominal electric output

Table 5 shows some technical data of these units.

Table 5 Technical data of the SE devices considered for SFH and MFH

Stirling device	SE1 for SFH	SE2 for MFH
Performance at flow water temperature		50°C
Electrical power $\dot{Q}_{el}$	0.75 kW	2 - 9.5 kW
Thermal output $\dot{Q}_{heat}$	7.00 kW	8 - 26 kW
Electrical efficiency (LHV) η_{el}	9.3 %	22 – 24 %
Overall efficiency (LHV) η_{tot}	> 82 %	92 – 96 %
Maximal flow temperature	85 °C	65 °C
Boundaries for flow rate	8.5 to 15 l/min	8 - 33 l/min

<u>SE1 0.75 kWe for SFH</u>

Table 5 shows some technical data. For the performance assessment the Annex 42 SE model calibrated with measured data of a prototype SE device has been used. (Beausoleil-Morrison (ed). 2007).

SE2 9.5 kWe for MFH

To model the performance characteristics of the SE2 unit for MFH a simple performance map model based on manufacturer data of a commercially available device has been used. Table 5 gives some technical data and Fig. 9 depicts the characteristics of this unit.

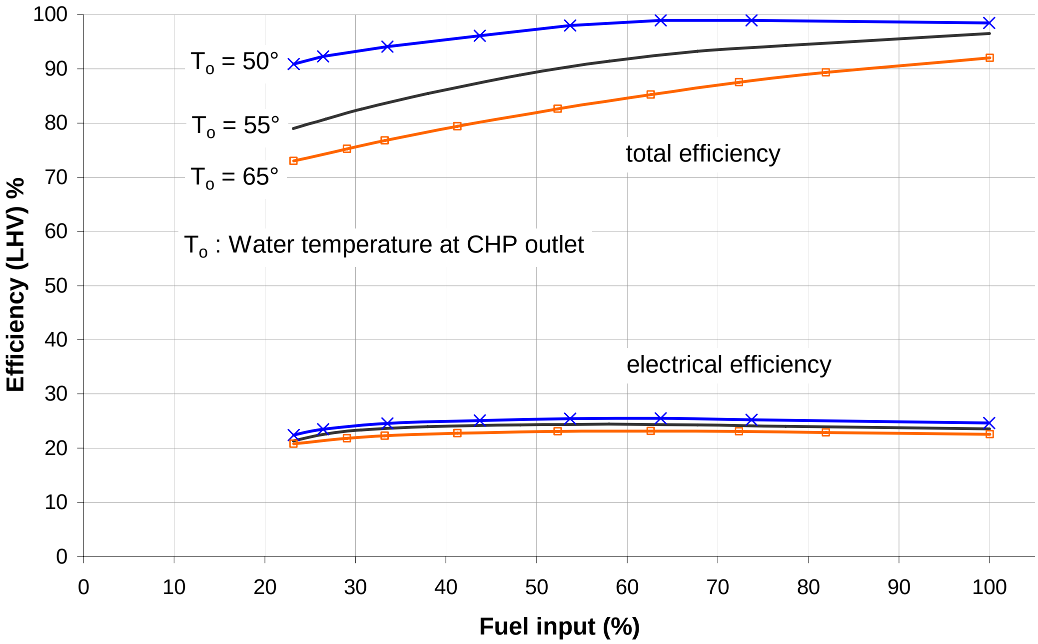

Fig. 9 Electrical and total efficiency performance characteristics of the 9.5 kWe SE unit considered for MFH, for three water temperature levels T_o for heat supply, at the outlet of the MCHP unit

7.2.4 Internal combustion engine (ICE) unit

Two different types of ICE units with different power levels are considered:

1. For SFH: ICE1 unit with 4.7 kW nominal electric output, with power modulation capacity
2. For MFH: ICE2 unit with 5.0 kW nominal electric output, with fixed power rate

Table 6 Technical data of the ICE devices considered for SFH and MFH

ICE device	ICE1 for SFH	ICE2 for MFH
Performance at flow water temperature		
Electrical power $\dot{Q}_{el}$	1.3 - 4.7 kW	5.0 KW
Thermal output $\dot{Q}_{heat}$	4.2 – 12.5 kW	14.6 kW
Electrical efficiency η_{el}	25 % (at max. power)	26 %
Thermal efficiency η_{tot}	69 %	63 %
Overall efficiency η_{tot}	94 % (at max. power)	89 %

ICE1 4.7 kWe for SFH

The basic performance data for the ICE unit considered are given in Table 6. and in Fig. 10. For a reasonable operation in SFH buildings, an ICE unit with an electric power output variability from 1.3 to 4.7 kWe was assumed. Data of a commercially available ICE MCHP device, measured in the frame of IEA Annex 42, have been used to calibrate a simple performance map model.

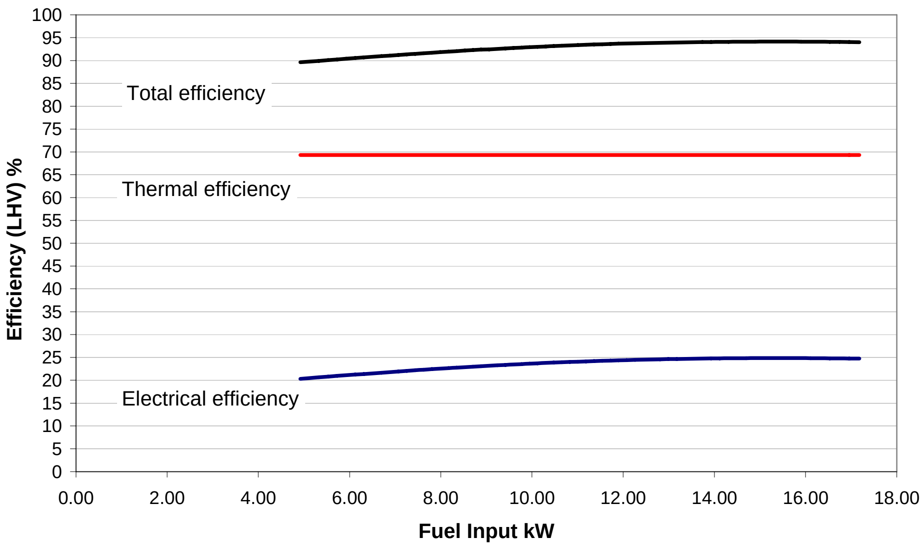

Fig. 10 Electrical, thermal and total efficiency performance characteristics of the 4.7 kWe ICE1 unit considered for SFH.

ICE2 5.0 kWe for MFH

For MFH the characteristics of an ICE unit with constant power output was considered. Table 6 shows the basic performance data. The IEA Annex 42 ICE model calibrated with data of an available unit measured within IEA Annex 42 (Beausoleil-Morrison (ed). 2007) has been used.

7.3 Reference and auxiliary heater

7.3.1 Condensing gas burner/boiler

State-of-the-art gas boilers, condensing and modulating in a wide range, were used for the reference cases and as back up/auxiliary heaters in the cogen systems. In both cases boilers with the same characteristics were used. The lowest modulation power and the nominal power for the different buildings are given in Table 7. The nominal utilization ratio is 108 % (LHV) for all types. Fig. 11 shows the assumed efficiency (LHV) of all used gas boilers depending on return flow water temperature and load. This characteristic is based on manufacturer data of an commercially available product. Dynamic thermal effects in relation to the thermal capacities of the boiler and water circuit involved were not considered.

Table 7 Lowest modulation power and nominal power of the gas boilers used for the different buildings

Building type	Swiss average building stock (Swiss av.)		SIA 380/1 target value (SIA target)		Passive House (PH)	
Lowest and nominal power (kW)	SFH	MFH	SFH	MFH	SFH	MFH
Reference used as benchmark	2.0 – 12.6	10.6 – 50.4	0.9 – 9	10.6 – 50.4	0.9 – 9	0.9 – 9
Back up heater for the FC system	0.9 – 9	10.6 – 50.4	0.9 – 9	2.0 – 12.6	0.9 – 9	0.9 – 9

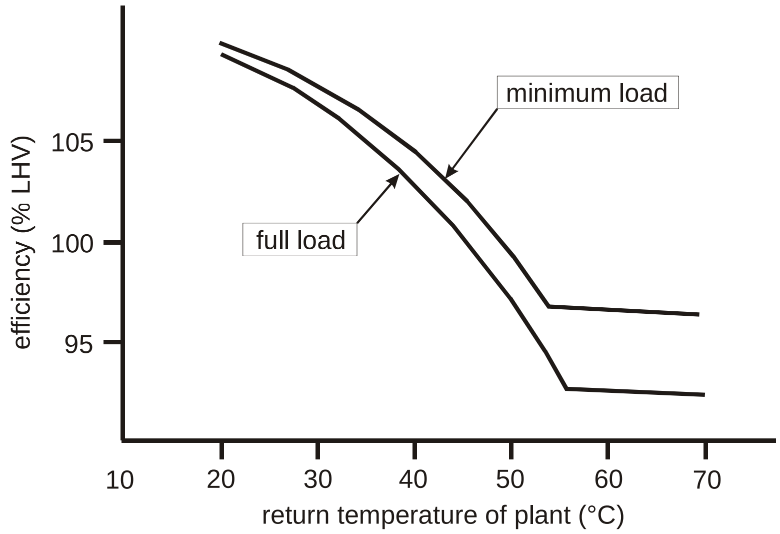

Fig. 11 Efficiency curve of the condensing gas boilers considered

7.3.2 Ground coupled heat pump (GCHP)

A ground coupled electrically driven heat pump was used as a reference system.

Heat pump

A heat pump with a nominal heating power of 6.0 kW was considered. The heating power and COP characteristics of the heat pump considered are depicted in Fig. 12for different heat source temperatures (at entry to evaporator) and supply temperatures (T_s). The values are based on manufacturer data and were used for the performance map model of the heat pump.

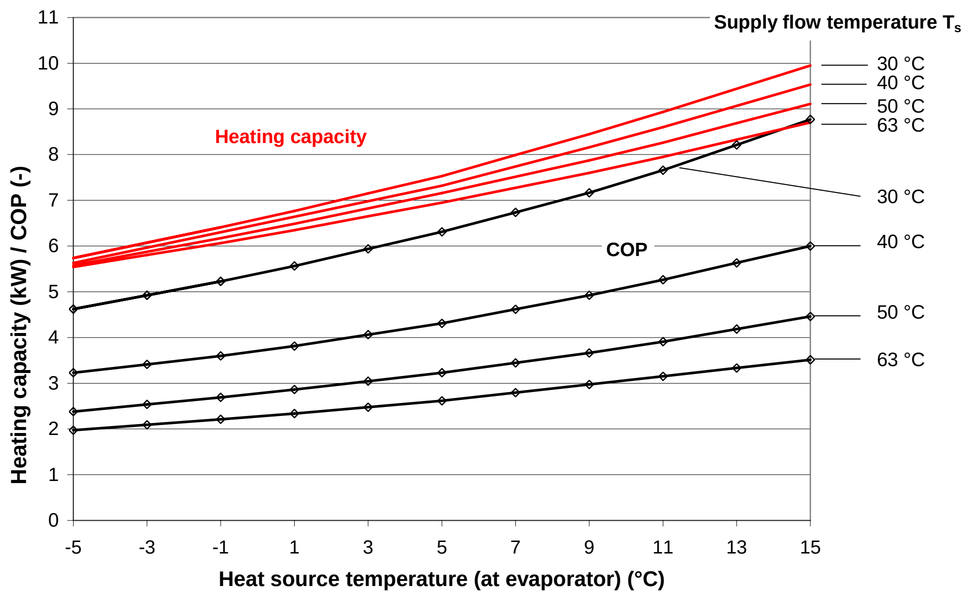

Fig. 12 Heating power capacity and COP curves of the considered heat pump, in function of the heat source temperatures (at entry to evaporator, for different levels of heat supply temperatures (Ts)

Ground coupling

In order to correctly reflect the energetic interaction of the heat pump and the ground, a dynamic ground storage model is used. The model by (Wetter & Huber, 1997) was used. This model calculates the transient heat flux in the earth within a radius of 2-3 m with the Crank-Nicholson algorithm. In the vertical direction, several layers can be considered. For the outer boundary conditions, an analytical formulation with a superposition scheme is applied. The long term (several years) transient effect of the ground storage leads to a reduction of the yearly mean earth temperature. Provided the borehole heat exchanger is correctly dimensioned, this reduction amounts to 0.5 to 1.0°C. In this study this has been accounted for by reducing the earth temperature at simulation start by 0.8°C.

For the SFH SIA building, a borehole of 100 m depth in dry soil / sand with a 32 mm diameter double U-pipe was assumed. The brine flow was 0.4 kg/sec. The electricity demand of the brine pump (120W) is accounting for approximately 7% of heat pump electricity demand. For the other buildings, the heat output of the borehole heat exchanger was scaled up or down, according to the heat demands for the building analyzed.

7.4 Hot water storage tank

Cylindrical tanks for DHW and buffer storage were used. For the buildings with low temperature floor heating, separate tanks for the DHW and the space heating buffer storage were assumed. For the buildings with high temperature radiator heating, and for all SFH with the non-modulating SE system, a combination storage was assumed. Basically. stratified storage is assumed, but the influence of mixed storage was analysed. The different storage sizes and types for all cases are given in Table 8. Rock wool insulation of 8 cm (thermal conductivity 0.04 W/m/K) was assumed for all storage sizes.

7.5 Solar collector

A solar collector for heating and DHW supply was combined with the SOFC cogen system and with the gas boiler. The flat-plate solar collector has an area of 6 m^2 per dwelling and is orientated along the building axes. The tilt angle was optimized for maximum solar yields. The solar fraction of the DHW production is 65-70 % with this system.

Solar collector thermal efficiency coefficients:

$$\eta = a_0 - a_1 \cdot \Delta T / G_k - a_2 \cdot \Delta T^2 / G_k$$

with:

ΔT = difference between mean collector fluid temperature and ambient temperature

G_k = solar irradiation

$a_0 = 0.787$; $a_1 = 3.68$; $a_2 = 0.0112$

In the non-heating period, the SOFC system is shut down, as the solar system delivers mostly enough heat in this period. The non-heating period is dependant on the individual building and load pattern.

7.6 Electric storage – grid connection

No electric storage (e.g. by batteries) was considered in this study. The electricity surplus generated by the cogen system was directly delivered to the grid and later potentially re-supplied, see 3.3.1 and Fig. 3. As mentioned already, a low voltage network loss of 10% was applied for home-generated electricity delivered into and re-supplied from the grid.

8 DESCRIPTION OF SYSTEMS

8.1 Systems

Basically the systems analysed comprise an energy conversion device, one combined or two separate storages for heating and domestic hot water, pumps and valves, and the control system.

Fig. 13 shows the schematics of all the system configurations analyzed in this study.

Three different systems were used as reference systems:

a) Condensing gas boiler as heat generator; grid electricity
b) Condensing gas boiler as heat generator combined with a solar collector; grid electricity
c) Electrically driven ground coupled heat pump; grid electricity

The performance of the following MCHP system configurations were compared with the performance of the above reference systems:

d) Grid coupled MCHP device with gas boiler as auxiliary heater
e) Grid coupled MCHP device with gas boiler as auxiliary heater combined with a solar collector

The configurations d) and e) differ depending on the building type: For building types "Passive House" and "SIA", configurations d1) and e1) apply, for building type "Swiss average", configurations d2) and e2) (see also Table 8).

The following 6 MCHP device types were used for configuration d) :

- SOFC 1.0 kWe
- PEMFC 4.6 kWe
- SE 0.7 kWe (for SFH) and 9.5 kWe (for MFH)
- ICE 4.7 kWe (for SFH) and 5.0 kWe (for MFH)

The system configuration e) was used only with the SOFC device. System configuration d) with the SOFC device was used to investigate the sensitivity of storage size and type and the influence of the demand profiles.

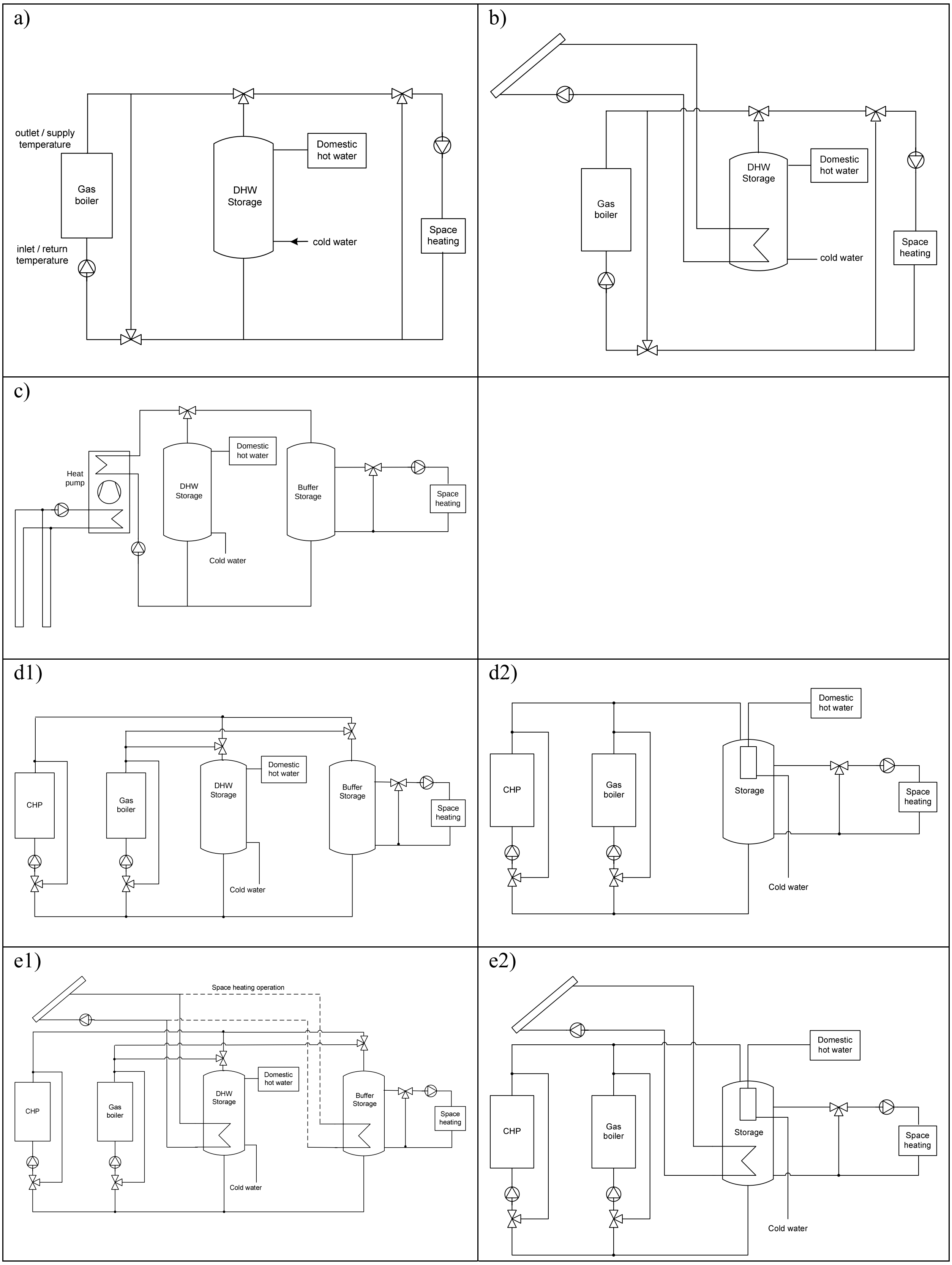

Fig. 13 Schematics of the investigated system configurations a) to e)

8.2 Control and energy management

8.2.1 General requirements for the control

The control system has to comply with a number of requirements. To some extent these requirements depend on the type of the MCHP or auxiliary heating device:

- Sufficient DHW available at any time
- Comply to the thermal comfort requirements of the building
- Minimize need for many load variations and changes in modulation of the device (i.e. equalize loads)
- Low supply temperature in order to allow for exhaust gas condensation
- Minimize the number of stop cycles in order to reduce the cool down losses (gas boiler and PEMFC)
- Maximize the run time of the MCHP device. The auxiliary burner should be used as rarely as possible
- No excess heat production (no heat dumping) (SOFC)

The requirement for an equalized load stems from the characteristics of the efficiency curve. As an example, one hour of full load operation and one hour in idle running does result in a lower average system efficiency compared to the systems running for two hours at 50% load.

