Methodologies for the Performance Assessment of Residential Cogeneration Systems

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

Annex 42 of the
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Participating countries in ECBCS:

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Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (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 were to develop simulation models that advance the design, operation, and analysis of residential cogeneration systems, and to apply these models to assess the technical, environmental, and economic performance of the technologies. This was accomplished by developing and incorporating models of cogeneration devices and associated plant components within existing whole-building simulation programs. Emphasis was placed upon fuel cell cogeneration systems and the Annex considered technologies suitable for use in new and existing single and low-rise-multi-family residential buildings. The models were developed at a time resolution that is appropriate for whole-building simulation.

To accomplish these objectives Annex 42 conducted research and development 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 was 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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Subtask C Leader

CONTENT

1 INTRODUCTION

1.1 Motivation

The reduction of greenhouse gas emissions in the building sector to a sustainable level will require tremendous efforts to increase both energy efficiency and the share of renewable energies. Apart from the lowering of energy demand by better insulation and fenestration, small combined heat and power (residential or micro cogeneration) systems may help improve the situation on the supply side by cutting both the non-renewable energy demand for residential buildings and peak loads in the electric grid.

Therefore, Subtask C of IEA Annex 42 was aimed at assessing the performance assessment of selected cogeneration system cases in terms of energy, emissions and economic criteria, using the models developed within IEA Annex 42.

1.2 Deliverables of ST C

The deliverables of ST C in respect to the performance assessment topic are (i) this methodology report, (ii) the individual study reports and (iii) the respective summary and conclusions in the Annex summary report.

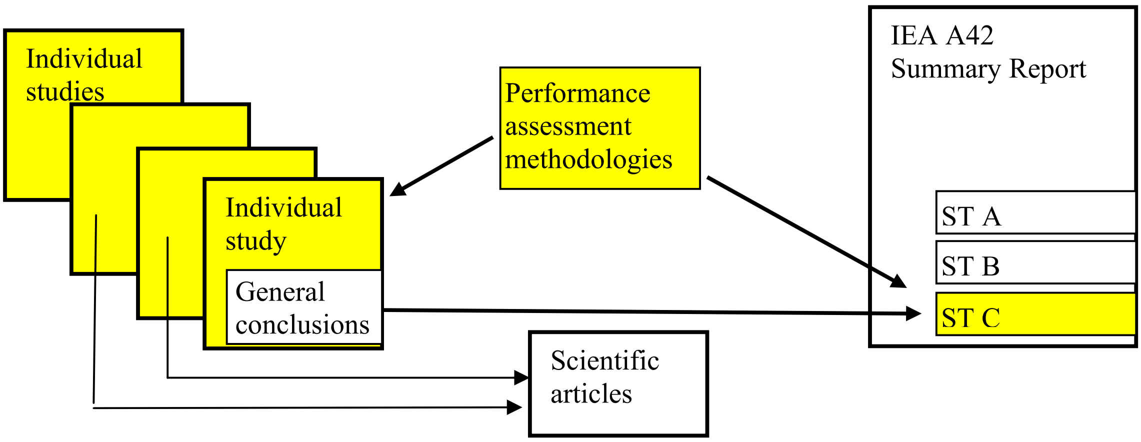


Fig. 1 ST C deliverables

1.3 Aim and purpose of this report

The purpose of this report is to give *guidance, the framework and the methodologies* for the individual performance assessment (PA) studies within ST C of Annex 42.

Thus, this report acts as a reference and standard for the individual studies. The aim is that the specified definitions, nomenclature, performance criteria, boundary conditions, reference cases and methods are commonly applied in all the individual performance assessment studies, as long as this is feasible and appropriate. However, in many aspects, the report just gives one possible approach or one definition of a specific performance assessment criteria while different approaches and criteria can be chosen as well (and are as valid). Therefore, the use of other approaches and criteria in the individual studies is also acceptable as long as such approaches and criteria are clearly defined.

The methodologies and respective definitions and nomenclature have been developed independently, however it has been attempted to follow standardized building performance assessment procedures, as e.g. [prEN 15203/15315, 2006], as much as possible.