8.2.2 Control modes

A heat demand following control mode was used in all cases analyzed. No restrictions on electricity export to the grid were assumed. The storage temperature level was controlled with a proportional-integral (PI) controller, described in more detail below. In cases with non modulating devices, 2- or 3-point controllers have been used.

8.2.3 PI – Control method

A proportional-integral (PI) control was used in most cases for the control of the storage. An individual heating curve (relation of space heating demand vs. outdoor air temperature) was determined for each building. A target value for the storage loading, established on the basis of this curve and the 24 h average outside air temperature, was used by a PI controller with anti-wind-up functions to define the actual heat production of the MCHP and/or the gas boiler system, see Fig. 14.

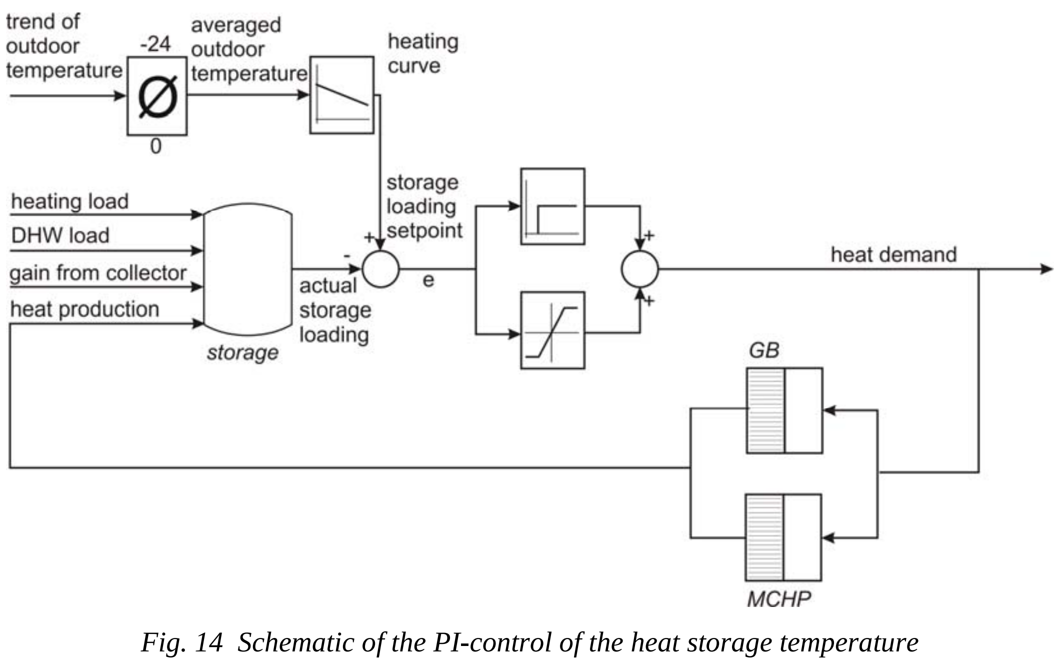

Fig. 14 Schematic of the PI-control of the heat storage temperature

The parameters selected for the PI controller had quite an important impact on the evolution of the temperature in the storage tank and as a consequence also on the split of the heat production between the MCHP unit and the gas burner, and in consequence on the primary energy demand. The usual objective of tuning the controller parameters, optimizing the accordance of the actual value with the set point value, does not lead to the best performance of the system. An example is given for the SFH SIA building with SOFC MCHP unit in Fig. 44 and Fig. 45.

8.2.4 Energy management and control strategies for the different systems

For the different systems, the following energy management and control strategies and methods were applied:

System a) gas boiler (GB)

The heat produced by the GB was transferred either directly into the space heating distribution system of the building or into the DHW storage. For space heating, the supply temperature was set according to the heating curve (dependant on the actual outdoor air temperature). The return temperature was determined by the model of the space heat distribution system (radiator or floor heating system). From the resulting supply-return temperature difference, the actual required space heating power $Q_{GBdemand}$ was determined. For the DHW heating, a 2-point control was used.

Systems b) gas boiler and solar collector (GB + SC)

The solar collector pump was operated with 2-point control as a function of temperature difference between collector inlet and outlet temperature.

Systems c) ground coupled heat pump (HP)

The ground coupled heat pump was operated with 2-point control for each storage, with an individual set point temperature for each storage. In order to enhance the individual operation periods of the heat pump, for the operation-on signal, the temperature at the top level in the storage tank was considered, and for the operation-off signal, the temperature at the lowest level in the storage tank.

System d) micro-cogeneration (MCHP)

For building types “Passive House” and “SIA”, configuration d1) with separate DHW storage and buffer storage for space heating was used. For the “Swiss average” building types, a combined storage for DHW and space heating was assumed according to schematics d2).

Also all SFH cases with the 0.75 kWe SE1 cogen unit were defined with a combined storage. In these cases a 3-point controller was used for the SE unit and the auxiliary GB.

A 2-point controller was used for the combined storage of the ICE2-system in the Swiss average MFH and an additional PI-controller for the auxiliary GB, as soon as the storage temperature fell below 55°C.

The heat for space heating was extracted from the buffer storage and mixed with water from return flow to get the required supply temperature according to the heating curve (dependant on actual T_a). The set-point temperature for the buffer storage was set about 10 K above the required supply temperature, dependant on the rolling 24 h average of the outside air temperature T_a. The actual required heat production was determined with a PI-controller (see Fig. 14) and the split of the heating power between MCHP and GB unit was defined as shown in Fig. 15.

For the SFH with SOFC cases: If the heat demand fell below $Q_{CHP-off,}$ the energy manager set the heat output on the level of Q_{CHPmin} to the DHW storage (overruling the two level controller set point) in order to avoid on/off cycling of the SOFC unit.

For the MFH SE2 cases, a second control loop was implemented in order to achieve long periods with continuous operation for the unit, in order to comply with the requirement that the SE2 unit should be shut down only once in an 24 h interval. This was particularly critical for PH buildings. When the PI controller output fell below Q_{CHPoff}, the energy manager kept the set point on Q_{CHPmin} and directed the heat output of the SE unit to the buffer storage, unless a threshold temperature of 63°C was reached in the buffer storage. If there was a heat demand for the DHW storage within this time sequence, the heat was supplied to the DHW storage (on the Q_{CHPmin} level).

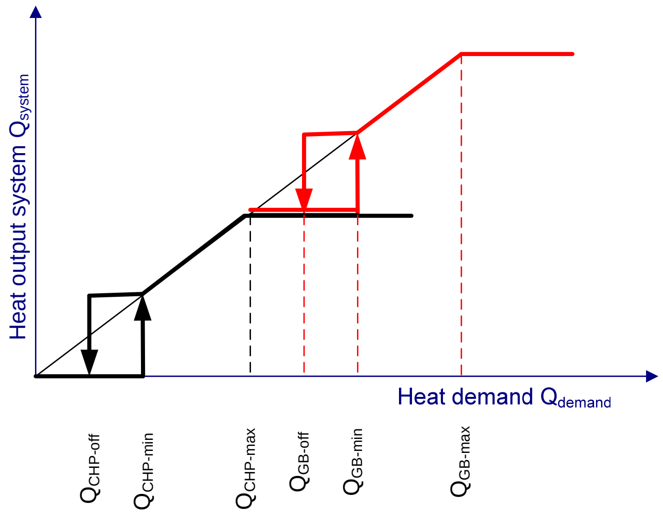

Fig. 15 Heat supply from MCHP and GB

For the cases with separate DHW storage, the DHW storage was controlled with a 2-level controller. For loading the DHW storage, the following strategies applied:

In the heating season:

- The SOFC and PEMFC units delivered Q_{CHPmax} to the DHW storage. During DHW-loading time periods, the auxiliary GB unit delivered heat according Q_{Demand} to the buffer storage
- The SE MFH unit simultaneously delivered (Q_{CHPmax} - Q_{Demand}) to the DHW storage and Q_{Demand} to the buffer storage.

Outside the heating season:

- SFH SOFC cases: The SOFC unit was shut down and the storage is loaded by the GB with Q_{GBmax}
- MFH SOFC cases: The 2-level controller switched between Q_{CHPmin} und Q_{CHPmax}
- MFH SE cases: The DHW storage was loaded with Q_{CHPmin}.

<u>System e) micro-cogeneration and solar collector (MCHP + SC)</u>

As for system b), the solar collector pump was operated with 2-point control as a function of temperature difference between collector inlet and outlet temperature.

During the heating season, the energy from the solar collector was supplied to the buffer storage, and outside the heating season to the DHW storage.

9 SYSTEM CASES AND CONFIGURATIONS

This chapter outlines the cases selected for the performance assessment. The influence of system parameters and external parameters on the selected assessment criteria was evaluated with a number of basic cases as the starting or reference case, mostly by performing single parameter sensitivity analysis methods. It is obvious that in this multi-dimensional parameter space only a very limited number of cases could be investigated. As a general approach, a base case was defined, from which then a variation in terms of lower/higher or less/more was defined, with the aim to identify the most influencing parameters.

9.1 Starting point for the definition of cases

For the selection and variation of cases, the definition of the starting points and the priority order of parameter are essential. In this respect of priority in parameter variation, two approaches were distinguished:

1. In the first approach, the definition of cases relied on cogen devices and systems which reflect existing products or prototypes in regard to performance levels and performance characteristics. The purpose of this approach was to investigate suitable application environments in terms of building type and size, and loads.
2. In the second approach, boundary conditions in terms of buildings, load profiles, etc. were fixed, and the investigations focused on which cogen unit capacity would be most appropriate for the selected case.

The first approach was mainly applied in this study for the definition of cases, however also the second approach was applied for selected cases (variation of MCHP capacity).

9.2 Reference cases

The reference cases were established on the following basis:

1. The external parameters and the buildings analysed are identical to the cases with the cogen devices.
2. The reference energy systems are based on best available conventional and already widely used supply technology, namely:
   - Condensing gas boiler, providing heat for space heating and for loading a DHW storage tank or condensing gas furnace for air heating and gas boiler for loading the DHW storage.
   - Ground coupled, electric driven heat pump
   - Electricity supply from the electric grid

Part load efficiencies were considered in an adequate manner as applied for the evaluation of the cogen systems.

9.3 List of cases analyzed

In Table 8 an overview of the cases analyzed in this study is given. First, the reference cases with traditional technology are listed, then the basis cogeneration systems, then the cases with combined solar thermal collectors, and the cases where individual system parameters, control options or boundary conditions were varied.

- Basic reference cases (16 cases)
- Basic MCHP system cases (20 cases)
- MCHP and solar collector (6 cases)
- Variations of storage type and size (9 cases)
- Variations of demand profiles (8 reference cases + 8 MCHP cases)
- Variation of capacity of SOFC and PEMFC units (7 cases each)
- Control parameters (2 cases)

Table 8 Overview of the cases

Basic reference cases (16 cases)

Case	Building		System	System configura-tion [1]	Storage size: DHW / Buffer Type: s / m [2]	Demand profiles	
	Size	Energy demand level				DHW	electrical
Gas boiler and grid electricity	SFH	PH SIA target Swiss average	Gas boiler	a)	200 l / - /s	moderate	moderate
	MFH	PH SIA target Swiss average	Gas boiler	a)	800 l / - /s	moderate	moderate
Gas boiler with solar collector and grid electricity	SFH	PH SIA target Swiss average	Gas boiler 6m^2 SC	b)	700 l / - /s	moderate	moderate
	MFH	PH SIA target Swiss average	Gas boiler 24m^2 SC	b)	2800 l / - /s	moderate	moderate
Earth coupled heat pump and grid electricity	SFH	PH SIA target (Swiss aver) [3]	Heat pump	c)	200 l / 500 l / s 200 l / 500 l / s	moderate	moderate
	MFH	PH SIA target (Swiss aver) [3]	Heat pump	c)	800 l / 2000 l / s 800 l / 2000 l / s	moderate	moderate

Basic MCHP system cases (20 cases)

Case	Building		System	System configura-tion [1]	Storage size: DHW / Buffer Type: s / m [2]	Demand profiles	
	Size	Energy demand level				DHW	electrical
MCHP device SOFC	SFH	PH SIA target Swiss average	SOFC 1 kWe	d1) d1) d2)	200 l / 500 l / s 200 l / 500 l / s 700 l comb / s	moderate	moderate
	MFH	PH SIA target Swiss average	SOFC 1 kWe	d1) d1) d2)	800 l / 500 l / s 800 l / 500 l / s 2800 l comb / s	moderate	moderate
MCHP device SE	SFH	PH SIA target Swiss average	SE1 0.7 kWe	d2) d2) d2)	700 l comb / s 700 l comb / s 700 l comb / s	moderate	moderate
	MFH	PH SIA target Swiss average	SE2 9.5 kWe	d1) d1) d2)	800 l / 2000 l / s 800 l / 2000 l / s 2800 l comb / s	moderate	moderate
MCHP device ICE	SFH	(PH) [4] SIA target Swiss average	ICE1 4.7 kWe	 d1) d2)	200 l / 500 l / s 200 l / 500 l / s 700 l comb / s	moderate	moderate
	MFH	PH SIA target Swiss average	ICE2 5.0 kWe	d1) d1) d2)	800 l / 500 l / s 800 l / 500 l / s 2800 l comb / s	moderate	moderate
MCHP device PEMFC	MFH	PH SIA target Swiss average	PEMFC 4.6 kWe	d1) d1) d2)	800 l / 500 l / s 800 l / 500 l / s 2800 l comb / s	moderate	moderate

[1] System configurations see Fig. 13
[2] Storage type: s: stratified / m: mixed
[3] Not analyzed, because supply temperature for the Swiss average houses are too high for a HP- system
[4] Not analyzed, because ICE system capacity is too high for this type of building

MCHP and solar collector (6 cases)

Case	Building		System	System configuration [1)]	Storage size: DHW / Buffer Type: s / m [2)]	Demand profiles	
	Size	Energy demand level				DHW	electrical
SOFC and solar collector (SC)	SFH	PH SIA target Swiss average	SOFC 1 kWe 6 m² SC	e1) e1) e2)	200 l / 500 l / s 200 l / 500 l / s 700 l comb / s	moderate	moderate
	MFH	PH SIA target Swiss average	SOFC 1 kWe 24 m² SC	e1) e1) e2)	800 l / 2000 l / s 800 l / 2000 l / s 2800 l comb / s	moderate	moderate

Variations of storage type and size (9 additional cases)

Case	Building		System	System configuration [1)]	Storage size: DHW / Buffer Type: s / m [2)]	Demand profiles	
	Size	Energy demand level				DHW	electrical
Storage type and size	SFH	PH SIA target Swiss average	SOFC 1 kWe	d1) d1) d2)	200 l / 100 l /s 200 l / 100 l /s 300 l comb /s	moderate	moderate
	SFH	*PH* *SIA target* *Swiss average*	*SOFC* *1 kWe*	*see basic MCHP system cases*			
	SFH	PH SIA target Swiss average	SOFC 1 kWe	d1) d1) d2)	200 l / 500 l /m 200 l / 500 l /m 700 l comb /m	moderate	moderate
	SFH	PH SIA target Swiss average	SOFC 1 kWe	d1) d1) d2)	200 l / 800 l /s 200 l / 800 l /s 1000 l comb /s	moderate	moderate

Variations of demand profiles (8 additional reference (GB) cases + 8 additional MCHP (SOFC) cases)

Case	Building		System	System configuration [1)]	Storage size: DHW / Buffer Type: s / m [2)]	Demand profiles	
	Size	Energy demand level				DHW	electrical
Demand profiles reference cases:	SFH	SIA target	GB	a)	200 l / - /s	low	low
	SFH	SIA target	GB	a)	200 l / - /s	low	moderate
Gas boiler and grid electricity	SFH	SIA target	GB	a)	200 l / - /s	low	high
	SFH	SIA target	GB	a)	200 l / - /s	moderate	low
	SFH	*SIA target*	*GB*	*see basic reference cases*		*moderate*	*moderate*
	SFH	SIA target	GB	a)	200 l / - /s	moderate	high
	SFH	SIA target	GB	a)	200 l / - /s	high	low
	SFH	SIA target	GB	a)	200 l / - /s	high	moderate
	SFH	SIA target	GB	a)	200 l / - /s	high	high
Demand profiles MCHP (SOFC) cases	SFH	SIA target	SOFC	d1)	200 l / 500 l /s	low	low
	SFH	SIA target	SOFC	d1)	200 l / 500 l /s	low	moderate
	SFH	SIA target	SOFC	d1)	200 l / 500 l /s	low	high
	SFH	SIA target	SOFC	d1)	200 l / 500 l /s	moderate	low
	SFH	*SIA target*	*SOFC*	*see basic MCHP system cases*		*moderate*	*moderate*
	SFH	SIA target	SOFC	d1)	200 l / 500 l /s	moderate	high
	SFH	SIA target	SOFC	d1)	200 l / 500 l /s	high	low
	SFH	SIA target	SOFC	d1)	200 l / 500 l /s	high	moderate
	SFH	SIA target	SOFC	d1)	200 l / 500 l /s	high	high

[1)] System configurations see Fig. 13
[2)] Storage type: s: stratified / m: mixed

Control parameters (2 cases)

Case	Building		System	System configuration [1]	Storage size: DHW / Buffer Type: s / m [2]	Demand profiles		PI control parameter K_p K_i
	Size	Energy demand level				DHW	electrical	
PI controller parameters	SFH	SIA target	SOFC 1 kWe	d1)	200 l / 500 l /s	moderate	moderate	K_p= 2095 [3] K_i= 83.8
	SFH	SIA target	SOFC 1 kWe	d1)	200 l / 500 l /s	moderate	moderate	K_p= 209.5 K_i= 8.38

Variation of capacity of SOFC and PEMFC units (7 additional cases each)

Case	Building		System	System configuration [1]	Storage size: DHW / Buffer Type: s / m [2]	Demand profiles	
	Size	Energy demand level				DHW	electrical
MCHP device SOFC	MFH	SIA target	SOFC 1 kWe, scaled from 0.5to 10 of nominal	d1)	200 l / 500 l /s	moderate	moderate
MCHP device PEMFC	MFH	SIA target	PEMFC 4.6 kWe, scaled from 0.1 to 2.0 of nominal	d1)	200 l / 500 l /s	moderate	moderate

[1] System configurations see Fig. 13
[2] Storage type: s: stratified / m: mixed
[3] PI – Parameters optimized for accordance of actual value with setpoint value

10 RESULTS

10.1 Basic MCHP system cases and reference cases

10.1.1 Annual non-renewable primary energy demand

For the basic systems analysed (see Table 8), the following figures show the results in terms of annual non-renewable primary energy (NRPE) demand, both for the energy carriers "grid electricity" and "natural gas". Results are given for the three electricity generation mixes, outlined in section 6.3.2.
A negative value of NRPE demand for grid electricity is given in cases where the net amount of electricity produced by the cogeneration systems is greater than the net amount of electricity demand (i.e. a net surplus of electricity delivered into the grid results).

Also included are results for the reference system "ground-coupled heat pump" (HP). The figures also include values in terms of reduction percentage of NRPE demand, compared to the reference system "gas boiler and grid electricity ". Negative percentage values indicate an increase.

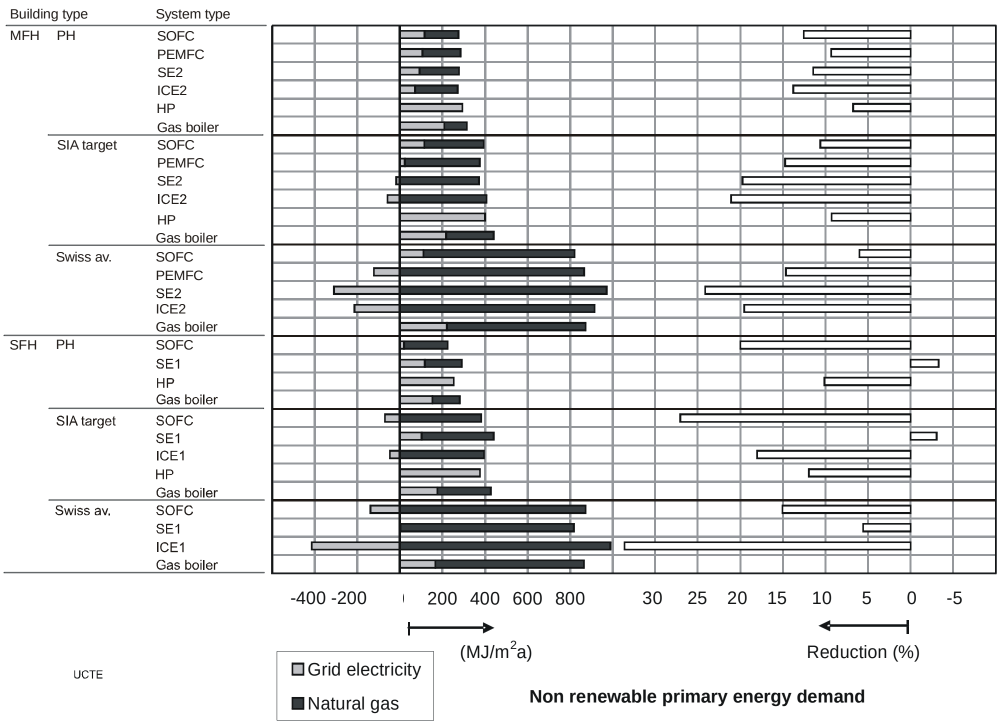

Fig. 16 Annual NRPE demand (MJ/m2.a) (for NG and grid electricity) of the basic building and system types analysed, and reductions of NRPE demand (%)compared to the GB reference system. UCTE mix

Compared to the "gas boiler and grid electricity" reference or benchmark system, for the UCTE electricity mix, most MCHP systems offered reductions in NRPE demand, except the SE system in the SFH SIA and PH building (Fig. 16).
Maximum reductions in NRPE demand resulted for the ICE in the Swiss average SFH building (34%) and the SOFC system in the SIA SFH building (27%), and for the SE unit in the Swiss average MFH building (24%). It has to be noted that all these reductions were also an effect of the surplus electricity generation, which was considered as a bonus and thus was subtracted from the energy demand value resulting for the house. However, also systems with no surplus electricity generation offered reductions of >10%. The increase for the SE system in the SFH SIA and PH building can be attributed to the low thermal and the very low electric effi-

ciency of the unit. Conversely the same SE unit gave a small NRPE reduction in the Swiss average SFH. This house has a high temperature heat distribution system for which the thermal efficiency of the reference GB system is also lower, as there was no possibility for flue gas condensation. High reductions resulted for the SE unit in the MFH buildings because this unit has relatively good overall and electrical efficiencies.

The results for the Swiss (Fig. 17) and the CC power plant (Fig. 18) mixes are practically identical, as the primary energy factors for these two electricity mixes are, coincidentally, practically identical. By far the largest NRPE reductions for these two electricity mixes resulted for the heat pump systems (up to 29%). The maximum reduction with a MCHP system was achieved with the ICE system in the Swiss av. SFH (14%), and with SOFC system in the SIA SFH building (12%). Again both these systems generated a surplus of electricity. Conversely, the SE systems in the PH and SIA SFH buildings led to a small increase in NRPE demand (due to the low electric and overall efficiency of the SE unit).

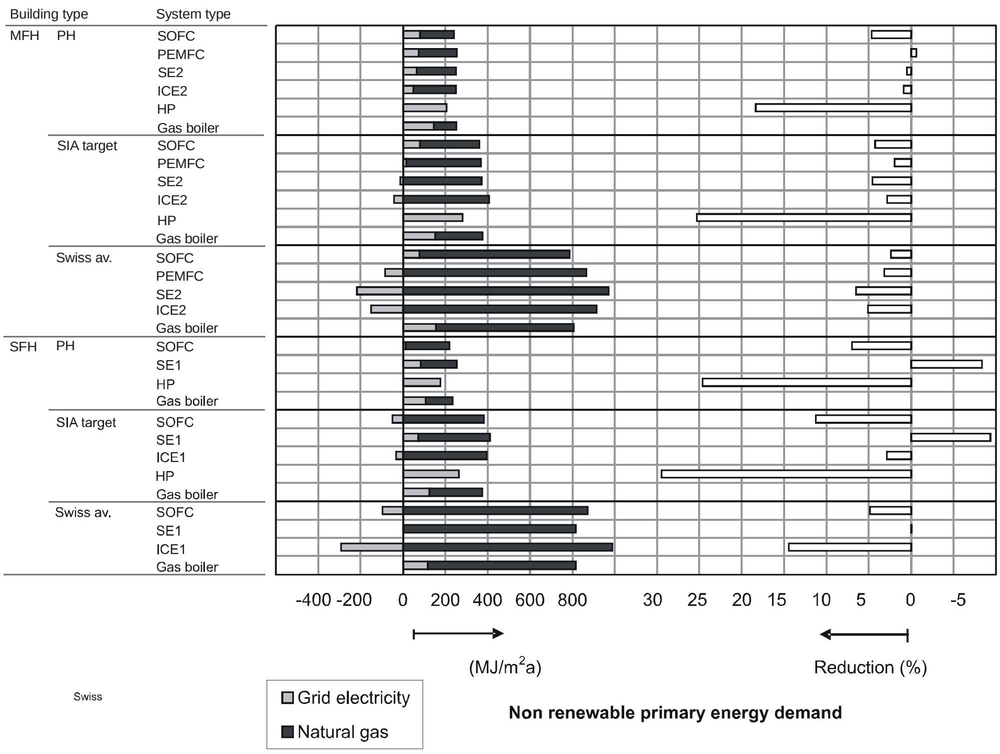

Fig. 17 Annual NRPE demand (MJ/m2.a) (for NG and grid electricity) of the basic building and system types analysed, and reductions of NRPE demand (%)compared to the GB reference system "Swiss incl. import" mix.

Fig. 19 summarizes the results for the reductions of annual NRPE demand compared to the GB reference system for the three grid electricity generation mixes considered.

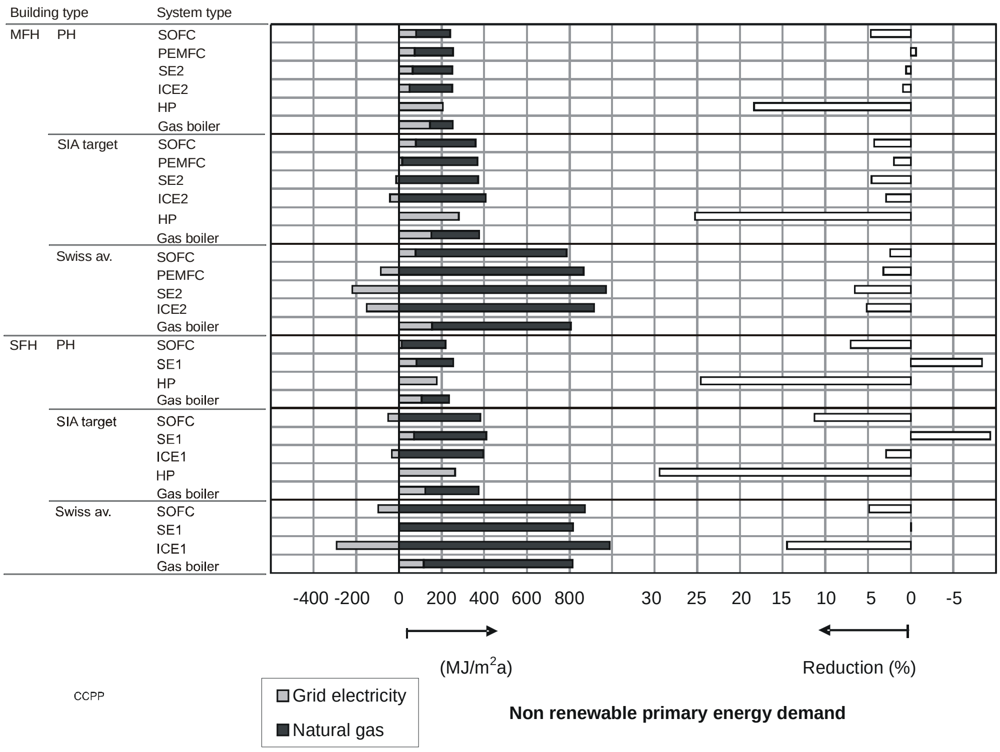

Fig. 18 Annual NRPE demand (MJ/m2.a) (for NG and grid electricity) of the basic building and system types analysed, and reductions of NRPE demand (%)compared to the GB reference system. "CC power plant" mix

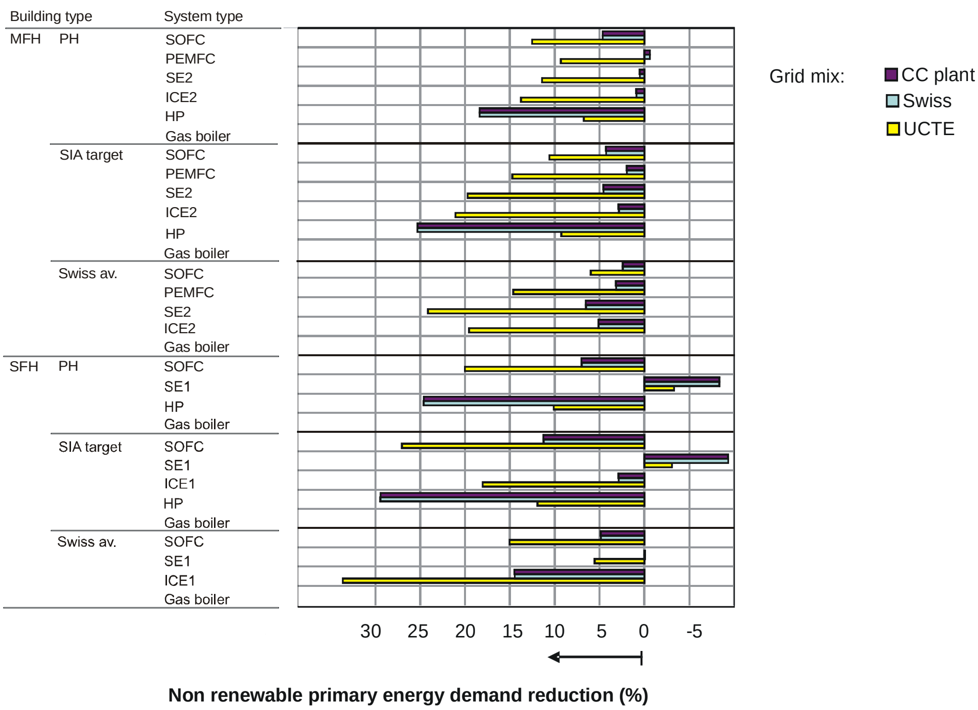

Fig. 19 Reductions of annual NRPE demand compared to the GB reference system for the three grid electricity generation mixes considered

10.1.2 *Non-renewable primary energy performance factor*

For the same basic systems as in 10.1.1 the following figures show the results in terms of non-renewable primary energy performance factor η_{NRPE} (see section 5.1.2). Results are again given for the three electricity generation mixes. The figures also include values in terms of improvement percentage, compared to the reference system “gas boiler and grid electricity “.

For the UCTE electricity mix (Fig. 20), an increase of up to 26% was achieved (SOFC in the PH SFH). For the Swiss and the CC plant mix (Fig. 21, Fig. 22) maximum improvements resulted again for the heat pump system (increase > 40%). For these mixes, the maximum increase with a MCHP system resulted for the SOFC system in the PH SFH (8%). For a number of systems, the performance factor was lower than for the reference system.