1.4 Content of this report

The following topics are covered in the sections of this report:

Section 2: general aims and purpose of the individual performance assessment studies, scope and target audience

Section 3: nomenclature, symbols and definitions to be used in the studies

Section 4: performance assessment criteria (metrics) in terms of energy, emissions and cost to be applied

Section 5: performance assessment methods to be applied

Section 6: guidance on the selection of the cogeneration and the reference systems, on external factors (like meteo data, primary energy factors, prices), and on the selection of heat and electric load profiles

Section 7: guidance on how to describe and document the systems in the studies and examples for the presentation of the results. As this report acts as a reference for the individual performance assessment studies, the examples shown were taken from earlier studies.

Section 8: references

2 PERFORMANCE ASSESSMENT TASK: PURPOSE, OBJECTIVES, SCOPE AND TARGET AUDIENCE

2.1 Purpose and objectives

The general purpose of the ST C performance assessment task is to analyze the performance of selected cogeneration system cases in terms of energy, emission technical, and economic criteria. Based on the results, the aim is to identify critical issues in the context of cogeneration technologies and to show the influence of major building, occupant and system parameters on the performance of fuel cell and other micro cogeneration devices.

The interaction of the cogeneration device 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 thermal systems, is analysed by computer simulations and evaluated in terms of the selected criteria, such as primary energy demand and CO_2 emissions. Typical heat and electricity demand load profiles for different types of residential buildings and occupant types are considered, and compared with reference systems comprising traditional energy supply systems.

Additional heat load applications for cooling purposes (e.g. desiccant cooling, absorption cooling) were originally considered but then not further pursued in the work of Annex 42.

Based on these results, conclusions are given in terms of application ranges for certain cogeneration systems, of storage configurations and in terms of influence of control strategies.

In short, the objectives of the performance assessment task are to:

- set up a generic framework for residential cogeneration evaluation
- demonstrate application potential of models and building simulation tools developed
- quantify the performance of selected cogen systems in terms of energy, emissions and costs, compared to conventional systems
- determine and show sensitivities and identify most influencing and thus most relevant parameters
- compare control strategies and methods
- document the successful elements of individual cogeneration configurations
- identify promising application fields for cogeneration systems
- give examples of optimizing and sizing components and systems

2.2 Scope

The performance assessment task concentrates on decentralized, building integrated energy supply in the residential sector. The focus is on the performance of the cogeneration system in its interaction with the individual building (or a cluster of buildings connected via a local network) and occupant loads in terms of control and energy management (Fig. 2). Even cooling is more important than heating in many countries, the focus within IEA Annex 42 remained on combined heating and power and was not extended to combined heating cooling and power (tri- or polygeneration).

The results of the simulation for the individual building may be extrapolated to larger scales (district, city, country), taking into account distributions of building types, climates etc., however in these cases not only building integrated generation system may be considered in the study.

The supply chain from primary energy to delivered energy is considered in terms of primary energy factors and in terms of emission factors, or by “on-margin" fuel mix to determine the displaced emissions (see § 6.7.3).

The ST C performance assessment studies do 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).

Dynamic energy prices may be considered in the performance assessment of control strategies and algorithms, however the development and assessment of dynamic price strategies and policies is out of scope of ST C.

Also not within the scope of ST C 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. Some information on this topics may be found in the ST A report [Knight & Usurgal 2007].

The ST C performance assessment work concentrates on the performance analysis of given cases and configurations. It is not intended to cover the topic of design procedures and methods. Nevertheless, certain aspects of design and dimensioning are covered by the sensitivity analysis and the optimizations conducted in the studies.

It is also outside the scope of the ST C work to optimize individual components and the respective control within a cogeneration device.

It was also decided that the ST C performance assessment task does only implicitly (by the cases analysed) demonstrate the application of the models developed within A42, and does not give explicit guidance on how to use the models.