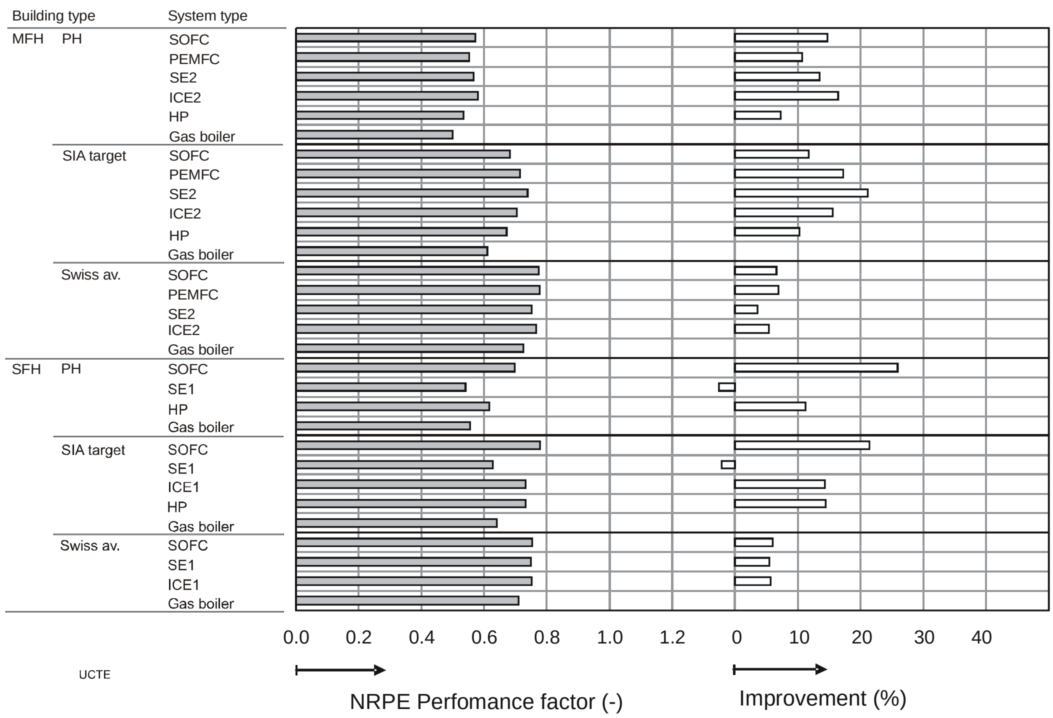

Fig. 20 NRPE performance factor of the basic building and system types analysed, and improvement compared to the NRPE performance factor of the GB reference system (%). UCTE mix

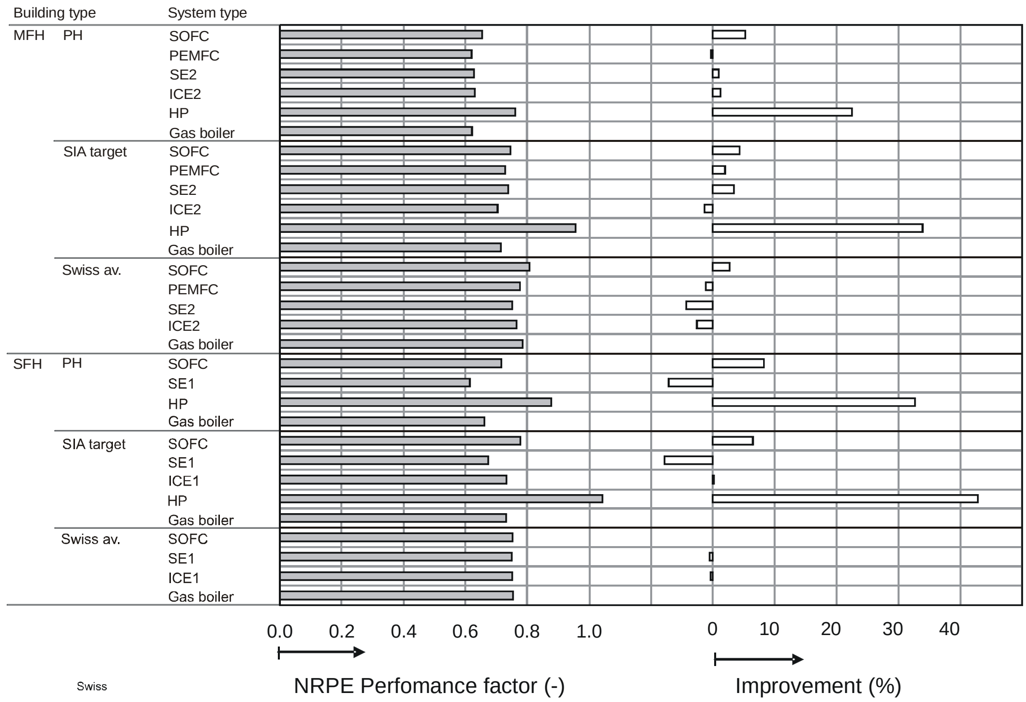

Fig. 21 NRPE performance factor of the basic building and system types analysed, and improvement compared to the NRPE performance factor of the GB reference system (%) "Swiss incl. import" mix

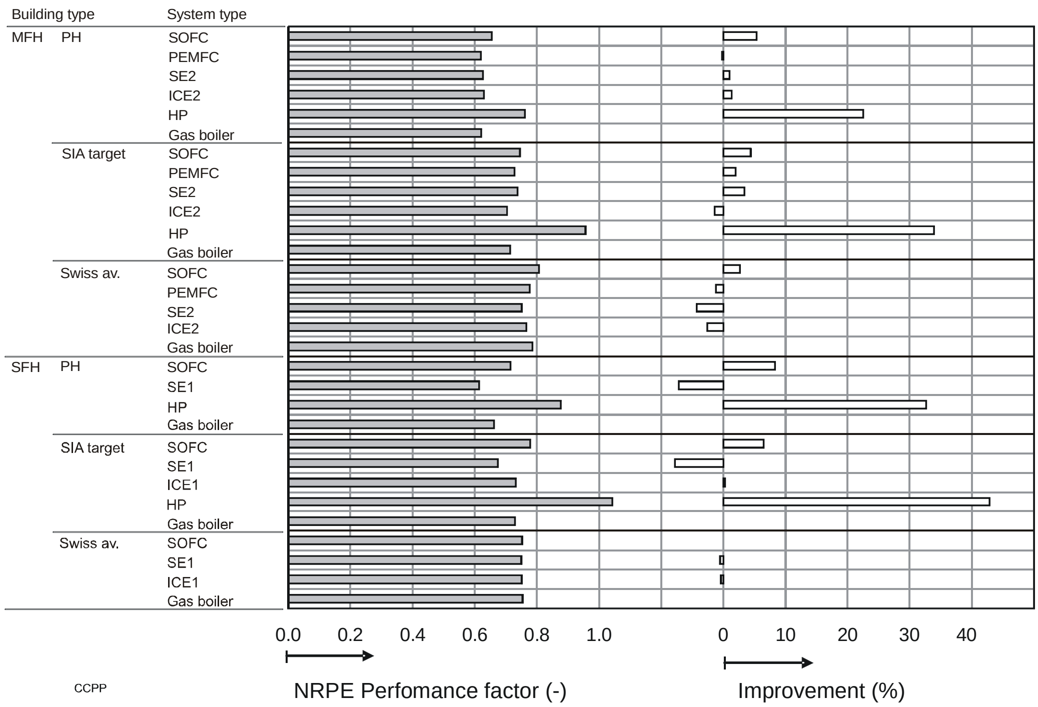

Fig. 22 NRPE performance factor of the basic building and system types analysed, and improvement compared to the NRPE performance factor of the GB reference system (%) "CC power plant" mix

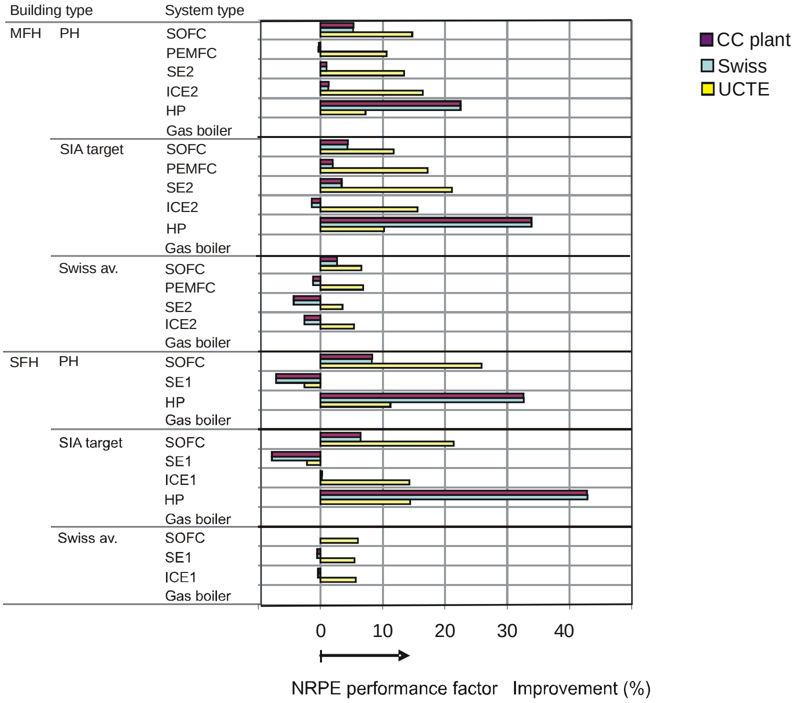

Fig. 23 Improvement of the NRPE performance factor, compared to the GB reference system for the three grid electricity generation mixes considered

10.1.3 Emissions

For the same systems as in 10.1.1 the following figures show the results in terms of CO_2-equivalence emissions. Results are given for the three electricity generation mixes, outlined in section 6.3.2. The figures also include values in terms of reduction percentage, compared to the reference system "gas boiler and grid electricity".

For the UCTE electricity mix (Fig. 24), most MCHP systems offered reductions in CO_2-eq emissions, except again the SE system in the SFH PH and SIA building due to its low thermal and electric efficiency. However, maximum reductions resulted not for a MCHP system, but for the heat pump system (24%). The maximum reduction with a MCHP system was achieved with the ICE system in the Swiss average SFH due to surplus electricity generation (23%), and with the SOFC system in the SIA SFH (17%).

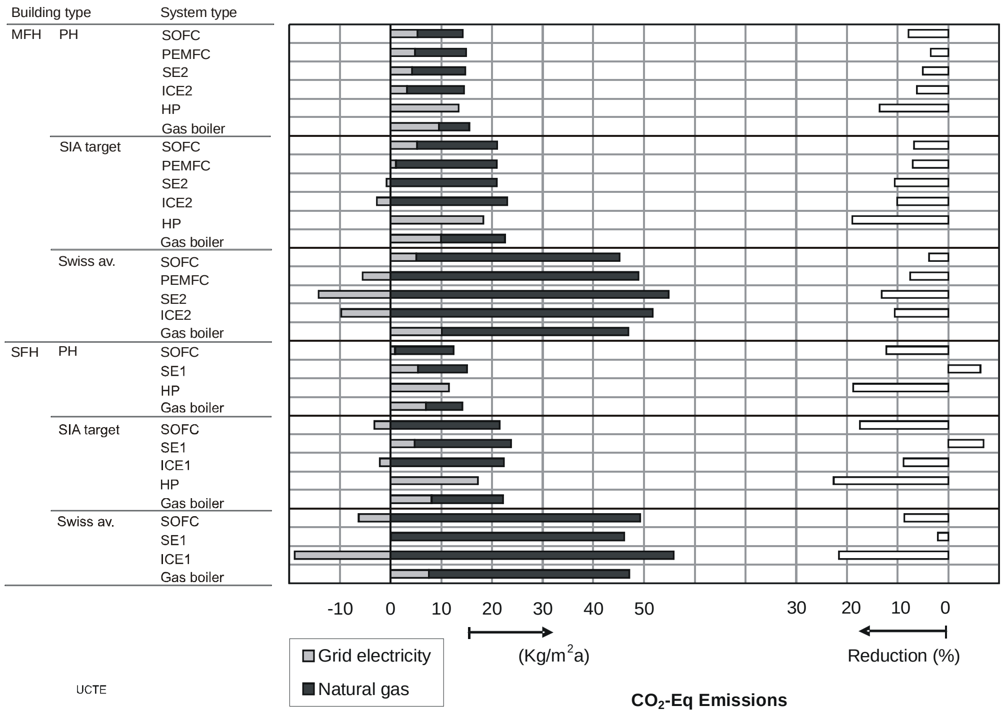

Fig. 24 Annual emissions of CO_2-eq(kg/m_2.a)(for NG and grid electricity) of the basic building and system types analysed, and reductions of $CO_{2,equiv}$ emissions compared to the GB reference system (%). UCTE mix.

For the Swiss mix with its very low CO_2 emission factor only the heat pump systems led to emission reductions, all of the MCHP system resulted in higher emissions (Fig. 25).

For the CC power plant mix (Fig. 26), maximum reductions resulted were again achieved with the heat pump systems (up to 29%). The maximum reduction with a MCHP system was achieved with the SOFC system in the SIA SFH (12%). Again, the SE systems in the PH and SIA SFH led to an increase in emissions.

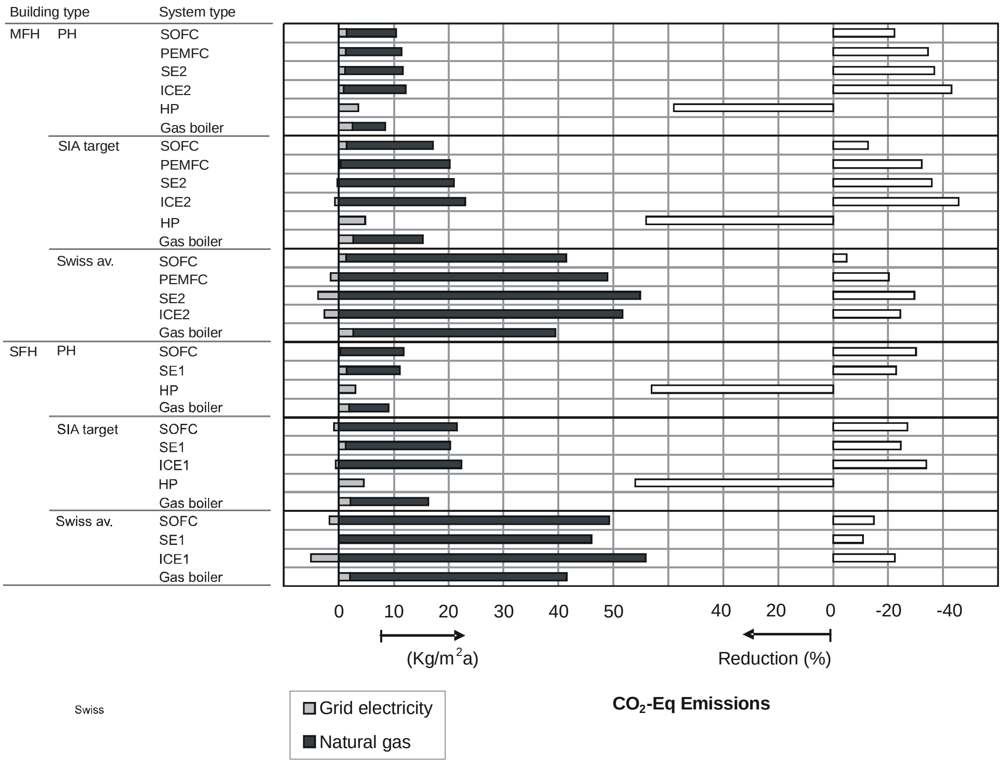

Fig. 25 Annual emissions of $CO_{2,equiv}$ (kg/m$_2$.a)(for NG and grid electricity) of the basic building and system types analysed, and reductions of $CO_{2,equiv}$ emissions compared to the GB reference system (%). "Swiss incl. import" mix

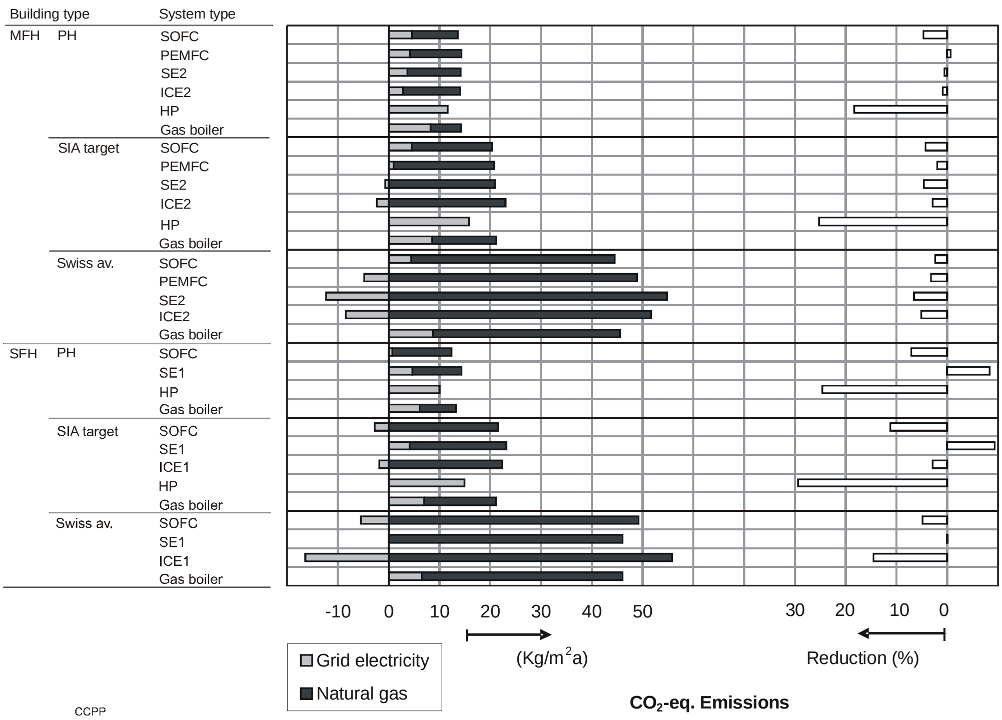

Fig. 26 Annual emissions of CO_2–eq (kg/m$_2$.a)(for NG and grid electricity) of the basic building and system types analysed, and reductions of CO_2–eq emissions compared to the GB reference system (%). "CC power plant" mix

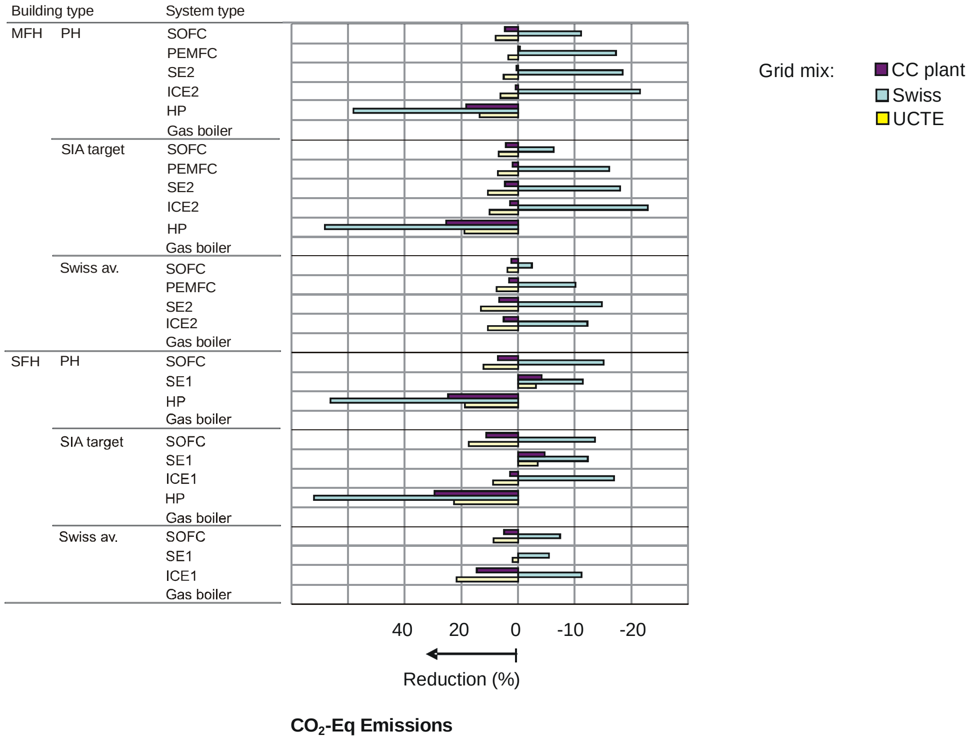

Fig. 27 ***R**eductions of annual CO_2–eq emissions (%), compared to the GB reference system for the three grid electricity generation mixes considered*

10.2 Combination with thermal solar system

The combination of a cogeneration system with a thermal solar system was analyzed for the SOFC system. The influence of a thermal solar system configuration is presented in relation to the system without thermal solar system and to the "gas boiler and grid electricity" reference case with and without solar thermal system. The results are shown graphically in the form of a relative performance p.

$$p_I = \frac{P_{system,I} - P_{ref}}{P_{ref}} \quad , \quad p_{II} = \frac{P_{system,II} - P_{ref}}{P_{ref}}$$

With:

- Reference system	Gas boiler (GB)
- System I:	SOFC system (SOFC)
- System II:	Gas boiler and solar collector (GB&SC)
- System III:	SOFC system and solar collectors (SOFC&SC)

The relative comparisons of the different systems might also be of interest, thus besides p_I and p_{II} , the incremental changes from the System I or II (SOFC or GB&SC) to system III (SOFC&SC). Thus, $p_{III\text{-}I}$ and $p_{III\text{-}II}$ are presented as:

$$p_{III-I} = \frac{P_{system,III} - P_{system,I}}{P_{ref}} \quad , \quad p_{III-II} = \frac{P_{system,III} - P_{system,II}}{P_{ref}}$$

Starting from the gas boiler system, an initial reduction can be achieved by one of the following two options: a) replacement of gas boiler by SOFC or b) combination of gas boiler with solar collector (GB&SC). Which of these two options is more favourable depends on the NRPE factor of the grid electricity. A further reduction can be achieved by the combination of the fuel cell with a solar collector (SOFC&SC). The result for the SFH and MFH buildings are shown in Fig. 28 and Fig. 29 respectively. For each building type, the upper bar shows the case where first the SOFC system was installed and then the solar collector (SC), and the lower bar shows the case where first the solar collector was installed, and then the SOFC system. The resulting reduction due to one of the two options a) or b) depends on which step it was applied. The application of a specific option in the second step usually showed a smaller incremental reduction than if the same option was applied in the first step. (compare e.g. the reductions due to the SC (white bar) in the upper and the lower bar of the same building).