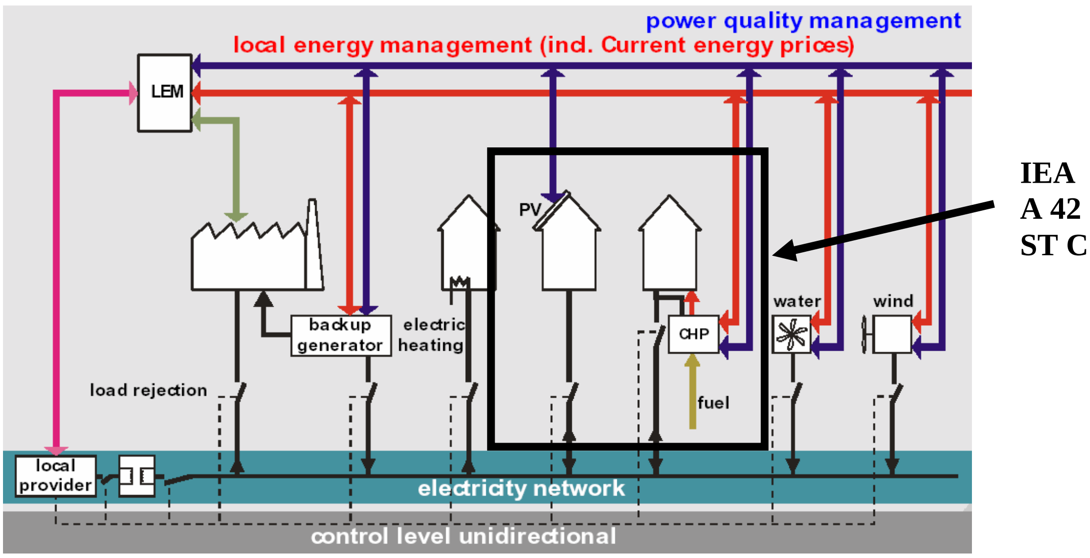


Fig. 2 Distributed power generation and the scope of ST C (Source: EU Project Dispower)

2.3 Target audiences

It is to differentiate between the target audience for the individual (national) studies, and the target audience for the Annex summary report.

The A42 ST C performance assessment reports aims at the following readership:

- Engineers and researcher involved in energy system analysis and HVAC design
- Users of the building simulation programs which are improved and amended in this Annex
- Manufacturers of cogeneration devices who want to analyze potential applications and performance of their products
- Energy supply and contractor companies who want to gauge the potential for residential cogeneration with a view to assessing their impact on the electricity supply network

2.4 Overview on individual studies

On overview on the individual studies (cases, topics) is given in the IEA Annex 42 Summary Report [Beausoleil-Morrison et al., 2008]

3 NOMENCLATURE AND SYMBOLS

The nomenclature outlined in this chapter, including the list of symbols and indices, is used as much as possible in the individual studies, in order to facilitate reading the reports and summarizing the results.

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 may consist of 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.
Trigeneration or Polygeneration	Combined generation of heat, cold and electricity.

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)
Build	Building
CC	Combined cycle (gas and steam power plant)
CCHP	Combined cooling heat and power (= tri- or polygeneration)
CGU	Cogeneration device (cogen unit)
CHP	Combined heat and power (= cogeneration)
CO2	Carbon dioxide
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
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
SC	Space cooling
SOFC	Solid oxide fuel cell
TBD	To be defined
TGU	Trigeneration unit (trigeneration device)
Th	Thermal
UCTE	Union pour la Coordination de la Production et du Transport de l'Electricité, Luxembourg

3.3 Energy terms

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

3.3.1 Definitions

No See Fig. 3	**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 provided 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. cogeneration system) may contribute as internal gains.
3	Net energy	Part of the energy demand which is provided by the HVAC and electric system (including renewable energy systems) to cover the energy demand for space heating/cooling, domestic hot water and electricity respectively.
4	Delivered energy *Equally valid terms, but not to be used in A42:* *- 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 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 sustainable grown 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 renewable energy it is not evident in Fig. 3.
7	Primary energy	Represents the energy usage associated to 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). Primary energy is subdivided in renewable/non renewable or in fossil/non-fossil primary energy.

No	Term	Description
8	Primary energy equivalence for locally generated renewable energy	Represents savings in non-renewable primary energy 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 primary to delivered energy 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 primary energy in (7) and reflected in the respective primary energy factors or emission factors.
9	Primary energy (exported energy)	Represents the primary energy associated with exported energy, which is subtracted from (7) to calculate the (net) primary energy use.

For additional information on how to apply and handle the different energies in the PA task, see § 4.2.1 and also Fig. 5.

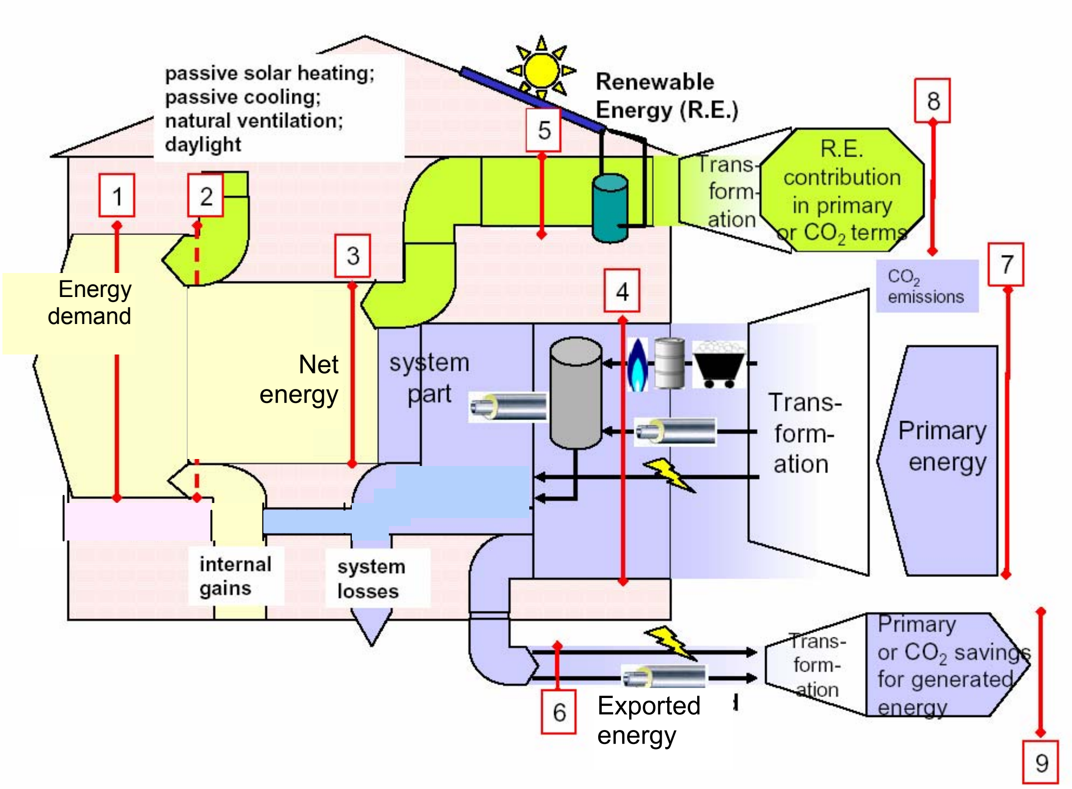


Fig. 3 Energy conversion processes and energy terms, as exemplified by residential building supply (Source: CEN/BT WG 173 EPBD N 27 rev)

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

3.3.2 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.

The energy values are valid for the selected simulation period, normally one year (annual energy values in MJ/a or MJ/m^2/a), see also § 4.1.3.

Energy values are based on LHV. Electricity input and output as used (normally AC, as electricity from and to grid). See also § 4.2 Energy analysis 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. 3)	MJ
DE	Delivered energy (No 4)	MJ
NE	Net energy (No 3)	MJ
OE	Energy output of cogeneration 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

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, either exported to grid, or delivered from grid
El-CGU	Electric energy output of cogeneration unit
Fuel	Fuel
H	Heat
HD	District heat
HEAT	Heat for space heating and domestic hot water
NRE	Non-renewable energy
NRPE	Non-renewable primary energy
NG	Natural gas from grid
PE	Primary energy
SH	Space heating
SC	Space cooling
Th	Thermal
Th-CGU	Thermal energy output of cogeneration unit

Examples	(parameters starting with a capital letter refer to amounts of energy, parameters starting in lower case represent energy amounts per reference area)	
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 cogeneration 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	-

3.3.3 Energy terms for electricity

Fig. 4 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. 4:

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

and

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

Grid loss factor

For electricity produced locally, delivered into the grid and consumed later on again from the grid, a grid loss factor $fl_{El\text{-}Grid}$ may be considered (e.g. grid loss factor of 10%: $fl_{El\text{-}Grid} = 0.1$). Thus (see again Fig. 4),