In general, higher reductions resulted for the SFH. Not surprisingly, the integration of solar collectors always lowered the NRPE demand. However, in the MFH, where the SOFC was operated continuously the whole year, the SC competed more with the SOFC. In the summer period, the heat provided by the solar collectors increased, and thus the number of full-load operating hours of the SOFC was reduced. Consequently, the amount of the electricity supplied from the grid (with a high NRPE factor) was raised. Hence, for the MFH, the difference of incremental reductions in the first or second step was more pronounced than for SFH. The benefits of the fuel cell system compared to the gas boiler system were less significant for configurations with solar collectors than for configurations without them.

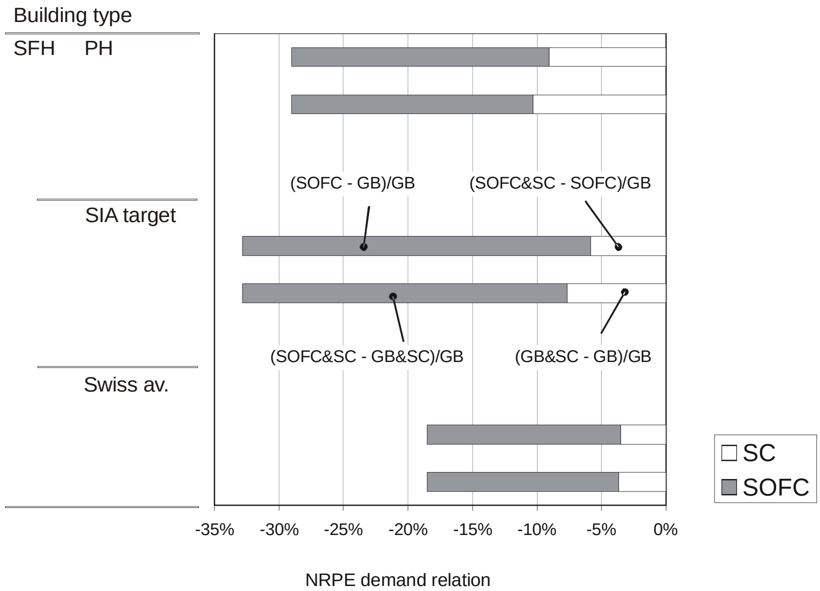

Fig. 28 Comparison of different systems without and with solar collectors ("& SC"), expressed as percentage ratio of NRPE demand of the system, related to the demand standard gas boiler system without solar collector (GB). SFH buildings. UCTE electricity mix.
Example: "(SOFC&SC- SOFC)/GB" is the NRPE demand reduction for the SOFC system with solar collector (SOFC&SC) compared to the demand of the SOFC system without solar collector (SOFC), in relation to the demand of the gas boiler system (GB).

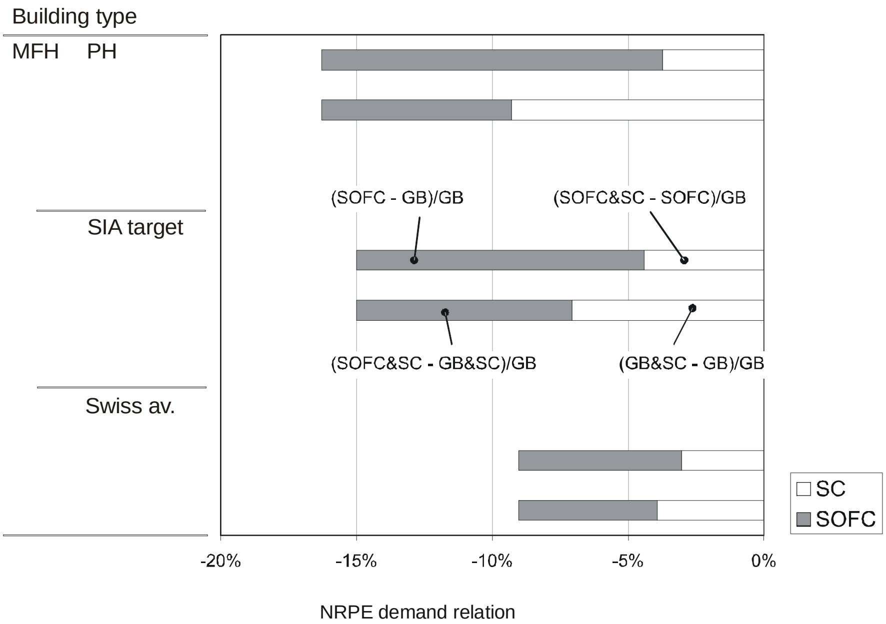

Fig. 29 Comparison of different systems without and with solar collectors ("& SC"), expressed as percentage ratio of NRPE demand of the system, related to the demand standard gas boiler system without solar collector (GB). MFH buildings. UCTE electricity mix.

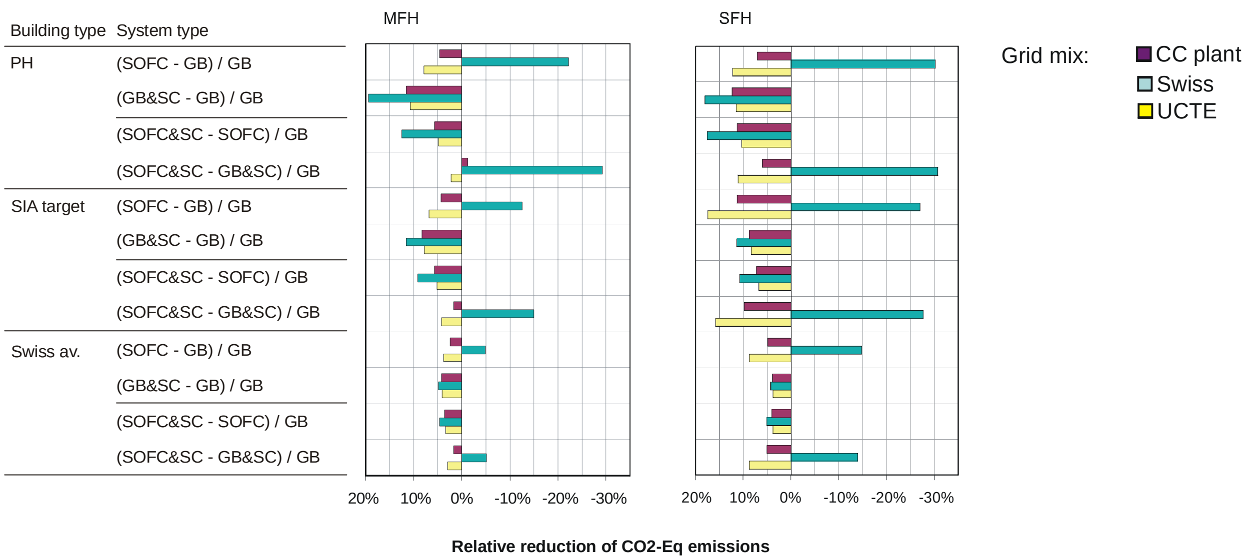

Fig. 30 Comparison of different systems without and with solar collectors ("& SC") in terms of annual CO_2–eq emissions, expressed as percentage of CO_2–eq emission reduction in relation to standard gas boiler system without solar collector (GB), for the three electricity generation mixes

10.3 Equivalent annual full load operation hours

Comparing heat load duration curves with the respective system heat output curves is very helpful to assess the dimensioning of the system (i.e. "does the system output match the effective heat loads?") or vice-versa to assess the applicability range for a certain type of MCHP unit (i.e. "do the loads match the system capacity?"). This is outlined for a number of cases in the sections below.

10.3.1 Load duration curves

The following figures give examples of thermal load duration curves and the respective heat output duration curves for the SOFC and the auxiliary gas burner unit respectively, for the SIA SHF and MFH building types.

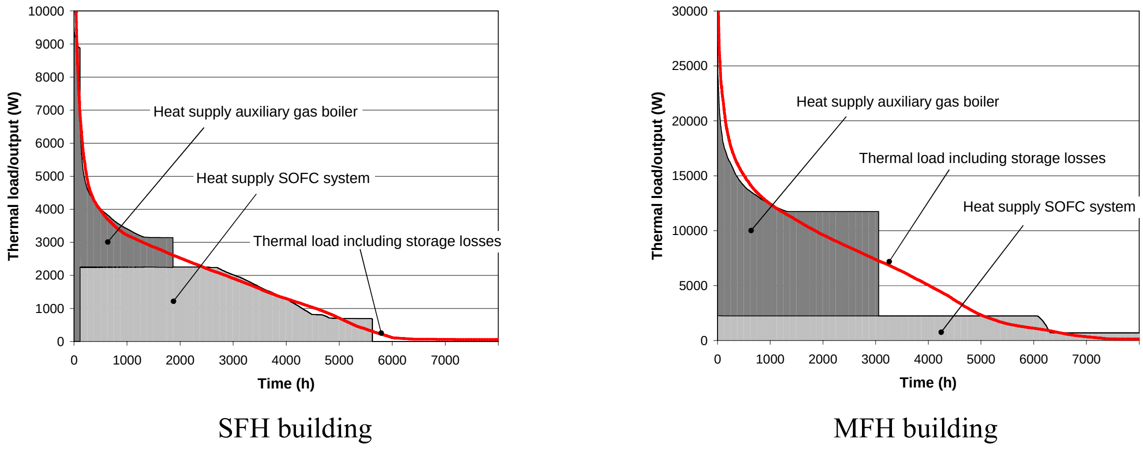

Fig. 31 Thermal load and heat output duration curves for the SOFC system and the SFH (left) and MFH (right) SIA building type

In the figure for the SFH, the duration curve for the SOFC does not start at time 0, because the GB is operated with its full capacity, namely for DHW heating, only during non-heating season, when the SOFC system was shut down. In the figure for the MFH, the function of the heat storage is clearly visible in the regions where the figures for load and output do no match. It is also obvious that the capacity of the SOFC actually is too small for this type of MFH building.

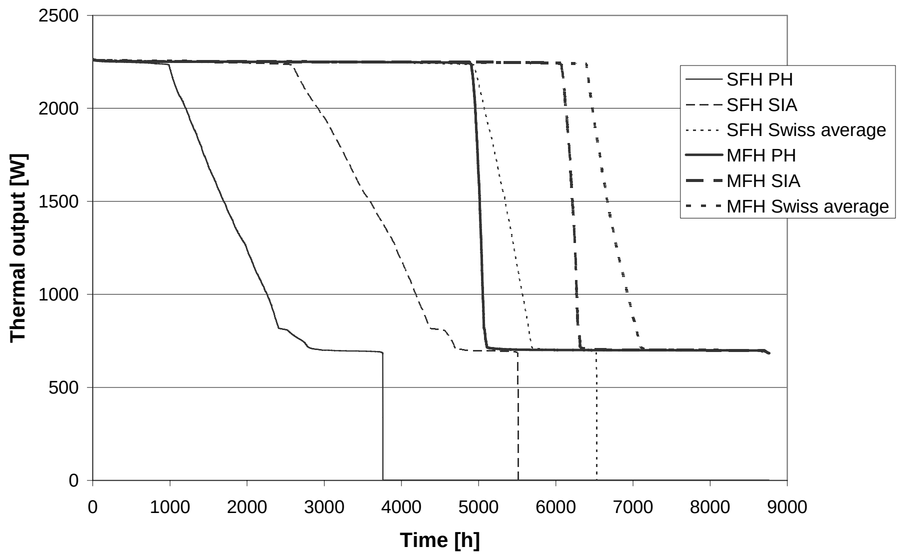

Fig. 32 Histogram of part-load (modulation) ratios for SOFC system without solar collector in heat-following mode, for one-year operation period, for the six building types considered.

Fig. 32 shows that only for the SFH buildings the SOFC system ran at part load for a significant period. In the MFH buildings, the system more or less either ran at full load, or was operated at minimum power.

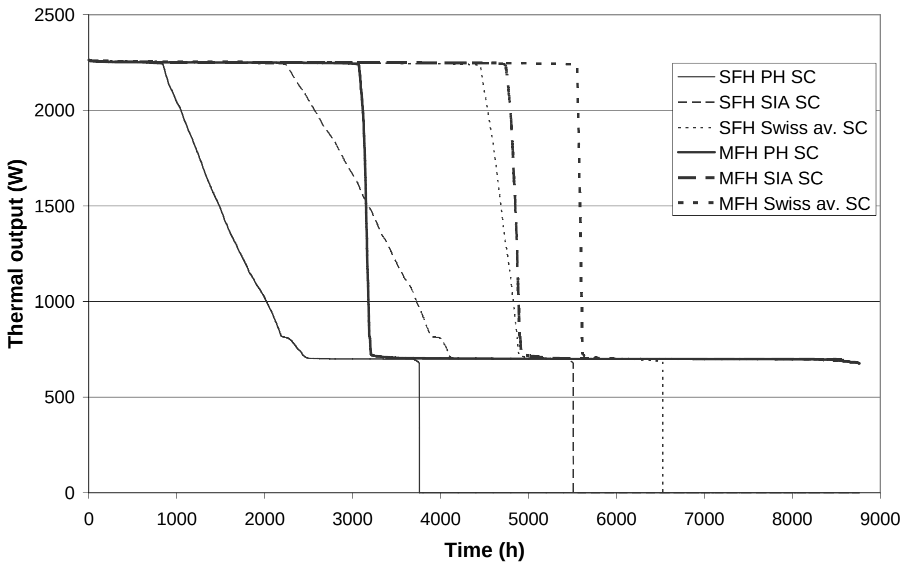

Fig. 33 Histogram of part-load (modulation) ratios for the SOFC system combined with solar collector, in heat-following mode, for one-year operation period, for the six building types considered.

Fig. 33 shows that the combination with the solar system, the number of operating hours was reduced for both the SFH and MFH buildings. This can be attributed to the reduced demand for heat from the cogeneration unit, as the solar system also contributes.

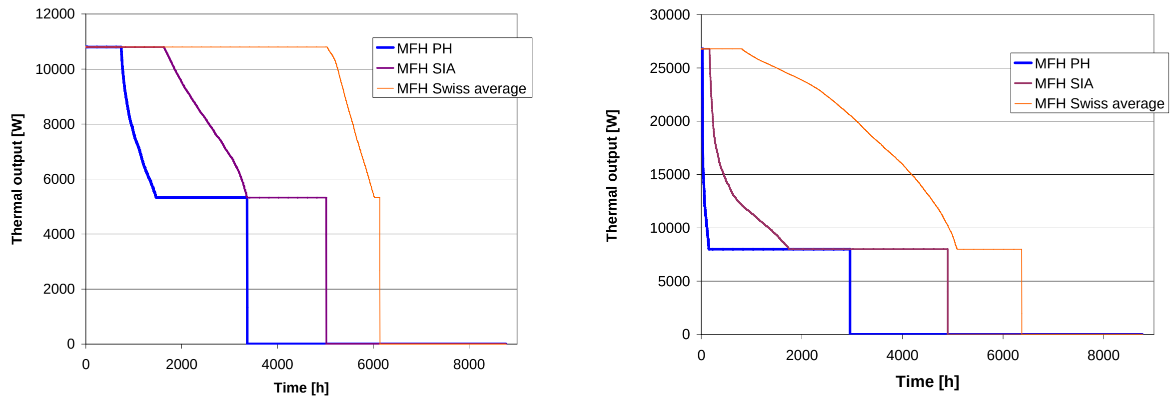

Fig. 34 Histogram of part-load (modulation) ratios for the PEMFC system (left) and the SE system (right), in heat-following mode, for one-year operation period, for the MFH building types considered.

For the PEMFC and SE systems, only reduced numbers of equivalent full load operating hours resulted, even for the MFH buildings. Especially for the SE system, only in the Swiss average building, the thermal system output was used on a reasonable level (Fig. 34 right). This clearly shows, that the thermal capacity of this type of SE system is actually too high for the selected building types. The same applies for the ICE system in the SFH, where in the SIA building type the full thermal capacity was actually used only for the DHW heating, and for space heating the system practically always ran at minimum power.