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

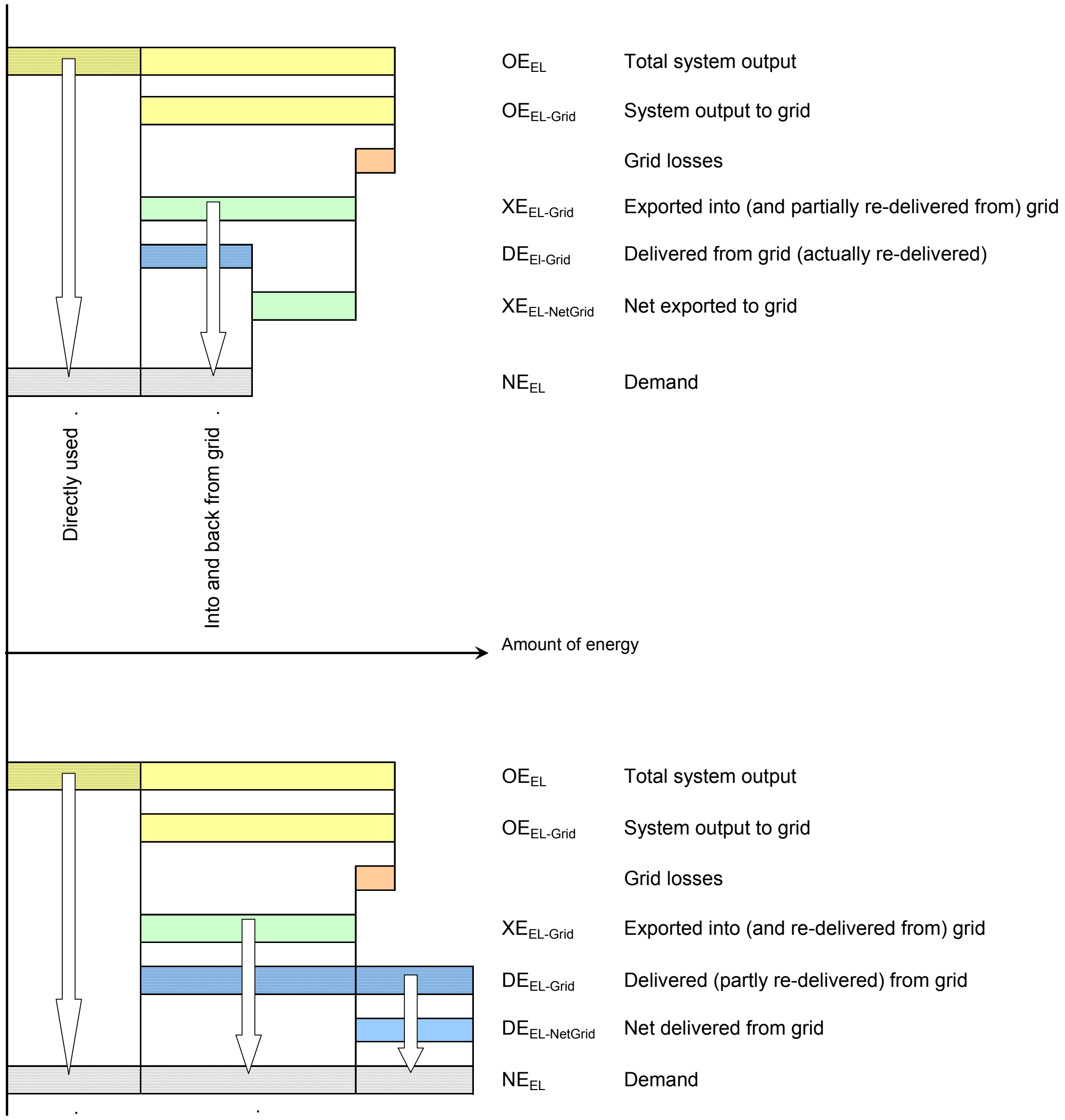


Fig. 4 Energy terms for electricity

3.3.4 Example case for the illustration of energy parameters and related factors

The example case is a fictitious single family house heated by a NG-fired heater and with electricity supply from onsite PV power production. 30% of yearly electricity demand is provided by the PV system, 70% of yearly electricity demand by the grid. Grid electricity is produced partly by coal fired power plants (80%) and partly from hydropower (10%) and PV (10%). Two thirds (2/3) of the electricity provided by the PV system are used directly, one third (1/3) is used indirectly (electricity delivered back into the grid and supplied again by the grid).

For the renewable energies, primary energies are not based on the original renewable energy source (fluid-dynamic or gravitational energy of water for hydro-power, solar irradiation for PV), but based on the output of the plant. Thus only grid losses are accounted for. For hydro power, these losses are assumed to be covered by electricity produced by non-renewable energies, while for PV it is assumed that the grid losses are covered by the (renewable) electricity generated by the PV system.

For the definition of system performance factors see § 4, and for primary energy factors see § 6.7.3.

Input values			
Primary energy factor (*pef*) for NG	pef_{NG}		1.13
pef for grid electricity from coal power plant (CPP)	pef_{EL-CPP}		3.09
pef for grid electricity from hydropower	$pef_{EL-Hydro}$		1.10
pef for grid electricity from PV	pef_{EL-PV}		1.10
Primary energy factor for grid electricity	pef_{EL}	80% pef_{EL-CPP} + 10% $pef_{EL-Hydro}$ + 10% pef_{EL-PV}	2.69
Non-renewable *pef* for NG	$nrpef_{NG}$		1.13
Non-renewable *pef* for grid electricity from coal power plant	$nrpef_{EL-CPP}$		3.09
Non-renewable *pef* for grid electricity from hydropower	$nrpef_{EL-Hydro}$		0.10
Non-renewable *pef* for grid electricity from PV	$nrpef_{EL-PV}$		0.00
Non-renewable *pef* for grid electricity	$nrpef_{EL}$	80% $nrpef_{EL-CPP}$ + 10% $nrpef_{EL-Hydro}$ + 10% $nrpef_{EL-PV}$	2.48
Demand and efficiency values (inputs or simulation results)			
Annual net heat demand for SH	nE_{SH}		155.0 MJ/m^2/a
Annual net heat demand for DHW	nE_{DHW}		50.0 MJ/m^2/a
Annual net electricity demand	nE_{EL}		80.0 MJ/m^2/a
Annual input of onsite PV system	rE_{EL} (PV)	30% of nE_{EL}	24.0 MJ/m^2/a
Efficiency of space heat generation	$\eta_{DE,SH}$		0.85
Efficiency of DHWgeneration	$\eta_{DE,DHW}$		0.70
Delivered energies			
Delivered energy for SH	dE_{SH}	$= nE_{SH} / \eta_{DE,SH}$	182.4 MJ/m^2/a
Delivered energy for DHW	dE_{DHW}	$= nE_{DHW} / \eta_{DE,DHW}$	71.4 MJ/m^2/a
Delivered energy as NG	dE_{NG}	$= dE_{SH} + dE_{DHW}$	253.8 MJ/m^2/a
Delivered energy as electricity from grid	dE_{EL}	$= nE_{EL} - rE_{EL, PV}$	56.0 MJ/m^2/a
Primary energies			
Primary energy demand for NG	pE_{NG}	$= dE_{NG} * pef_{NG}$	286.8 MJ/m^2/a
Non-renewable primary energy demand NG	$pE_{NRE,NG}$	$= dE_{NG} * nrpef_{NG}$	286.8 MJ/m^2/a
Primary energy demand for grid electricity	$pE_{EL-Grid}$	$= dE_{EL} * pef_{EL}$	150.8 MJ/m^2/a
Non-renewable energy demand for grid electricity	$pE_{NRE,EL-Grid}$	$= dE_{EL} * nrpef_{EL}$	139.0 MJ/m^2/a
Primary energy demand	pE	$= pE_{NG} + pE_{EL-Grid}$	437.5 MJ/m^2/a
Non-renewable primary energy demand	pE_{NRE}	$= pE_{NRE,NG} + pE_{NRE,EL-Grid}$	425.7 MJ/m^2/a
System energy performance factors			
Primary energy performance factor	η_{PE}	$= (nE_{SH} + nE_{DHW} + nE_{EL}) / pE$	0.65
Non-renewable primary energy performance factor	η_{NRPE}	$= (nE_{SH} + nE_{DHW} + nE_{EL}) / pE_{NRE}$	0.67

4 PERFORMANCE ASSESSMENT AND PERFORMANCE CRITERIA

4.1 General

4.1.1 Types of performance assessments

The following analysis types are applied within ST C:

- Energy analysis
- CO_2 or GHG emission analysis (environmental impact analysis)
- Economic analysis

Below, individual criteria are listed which are considered in the performance assessment task.