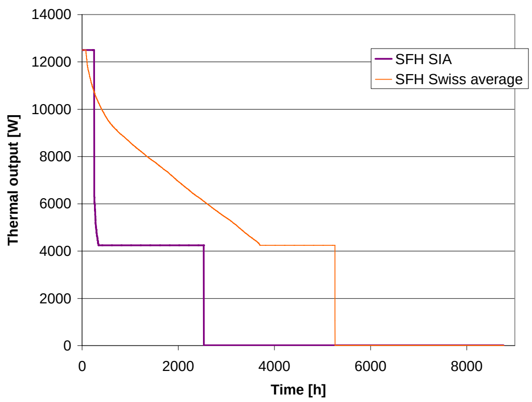

Fig. 35 Histogram of part-load (modulation) ratios for the ICE system, in heat-following mode, for one-year operation period, for the SFH SIA and Swiss av. building types.

For a number of basic cases, in Table 9 values are given for the annual equivalent annual full-load operating hours ratio. This ratio relates the number of equivalent annual full-load operating hours to the total number of hours per year (8760 h/a).

Table 9 Equivalent annual full-load operating hours ratio of different MCHP systems and of combined SOFC-solar system. Basic configurations and boundary conditions.

Equivalent annual full load operating hours ratio (h/ 8760 h)	Swiss average	SIA	Passive House (PH)
SOFC system			
SFH *)	0.65	0.48	0.27
MFH *)	0.84	0.80	0.71
SOFC and solar thermal system			
SFH *)	0.60	0.45	0.25
MFH *)	0.75	0.69	0.56
PEMFC system			
MFH *)	0.67	0.43	0.25
SE system			
SFH	0.52	0.15	0.08
MFH *)	0.49	0.21	0.10
ICE system			
SFH *)	0.31	0.12	-
MFH	0.68	0.42	0.23

*) System operating with power modulation

For a number of systems, very low equivalent annual full load operating hours resulted (especially for the SE systems in the SIA and PH SFH and MFH buildings, and the ICE system in the SIA SFH. This indicates that the (thermal) capacity of the systems is oversized for the respective type of building.

10.4 Influence of MCHP capacity (power size of MCHP unit) on NRPE demand

Dynamic simulations were performed for the MFH SIA building type for a one year period in order to investigate the influence of the capacity of the MCHP unit on the NRPE demand and on the emissions for a given situation. The MCHP capacity was scaled (scaling factor = 1.0 means the simulations with the original units as used in the basic cases). For simplification, the efficiency characteristics of the MCHP unit relative to the scaled capacity were kept unchanged, albeit larger system normally have better efficiencies.

In the analysis, additional functionalities of the energy manager were necessary for larger unit capacities to avoid on/off cycling of the SOFC. This could be achieved e.g. by switching the thermal output of the SOFC (at minimum rate) to the DHW storage instead of switching it off according to the PI-controller output. The heat output was then switched back to the buffer if, as a consequence, the temperature in the DHW storage raised above a defined threshold. Increasing the unit capacities also required the integration of functions to allow for heat dumping.

The influence of the MCHP capacity was analyzed in terms of relative savings in NRPE demand, as a function of the ratio annual heat output of FC unit ($OE_{th\text{-}FCU}$) to annual net thermal energy demand of the building (for SH and DHW) ($NE_{th\text{-}Build}$). The analysis was performed for the SOFC (Fig. 36) and the PEMFC (Fig. 37) system, for the two electricity generation mixes UCTE and Swiss.

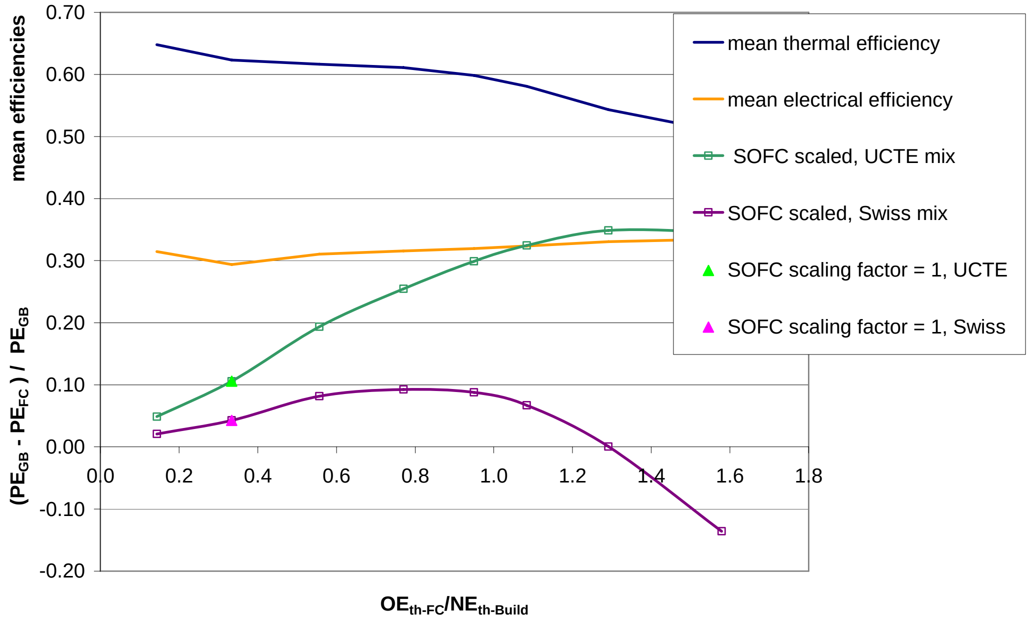

Fig. 36 Difference between NRPE demand of SOFC fuel cell system equipped building (PE_{FC}) and NRPE demand of reference building with gas boiler system (PE_{GB}), weighted with PE_{GB} , as a function of the ratio of specific annual thermal output of fuel cell cogen unit ($OE_{th\text{-}FC}$) to total annual heat demand of building ($NE_{th\text{-}Build}$), Also shown are the resulting mean electrical and thermal efficiencies. Results are given for the UCTE and the Swiss electricity mix.

The results showed that the optimal ratio of annual FC unit thermal output to annual building heat demand was dependant on the electricity mix and on the characteristics of the electric efficiency curve of the FC unit. While for the PEMFC the optimal ratio value depending on the electrical mix was between 0.7 and 0.9, for the SOFC values around 0.8 for the Swiss mix and values around 1.3 resulted for the UCTE mix. This is because the optimum electrical efficiency of the SOFC unit is at part load. Therefore a larger unit, operating for a longer time period at part load than a smaller unit, is more favourable even if some of the generated heat had to be dumped at certain times. The opposite is true for the PEMFC were the highest electrical efficiency is at full load.

The original SOFC system (scaling factor=1) had a ratio FC unit output/building heat demand of 0.33. To reach a ratio of 0.8, a SOFC system with 3 times larger capacity would be required in this MFH SIA type of building. To reach a ratio of 1.3, which is a the optimum at UCTE electrical mix, a scaling factor of 7 would be required. On the other hand, looking at the PEMFC system, the original PEMFC capacity matched quite optimally the heat demand level.

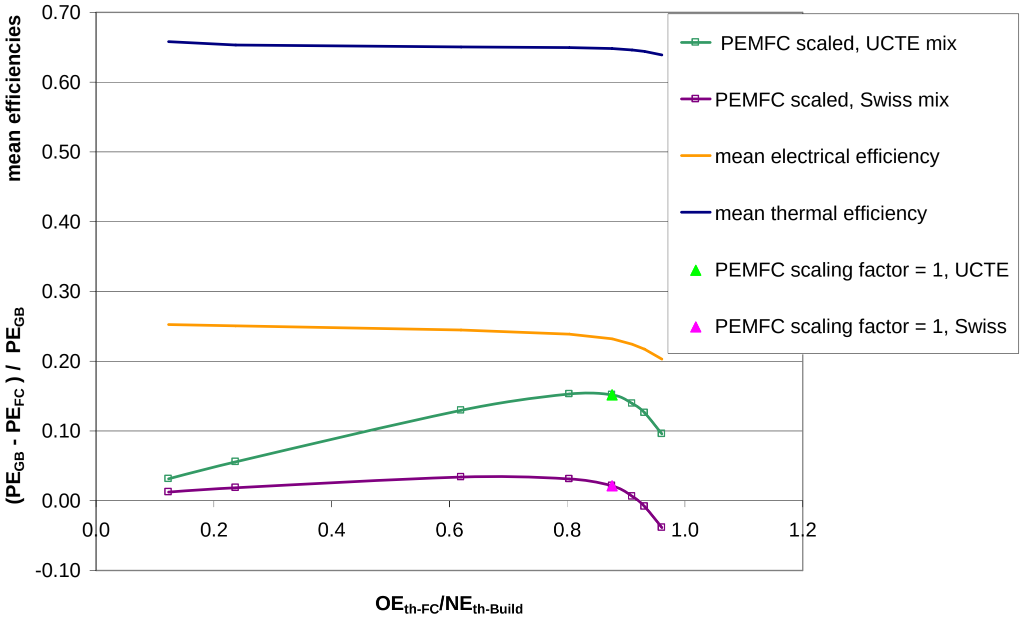

Fig. 37 Difference between NRPE demand of PEMFC cogen system equipped building PE_{PEMFC} and NRPE demand of reference building with gas boiler system PE_{GB}, weighted with PE_{PEMFC} , as a function of ratio of specific annual thermal output of fuel cell cogen unit ($OE_{th\text{-}FC}$) to total annual heat demand of building ($NE_{th\text{-}Build}$), for UCTE and Swiss electricity mix. Also shown are the mean electrical and thermal efficiencies.

10.5 Influence of storage size

The influence of the storage size on the NRPE demand was investigated for SFH building types equipped with SOFC system, for moderate DHW demand profiles (Fig. 38). In (Fig. 39) the influence on the NRPE performance factor is given for the three electricity mixes considered.

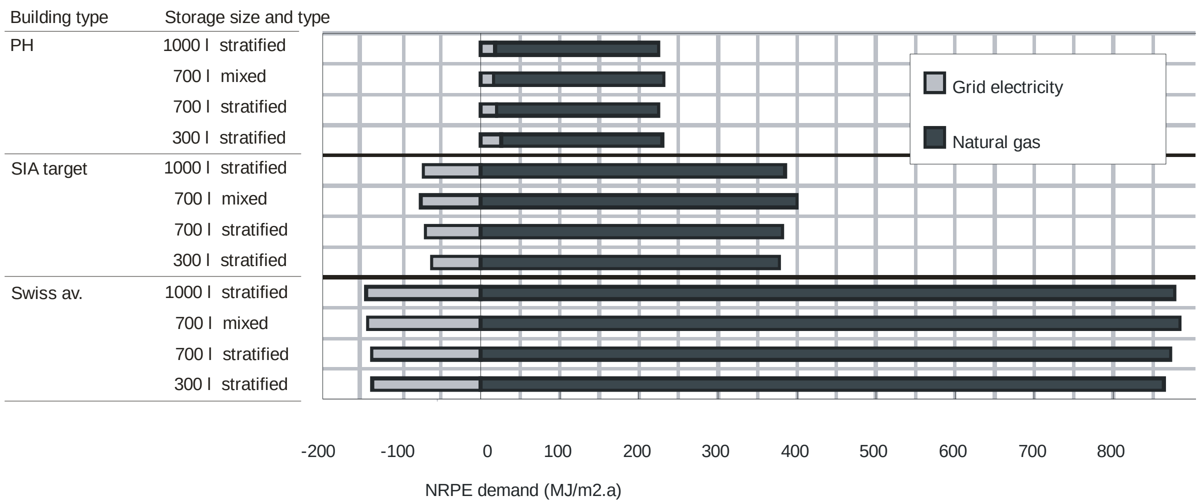

Fig. 38 Influence of storage size on NRPE demand for the SHF building types equipped with SOFC system, for moderate DHW demand profile and UCTE mix.

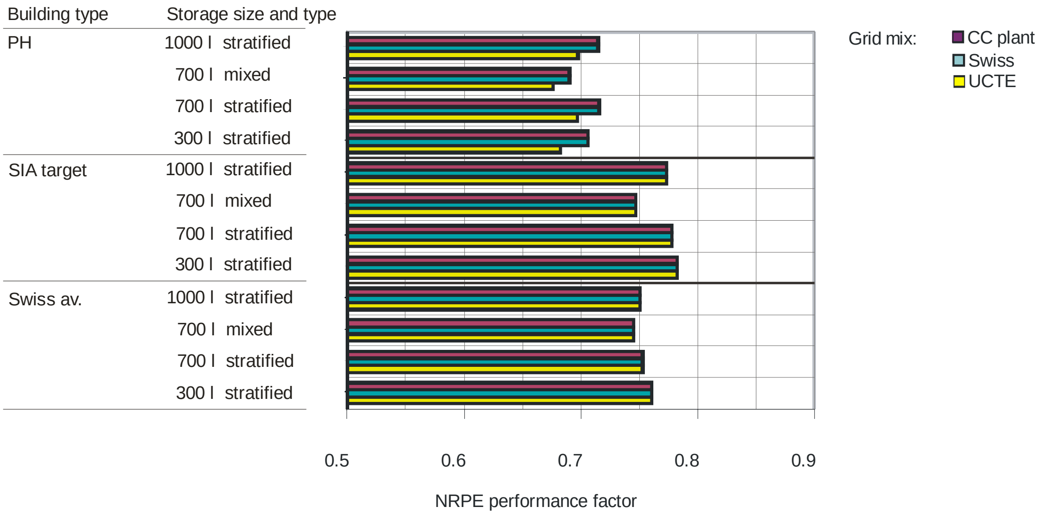

Fig. 39 Influence of storage size on NRPE performance factor for the three electricity generation mixes. SHF building types equipped with SOFC system, for moderate DHW demand profile

In the simulations, the control parameter were adapted to the storage size, for better utilization of the storage. The results show that, in general, the influence of the storage size is small. Nevertheless, two contradictory effects can be observed: (i) a larger storage tank gives higher flexibility in operation of the MCHP unit, which results in a higher production of electricity, and thus in a better energy performance, (ii) a larger storage tank leads to higher heat losses and thus to a poorer energy performance. Thus, there exists an optimal storage size which has to be determined by dynamic simulations.

10.6 Influence of demand profile

10.6.1 Demand level

In Fig. 40, the NRPE demands for the SHF SIA building equipped with SOFC system and for the gas boiler reference system are given for a number of different combinations of DHW and electric demand levels, considering UCTE mix. Also shown are the demand reductions of the SOFC system compared to the demand of the reference system for the respective load combination. Fig. 41 shows the relative reductions for all three types of grid electricity mixes.

The results show that the NRPE demand is governed by the electric demand and that the demand difference between SOFC and reference system is quite insensitive to the load combination. The relative reduction figures are higher for low electric demand because of the lower absolute demand values (quite constant difference value divided by a smaller absolute demand value).

The same findings apply also to the results in respect to GHG emissions (CO_2-eq) (Fig. 42 and Fig. 43).

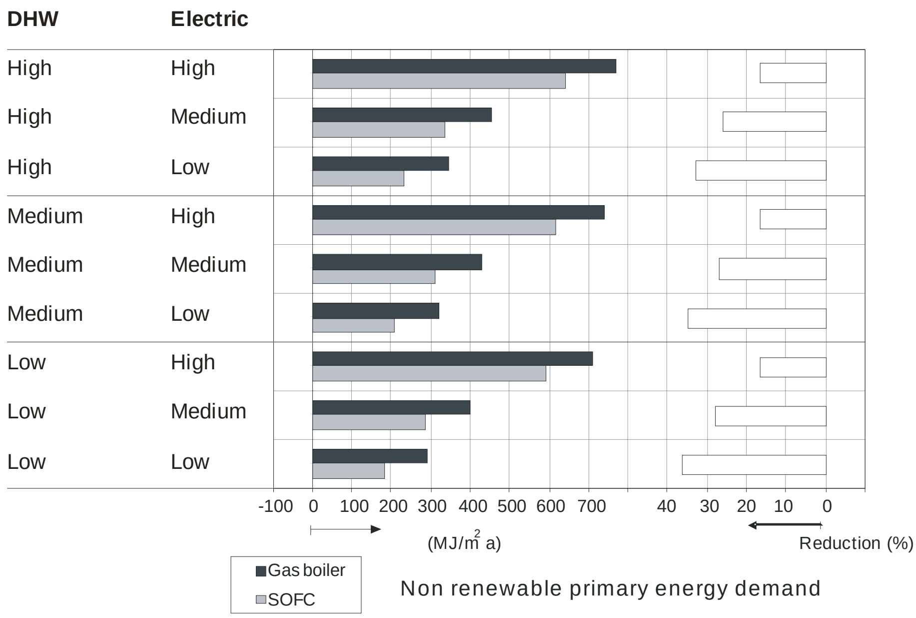

Fig. 40 NRPE demand for the SHF SIA target building equipped with SOFC system for different DHW and electric demand levels, compared to the gas boiler grid reference system. UCTE electricity mix.

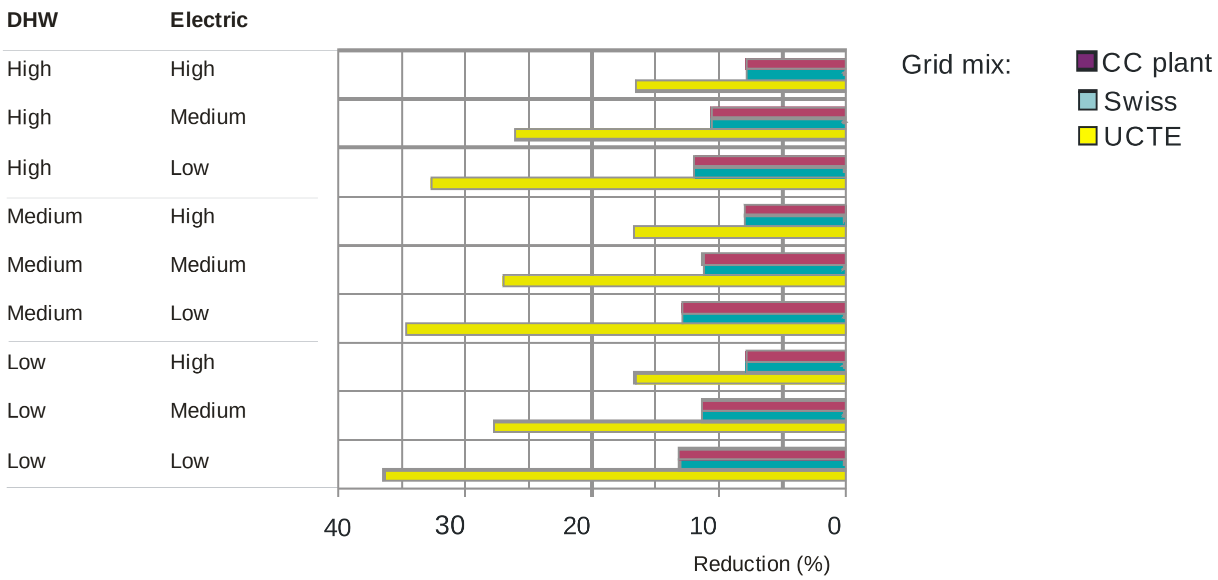

Fig. 41 Relative reductions of NRPE demand for the SHF SIA target building equipped with SOFC system compared to the gas boiler grid reference system, for different DHW and electric demand levels, and for the 3 electricity mixes.

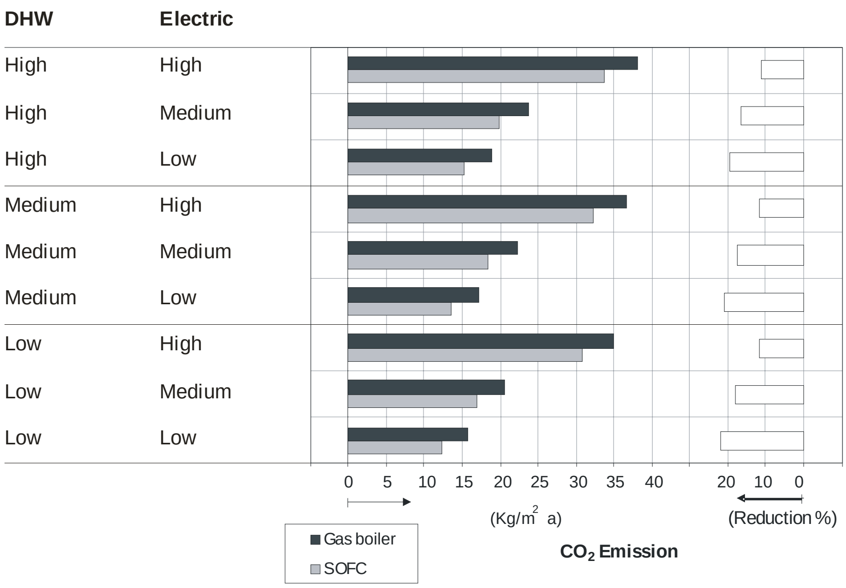

Fig. 42 CO_2–eq emission for the SHF SIA target building equipped with SOFC system for different DHW and electric demand levels, compared to the gas boiler grid reference system. UCTE electricity mix.

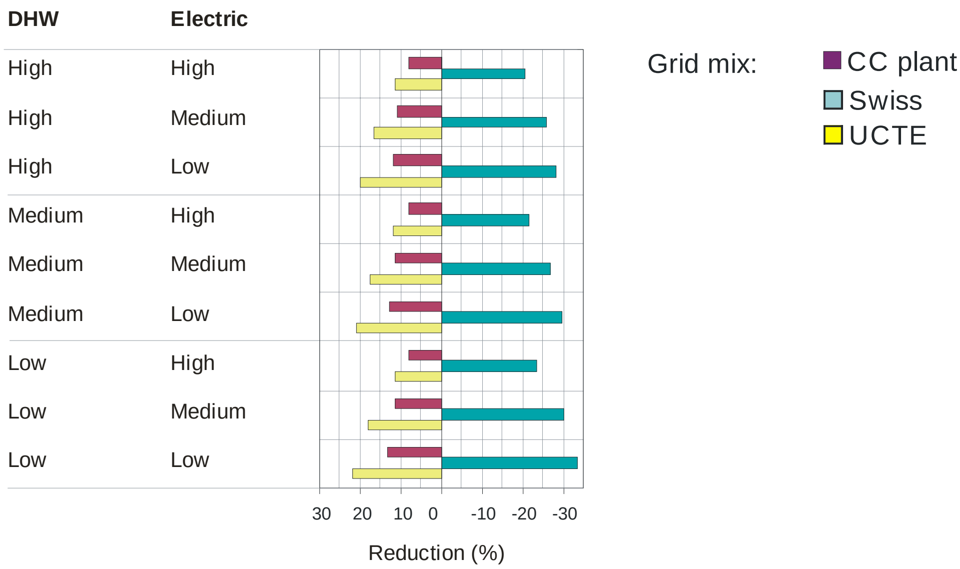

Fig. 43 Relative CO_2–eq emission reductions for the SHF SIA target building equipped with SOFC system compared to the gas boiler grid reference system, for different DHW and electric demand levels, and for the 3 electricity mixes.

10.6.2 Temporal precision of demand profiles

The influence of the temporal resolution of the demand profiles, namely the electric demand profile, was not studied here. Studies, e.g. by (Hawkes, Leach, 2005) and (Ribberink, 2007) show that with higher resolution, the electric demand becomes "peakier", and as a consequence, less electric energy produced by the cogeneration unit can be directly used in the building.

On the other hand, more electricity is exported to the grid and may be re-used later. Thus, in the overall energy balance calculated, with a finer resolved electric profile, the resulting energy performance of the cogeneration system is somewhat lower, due to the higher grid losses.

10.7 Influence of control method

10.7.1 Influence of parameters selected for storage temperature control

The parameters selected for the PI controller of the storage temperature control had quite an important impact on primary energy demand of the system, as narrower temperature bands requested more heat from the auxiliary burner and thus reduced the power and heat output of the MCHP unit. An example is given for the SFH SIA building with SOFC MCHP unit in Fig. 44 and Fig. 45. In the first case the parameters are tuned, as usual for PI controllers, to optimize the accordance of actual and set point value. (K_p=2095, K_i=83.8, Fig. 44), the fluctuation of the temperatures in the storage was small, and the fluctuation of the heat output of the gas burner and the MCHP unit high. In the second case the parameters were reduced by a factor of 10. Thereby the fluctuation of the temperatures in the storage was increased, but the fluctuation of the heat output of the gas burner and the MCHP unit reduced. I.e. in the second case, compared to the first case, the storage capacity was more utilised and as a consequence a larger part of the thermal load could be covered by the MCHP unit, resulting in a higher electricity generation of approximately 3%.

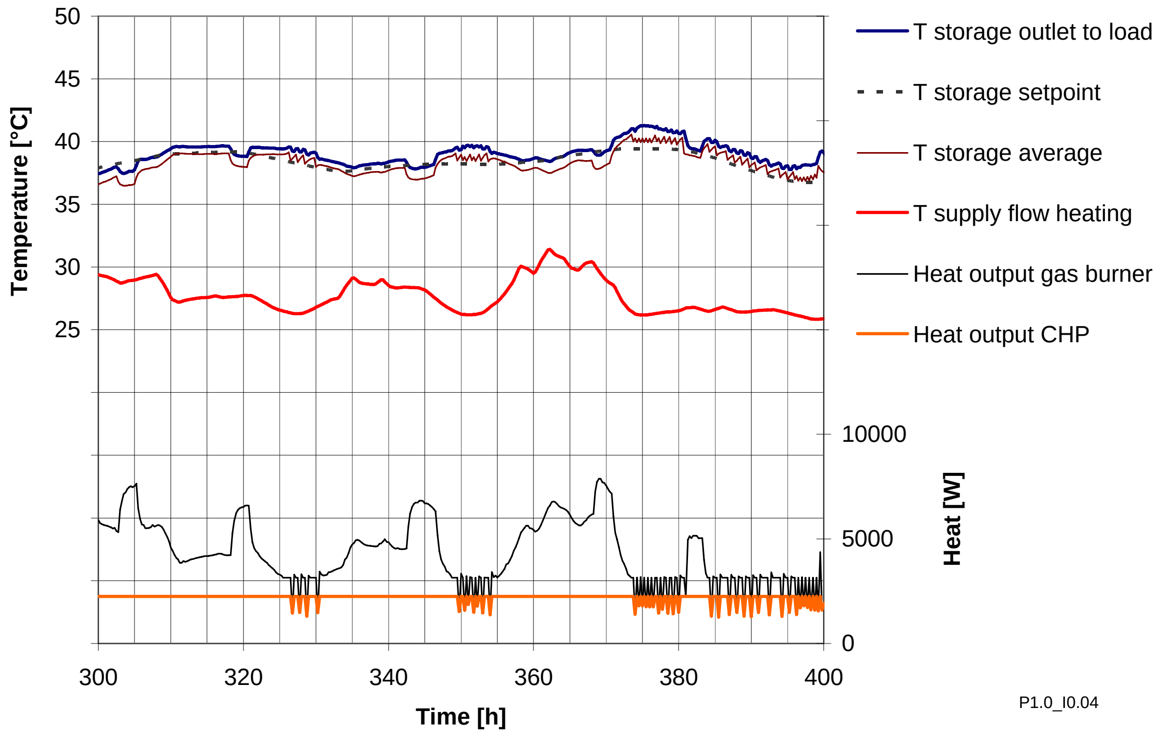

Fig. 44 Influence of PI controller parameters on the storage temperatures and the heat output of the SOFC unit and the auxiliary gas burner. Parameters tuned to optimize the accordance of actual and set point value (K_p=2095, K_i=83.8). (case SFH SIA building with SOFC MCHP unit)

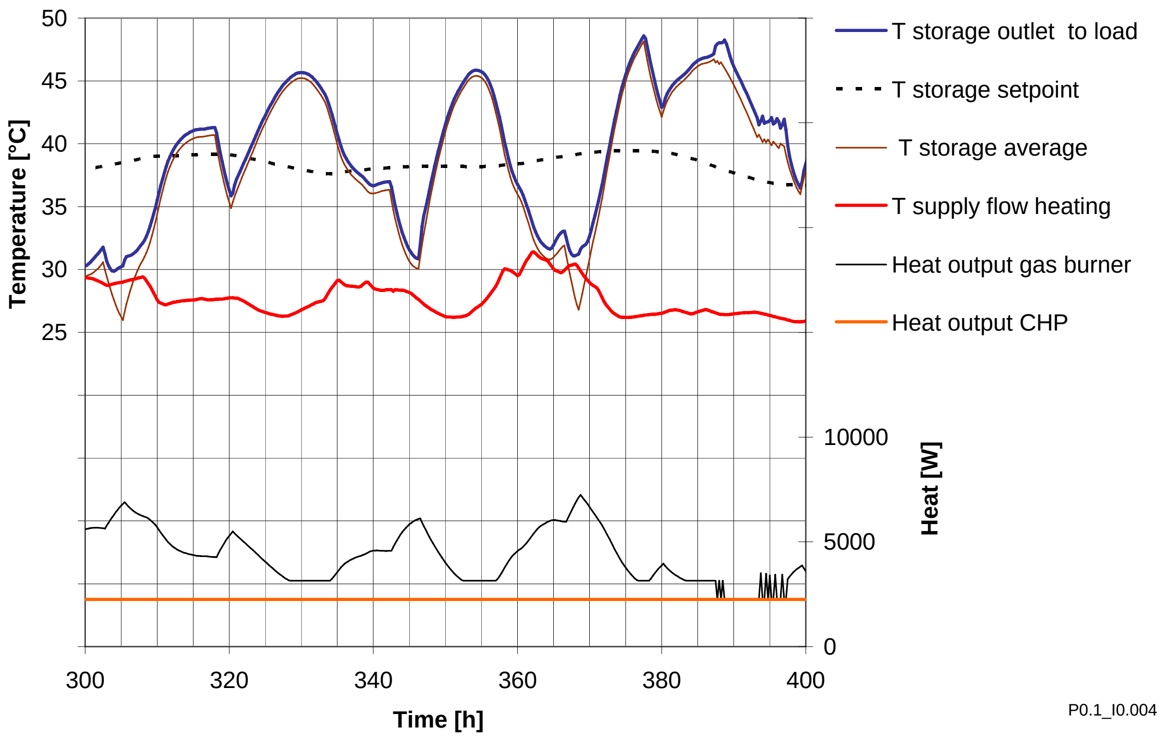

Fig. 45 Influence of PI controller parameter on the storage temperatures and the heat output of the SOFC unit and the auxiliary gas burner. Parameters reduced by a factor of 10 (K_p=209.5, K_i=8.38). (Case SFH SIA building with SOFC MCHP unit)

10.7.2 PI control versus predictive control

The influence of the control method on the NRPE demand was analyzed in an earlier study, see (Dorer et al. 2005) for the SFH building types equipped with a SOFC unit quite similar to the one considered in this study. The control with the PI controller was compared to an performance bound calculation, assuming an optimal predictive control. The results showed very little influence of the control method on the NRPE demand and the respective NRPE performance factor.

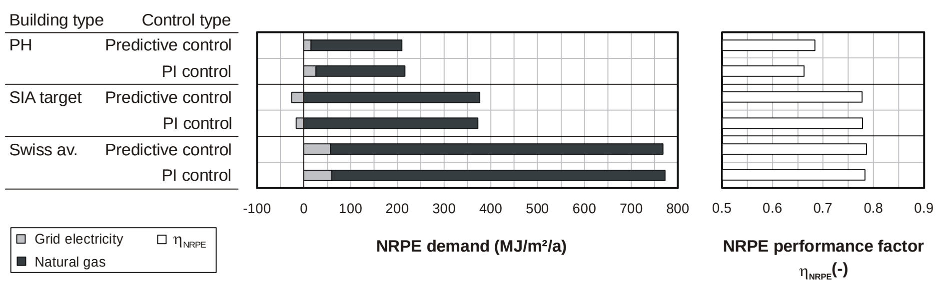

Fig. 46 Non-renewable primary energy (NRPE) demand and NRPE energy performance factor for SFH equipped with SOFC system with optimal predictive and PI control (results from an earlier study (Dorer et al.2005)).

11 CONCLUSIONS

The performance in terms of non-renewable primary energy demand and of CO_2-equivalence (CO_2-eq) emissions was analysed for different cogenerations technologies, namely natural gas fuelled solid oxide fuel cells (SOFC), polymer electrolyte membrane fuel cells (PEMFC), Stirling engines (SE) and internal combustion engines (ICE). The cogeneration devices analyzed were selected according to existing prototype or commercially available micro cogeneration units and the performance characteristics specified based on data from laboratory measurements or provided by the manufacture. The cogeneration units were integrated in SFH and MFH buildings of different energy standards. The simulations were made using TRNSYS in 15 min time steps for one year periods using the standard DHW and electric demand profiles specified within IEA Annex 42. For the cogeneration systems, the Annex 42 models with calibrated results were used where available.

The plurality of factors influencing system performance, coupled with the wide divergence between energy codes and electricity mix data at national, even regional level, makes it very difficult to draw generally valid conclusions out of systems comparison. Particular cases need to be studied individually by dynamic simulation. The availability of detailed models and simulation tools in the field of building-integrated cogeneration is thus of paramount importance.

The reader must be aware that all the results and the conclusions presented here are strictly applicable to a single buildings perspective. The results and conclusions cannot directly be applied to energy scenarios where a greater number of buildings or even a sector of an urban/regional/national building stock is analyzed. For such scenarios, further energy system options and cases have to be included in the analysis.

Below, the findings given in the individual results chapters above are consolidated and summarized, and the respective conclusions drawn.

11.1 Basic system configurations

NRPE demand and performance factor

For the UCTE electricity mix, most MCHP systems offered reductions in NRPE demand, except the SE1 system in the SFH SIA and PH building due to the low electric and overall efficiency of this SE unit. Maximum reductions were achieved with the ICE1 in the Swiss average SFH building (34%), the SOFC system in the SIA SFH building (27%), and with the SE2 unit in the Swiss average MFH building (24%). It has to be noted that all these reductions are also an effect of the surplus electricity generation, which is considered as a bonus and thus was subtracted from the primary energy demand resulting for the house. However, also systems with no surplus electricity generation offered reductions of >10%.

The results for the Swiss and the CC power plant mixes are identical, as the primary energy factors are identical. By far the largest NRPE reductions for these two mixes resulted from the heat pump systems (up to 29%). The maximum reduction with a MCHP system was achieved with the ICE1 system in the Swiss average SFH (14%), and with SOFC system in the SIA SFH building (12%). Again both systems generated a surplus of electricity. Conversely, the SE systems in the PH and SIA SFH buildings lead to a small increase in NRPE demand.

In terms of NRPE performance factor, an increase of up to 26% was achieved (SOFC in the PH SFH) for the UCTE electricity mix. For the Swiss and the CC plant mix, maximum improvements resulted again for the heat pump system (increase > 40%). For these mixes, the maximum increase with a MCHP system resulted for the SOFC system in the PH SFH (8%). For a number of systems, the performance factor was lower than for the reference system.

CO_2-eq emissions

Compared to the reference gas boiler system, for the UCTE electricity mix, most MCHP systems offer reductions in CO_2-eq emissions, except again the SE1 system in the SFH PH and SIA building. However, maximum reductions result not for a MCHP system, but again for the heat pump system (24%). The maximum reduction with a MCHP system is achieved with the ICE1 system in the Swiss average SFH due to surplus electricity generation (23%), and with the SOFC system in the SIA SFH (17%). For the Swiss mix, only the heat pump systems lead to emission reductions, all the MCHP system result in higher emissions. For the CC power plant mix, maximum reductions result again by far with the heat pump systems (up to 29%). The maximum reduction with a MCHP system is achieved with the SOFC system in the SIA SFH (12%). The SE1 systems in the PH and SIA SFH lead to an increase in emissions.

Conclusions

The analysis showed that, compared to the gas boiler/grid electricity reference system, primary energy reductions can be achieved with most MCHP systems. Higher primary energy demands and emissions may result for MCHP devices with low overall and electric efficiencies. However, in many cases, except for the UCTE mix, the ground coupled heat pump will perform better than the MCHP system. The comparison in terms of emission is strongly dependant on the grid electricity emission factor. For the Swiss mix, higher emissions result for the MCHP systems.

11.2 Combination with solar thermal system

SOFC systems were analyzed in combination with solar thermal collectors. Not surprisingly, the integration of solar collectors always lowered the NRPE demand. Hence, for the combination of cogeneration and solar thermal system higher reductions can be achieved as with either system individually (solar or cogen system). In general, SFH buildings exhibited the higher reductions. However, in the MFH, where the SOFC is operated continuously the whole year, the SC competed more with the SOFC. In the summer period, the heat provided by the solar collectors increases, and thus the number of full-load operating hours of the SOFC is reduced. Consequently, the amount of the electricity delivered from the grid (with a high NRPE factor) is raised. Hence, the benefits of the fuel cell system compared to the gas boiler system are less significant for configurations with solar collectors than for configurations without solar collectors.

11.3 Demand/capacity match (part load operation)

Comparing heat load duration curves with the respective system heat output curves is very helpful to assess the dimensioning of the system (i.e. “does the system output match the effective heat loads?”) or vice-versa to assess the applicability range for a certain type of MCHP unit (i.e. “do the loads match the system capacity?”). Such comparisons (for periods where load and system output do not match) also give an indication of the required size of storage. The results show that the capacity of the selected SOFC unit actually is too small for the MFH SIA (and consequently the Swiss average) building. For the SOFC systems combined with solar collector, the number of operating hours is reduced for both the SFH and MFH buildings. For the PEMFC, SE1 and SE2 systems, only small numbers of equivalent full load operating hours result, even for the MFH buildings. Especially for the SE2 system, only in the Swiss av. building type the thermal system output is used on a reasonable output power level. Also the ICE1 unit in the SFH SIA building type practically always ran at minimum power for space heating.

11.4 Dimensioning of MCHP unit

Besides the efficiencies of the MCHP unit, the correct sizing is of paramount importance. This was demonstrated for the SIA MFH building by varying the size of the SOFC and PEMFC unit by scaling-up and -down the capacity of the original FC unit, and analyzing the system in terms of NRPE demand. The optimal ratio of annual FC unit thermal output to annual building heat demand is dependant on the electricity mix and the characteristics of the electric efficiency curve of the FC unit. While for PEMFC the optimal value is around

0.8, for the SOFC ratio values >1.0 result in case of UCTE electrical mix. In general, it can be concluded that the annual heat output of any cogeneration unit should be dimensioned to about 0.8 to 1.0 of the annual building heat demand.

11.5 Influence of storage size

In general, the influence of the storage size on the NRPE demand is small. With a larger storage the energy performance (i) is improved due to a higher flexibility in operation of the MCHP unit, which results in a higher production of electricity, and (ii) is decreased due to higher heat losses across the storage shell. Therefore the optimum storage size has to be determined by dynamic simulations.

11.6 Influence of demand profile

The results showed that the NRPE demand is governed by the electric demand and that the demand difference between SOFC and reference system is quite insensitive to the load combination.

The influence of the temporal resolution of the demand profiles, namely the electric demand profile, was not studied here. Other studies, e.g. (Hawkes, Leach, 2005), (Ribberink, 2007) show that with higher resolution, the electric demand becomes “peakier”, and as a consequence, less electric energy produced by the cogeneration unit can be directly used in the building. On the other hand, more electricity is exported to the grid and may be re-used later. Thus, in the overall energy balance, with a finer resolved electric profile the resulting energy performance of the cogeneration system is somewhat lower, due to the higher grid losses.

11.7 Influence of controller parameters and control method

The parameters selected for the storage temperature PI controller had quite an important impact on primary energy demand of the system, as narrower temperature bands requested more heat from the auxiliary burner and thus reduced the power and heat output of the MCHP. This contradicts the findings from an earlier study with PI control and an ideal predictive control, which showed very little influence of the control method on the NRPE demand and the respective NRPE performance factor.

11.8 Outlook

The current study has focused on typical prototype and commercially available residential cogeneration units. The performance characteristics of these units were either based on data calibrated by laboratory measurements or characteristics based on manufacturers data or on data assumed by the authors of this report. The results of this study provide only a present-day picture of the development of residential cogeneration systems, and do not reflect the full potential of the technologies. Further investigations into the future potential of residential cogeneration technologies are recommended, including clusters of buildings and a more comprehensive comparison with other efficient and renewable energy technologies, such as solar thermal and photovoltaic systems, ground coupled heat pumps and biofuel systems. Future investigations should more rigorously address the influence of the thermal dynamic effects within the energy generation units — the current study was hampered by lack of corresponding empirical data.

This study gave some hints concerning the dimensioning of systems, however proper system design and dimensioning methods are still to be further developed and properly applied. Due to the many interactions, optimisation methods as e.g. outlined by (Marechal et al., 2005) may be applied in the dimensioning process.

Also control aspects need more careful consideration, as the control method and the respective control parameters can have a strong impact on the system performance.

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13 APPENDIX

TRNSYS models used

Table 10 gives an overview on the models used for the simulation of the different cases.

Table 10 TRNSYS models used for the individual components

Component	**TRNSYS model**
Building	Type 56 Multizone building
Radiator with thermostatic valves for heat distribution	Non-standard Type by Empa (Types 255 and 251)
Gas boiler	Non-standard Type by Empa
SOFC	Annex 42 FC model, implemented in TRNSYS
PEMFC	Simplified performance map model calibrated with Annex 42 measurements
SE	For SFH (SE1): Annex 42 FC model, implemented in TRNSYS For MFH (SE2): simplified performance map model (manufacturers data)
ICE	For SFH (ICE1): Simplified performance map model calibrated with Annex 42 measurements For MFH (ICE2): Annex 42 FC model, implemented in TRNSYS
Heat pump	Type 42 HVAC conditioning equipment (2 independent variables)
Ground source circuit	EWS model Type 451 by (Wetter, Huber, 1997)
Storage	Type 4 Stratified storage tank
Solar collector	Type 1 Flat plate collector
Controllers: PI controller On/off controller with hysteresis	 Non-standard Type by Empa Type 2 On/off controller with hysteresis

Annex 42 SOFC model input parameters

Parameter description:

Number	Description	Symbol
	FCPM electrical performance	
1	Polynomial coeff that expresses FCPM electrical efficiency	ε_0
2	Ditto	ε_1
3	Ditto	ε_2
4	Fractional performance degradation for off-on cycling	D
5	Fractional performance degradation due to operating time (1/hrs)	L
6	Time threshold (hrs) before which no degradation due to operating time occurs	$t_{threshold}$
7	FCPM's min electric output (W)	P_{el-min}
8	FCPM's max electric output (W)	P_{el-max}
	FCPM transient response	
9	Max allowable time derivative for elec output in W/s (power increasing)	$(dP_{el}/dt)_{max}$
10	Max allowable time derivative for elec output in W/s (power increasing)	$(dP_{el}/dt)_{max}$
11	Duration of start-up period (seconds).	$\delta t_{start-up}$
12	Fuel consumption during start-up period (kmol)	$kmol_{fuel,start-up}$
13	Electrical consumption during start-up period (MJ)	$E_{heat+anc\_start-up}$
14	Net DC electrical production during start-up period (MJ)	$E_{el,startup}$
15	Duration of cool-down period (seconds)	$\delta t_{cool-down}$
16	Fuel consumption during cool-down period (kmol)	$kmol_{fuel,cool-down}$
17	Electrical consumption during cool-down period (MJ)	$E_{heat+anc\_cool-down}$
	AC power supply to FCPM for ancillaries	
18	Coeff to polynomial determining FCPM AC ancillary power draw	anc_0
19	ditto	anc_1
	Fuel constituents	
20	Molar fraction of hydrogen	χ_i
21	Molar fraction of methans	χ_i
22	Molar fraction of ethane	χ_i
23	Molar fraction of propane	χ_i
24	Molar fraction of butane	χ_i
25	Molar fraction of pentane	χ_i
26	Molar fraction of hexane	χ_i
27	Molar fraction of methanol	χ_i
28	Molar fraction of ethanol	χ_i
29	Molar fraction of carbon dioxide in fuel (inert)	χ_i
30	Molar fraction of nitrogen in fuel (inert)	χ_i
31	Molar fraction of oxygen in fuel (inert)	χ_i

Number	Description	Symbol
	Fuel supply compressor	
32	Indicates temp of fuel entering compressor 1 = room ; 2 = outdoor	
33	Coeff to polynomial that establishes compressor power draw	c_0
34	Ditto	c_1
35	Ditto	c_2
36	Ditto	c_3
37	Ratio of heat loss from compressor to electric power supply	$\alpha_{comp\text{-}heat\text{-}loss}$
	Air constituents	
38	Molar fraction of nitrogen	χ_i
39	Molar fraction of oxygen	χ_i
40	Molar fraction of water vapour	χ_i
41	Molar fraction of argon	χ_i
42	Molar fraction of carbon dioxide	χ_i
	Air supply	
43	Method used to establish air supply to FCPM: 1 = constant air excess ratio; 2 = Air supply is function of electric output 3 = Air supply is function of fuel supply	
44	Excess air ratio or coeff to polynomial (depends on method)	λ or a_0
45	Coeff to polynomial determining air supply.	a_1
46	Ditto	a_2
47	Ditto	a_3
	Air supply blower	
48	Indicates source from which air is drawn 1 = room ; 2 = outdoor	
49	Coeff to polynomial that establishes blower power draw.	b_0
50	Ditto	b_1
51	Ditto	b_2
52	Ditto	b_3
53	Ratio of heat loss from blower to electric power supply	$\alpha_{blower\text{-}heat\text{-}loss}$
	Water supply	
54	Coeff to polynomial determining water supply	w_0
55	Ditto	w_1
56	Ditto	w_2
	Water pump	
57	Indicates temp of water entering pump: 1 = room; 2 = mains	
58	Coeff to polynomial that establishes pump power draw	p_0
59	Ditto	p_1
60	Ditto	p_2
61	Ditto	p_3
62	Ratio of heat loss from pump to electric power supply	$\alpha_{pump\text{-}heat\text{-}loss}$

Number	Description	Symbol
	Gas-to-water heat exchanger	
63	Indicates which method is used to calculate heat exchange	
	Fixed effectiveness (HX_method =1)	
64	Fixed effectiveness	ε_{HX}
	Empirical LMTD model (HX_method =2) and (HX_method =4)	
65	Coeffs to polynomial to calc UA	$hx_{s,0}$
66	Ditto	$hx_{s,1}$
67	Ditto	$hx_{s,2}$
68	Ditto	$hx_{s,3}$
69	Ditto	$hx_{s,4}$
	Deterministic LMTD model (HX_method =3)	
70	HX coeff to gas at nominal gas flow (W/m^2/K)	h^0_{gas}
71	Nominal gas flow rate (kmol/s)	N^0_{gas}
72	Exponent to gas flow rate	n
73	Reference heat exchange area to gas (m^2)	A_{gas}
74	HX coeff to water at nominal water flow (W/m^2/K)	h^0_{water}
75	Nominal water flow rate (kmol/s)	N^0_{water}
76	Exponent to water flow rate	m
77	Reference heat exchange area to water (m^2)	A_{water}
78	Adjustment factor (K/W)	F_{HX}
	Empirical LMTD model with condensation (HX_method =4)	
79	Coeffs to polynomial to calc rate of condensation	$hx_{l,1}$
80	ditto	$hx_{l,1}$
81	Temperature threshold for condensation (°C)	$T_{cond\text{-}threshold}$
	FCPM skin losses	
82	Method used to determine skin losses from FCPM 1 = Constant skin loss 2 = Skin losses a function of temp diff 3 = Skin losses a function of fuel flow rate	
83	Fraction of heat loss that is convective	
84	Skin loss (W), UA-value (W/K), or coeff (depends on method)	$q_{skin\text{-}loss}$; UA ; s_0
85	Coeff to polynomial for `fuel flow' method	s_1
86	Ditto	s_2
	Auxiliary burner	
87	Indicates whether there is an auxiliary burner: 0 = No; 1 = yes	
88	Indicates how burner capacity is specified: 1 = heat output ; 2 = fuel input	
89	Minimum operating point for burner (W or kmol/s)	
90	Maximum operating point for burner (W or kmol/s)	
91	Indicates where the heat loss from the burner goes: 1 = room; 2 = FCPM air intake	
92	Heat loss coefficient for burner (W/K).	$(UA)_{aux}$
93	Coeff to polynomial that determines burner ancillary power draw	x_0

Number	Description	Symbol
94	Ditto	x_1
95	Auxiliary burner excess air ratio (-)	λ_{aux}
	Dilution air system and associated HRV	
96	Indicates whether there is a dilution air system: 0 = No; 1 = yes	
97	Flow rate of dilution air (kmol/s)	$N_{dilution-air}$
98	Electrical power of fan drawing dilution air (W)	$P_{el,dilution-fan}$
99	Heat transfer from FCPM to dilution air (W)	$q_{FCPM-to-dilution}$
100	Indicates whether an HRV is present: 0 = No; 1 = yes	
101	Flow rate of fresh air through HRV (kmol/s)	N_{OA}
102	Electrical power of fan drawing air through HRV (W)	$P_{el,fresh-air-fan}$
103	Effectiveness of gas-to-air heat exchange (-)	ε_{HRV}
	Battery	
104	Battery's energy storage capacity (J)	$Q_{battery-max}$
105	Max rate at which battery can be charged (W)	$P_{battery-charge-max}$
106	Max rate at which battery can be discharged (W)	$P_{battery-discharge-max}$
107	Energetic efficiency during charging (-)	ε_{charge}
108	Energetic efficiency during discharging (-)	$\varepsilon_{discharge}$
109	Battery's SOC (fraction of battery_capacity at start of simulation (-)	$Q_{battery-initial}$ / $Q_{battery-max}$
110	Indicates where heat loss from battery goes: 1 = room; 2 = FCPM air intake	
	PCU	
111	Coeff to polynomial to calculate efficiency of PCU	u_0
112	Ditto	u_1
113	Ditto	u_2
114	Indicates where heat loss from PCU goes: 1 = room; 2 = FCPM air intake	
	Heat extraction for stack cooling (PEMFC)	
115	indicates whether there is a stack cooling system: 0 = No; 1 = yes	
116	Stack temperature (°C)	T_{stack}
117	Nominal stack temperature (°C)	T^0_{stack}
118	Coeff to polynomial to calculate heat extracted from stack	r_0
119	Ditto	r_1
120	Ditto	r_2
121	Ditto	r_3
122	UA value of stack cooling heat exchanger (W/K)	$(UA)_{s-cool}$
123	Massflow rate in stack cooling heat exchanger (kg/s)	$M_{water} \cdot \dot{N}_{s-cool}$
124	UA value of heat exchanger for cogen from stack cooling (if a constant value is used) (W/K)	$(UA)_{s-cogen}$
125	Nominal massflow rate in heat exchanger for cogen from stack cooling (kg/s)	$M_{water} \cdot \dot{N}^0_{s-cogen}$
126	Area of heat exchanger for cogen from stack cooling (m^2)	$A_{s-cogen}$

Number	Description	Symbol
127	Constant part of heat exchanger resistant (K/W)	$F_{s\text{-}cogen}$
128	Nominal film heat transfer coefficient (W/m^2/K)	$h^0_{s\text{-}cogen}$
129	Exponent to water flow rate	n_s
130	Coeff to polynomial to calculate electrical power consumption of air cooler fan	f_0
131	Ditto	f_1
132	Ditto	f_2
133	Ratio of heat loss of the stack cooling pump (-)	$\alpha_{stack\text{-}pump\text{-}heat\text{-}loss}$
134	Electrical power consumption of the stack cooling pump (W)	$P_{stack\text{-}pump\text{-}el}$
135	Indicates where heat loss from air cooler goes: 1 = room; 2 = FCPM air intake	

Used parameter values:

```
2.2247E-01  6.3918E-04  -4.3698E-0                                    ! 1 - 3  electrical efficiency coefficients
0.          0.          0.                                            ! 4 - 6  no degradation
480.        1000.                                                     ! 7 - 8  min and max electrical power
10.         10.                                                       ! 9 -10 transient  (not calibrated)
900.        0.02        0.001       0.                                !11-14 start-up (not calibrated)
900.        0.02        0.001                                         !15-17 cool-down (not calibrated)
0.          0.                                                        !18 -19 ancillaries (not calibrated)
0.          0.93882     0.02210     0.00653     0.00229     0.00092   !20 - 25 fuel mixture
0.0         0.0         0.0         0.01353     0.01581     0.000     !25 - 31 fuel mixture
1.          0.          0.          0.          0.          1.        !32 - 37 Compressor nullified
0.7728      0.2073      0.0104      0.0092      0.0003                !38 - 42 air mixture
3.          -3.0777E-05 3.2829E+01  3.3292E+06  0.                    !43 - 47 air supply
1.          0.          0.          0.          0.          1.        !48 - 53 Blower nullified
0.          0.          0.                                            !54 - 56 water supply (not used)
1.          0.          0.          0.          0.          1.        !57 - 62  Pump nullified
4.          99.                                                       !63 - 64 empir. LMTD HX model with condens.
3.          0.          0.          80000       -50000000.            !65 - 69  sensible HX coefficients
99.   99.   99.   99.   99.   99.   99.   99.   99.                   !70 - 78 deterministic lmtd HX model not used
2.5E-05     -20.303E-055                                              !79 - 80 latent HX coefficients
36.                                                                   !81 HX condensation threshold temperature
3.          0.5         6.7270E+02  -1.8720E+08 1.1577E+13            !82 - 86  skin_loss
0.    99.   99.   99.   99.   99.   99.   99.   99.                   !87 - 95 auxiliary burner nullified
0.    99.   99.   99.                                                 !96 - 99  dilution not present
0.    99.   99.   99.                                                 !100 - 103 HRV not present
0.    0.    0.    1.    1.    0.5   1.                                !104 - 110 battery not present
3.7053E-01  7.4161E-04  -3.1828E-07                                   !111 - 113  PCU_ efficiency coefficients
2.                                                                    !114 PCU heat goes to air intake
0.                                                                    !115 stack cooling not present
!116 -135 input parameters for stack cooling loop not used
99.   99.   99.   99.   99.   99.   99.   99.   99.   99.
99.   99.   99.   99.   99.   99.   99.   99.   99.   99.
```