4.1.2 Aggregation of criteria

The assessment of integrated energy systems regarding energy, emissions, technical and economic issues can be performed by formulations, which concentrate all criteria within a single objective aggregated function. Aggregation is based on a weighting of the individual criteria. In the ST C PA work, generally, aggregation is not applied. Instead of trying to weight and/or to aggregate the individual criteria, a multi-criteria assessment/optimization procedure might be more appropriate (see chapter on PA methods, on optimization, and on data presentation).

As an example, aggregated formulations allow to minimize the overall internalized cost of an energy system, accounting for design, installation, operation but also pollution through the introduction of pollution cost factors. However, given the difficulty encountered sometimes when trying to express certain criteria in financial terms, a multi-criteria optimization may be preferred.

4.1.3 Evaluation period

The evaluation period depends (i) on the selected analysis type, (ii) on the selected criteria, and (iii) on the topic dealt with.

Period		**Application**
lifetime	years	- generally for energy, emissions and cost life cycle evaluations - for comparison of different cases or configurations
annual	Jan. to Dec.	- generally for energy, emissions and cost evaluations - for comparison of different cases or configurations - Periods of several years might be necessary if cases with larger storage processes are studied
heating season / cooling season	depending on climate region, and possibly building	- for cases where a cogeneration/trigeneration device is operated seasonally - for comparison of different cases or configurations
several weeks		- for detailed presentation of dynamic effects for physical parameters like temperatures, e.g. for storage loading - mainly for an individual case and comparison between system configurations or with reference system
week		- for detailed comparison of dynamic effects for physical parameters if occupant load schedules are defined on weekly basis - for detailed evaluation of start-up, shut-down processes of FC's, especially SOFC - for individual cases

Period		Application
day		- for detailed comparison of dynamic effects for physical parameters if occupant load schedules are defined on daily basis
selection of typical days	days representing typical climatic seasons	- for optimization purposes
one to several hours	E.g. in 5 min interval as given by electric load profiles	- for detailed evaluation of start-up, shut-down processes - for detailed analysis of load following dynamics (especially for electric loads)
other relevant periods		- depending on the problem

4.2 Energy analysis

4.2.1 Energies considered

Energy values are used for technological, environmental as well as economic evaluations.

Three types of energies are considered for the assessment of the energy consumption:

- Net energy demand (energy demanded from the HVAC, the cogeneration and the RE systems to cover the demands for space heating (cooling), 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 energy
  - 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 hydraulic vs. nuclear power generation, and on the use of solar heat or electricity.

Delivered energy is used for cost evaluations. Net vs. delivered or primary energies are used for system efficiency assessments.

4.2.2 Reference and units for energy values

In order to compare different cogeneration system and building type cases, annual energy demand values are normalized to a certain reference parameter. This parameter shall be consistent with the energy reference unit used for space heating.

For ST 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).

<u>Energy reference floor area (ERFA)</u>

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

Comment:
There are quite different definitions of energy reference floor areas, according to the different standards and national energy codes. It seems not very crucial to have a common definition of the energy reference

floor area throughout our ST C studies. Most cogeneration performance studies focus on the comparison of energy ratios (such as the energy performance factor defined as the ratio of net energy demands to the delivered energies, see below). Theses ratio values are independent of whether absolute energy values or values per energy floor area are determined. Of course, a specific building should have one clear definition of energy floor area. But it seems not so crucial that different buildings use exactly the same definition.

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

Different types of boundaries or control volumes and types of balance analysis can be made (see Fig. 5)

a) analysis of the cogeneration device in terms of power oriented assessments
b) analysis of building energy supply system (cogeneration device and other HVAC components) in terms of net power
c) analysis of the building in terms of delivered energy demand (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 energies, for the whole simulation period (normally one year).

ST C studies mainly focus on analysis type (c) and (d) (delivered and related primary energy demand), however, analysis type (b) may be applied e.g. for the analysis of different control algorithms or of the size of components.

For analysis type (c) and (d), the control volume for the simulation includes the building with the cogeneration system (and optional further renewable energy supply components), but it can also include a row of buildings if they are connected to a common storage or cogeneration plant by a local heat network. 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.

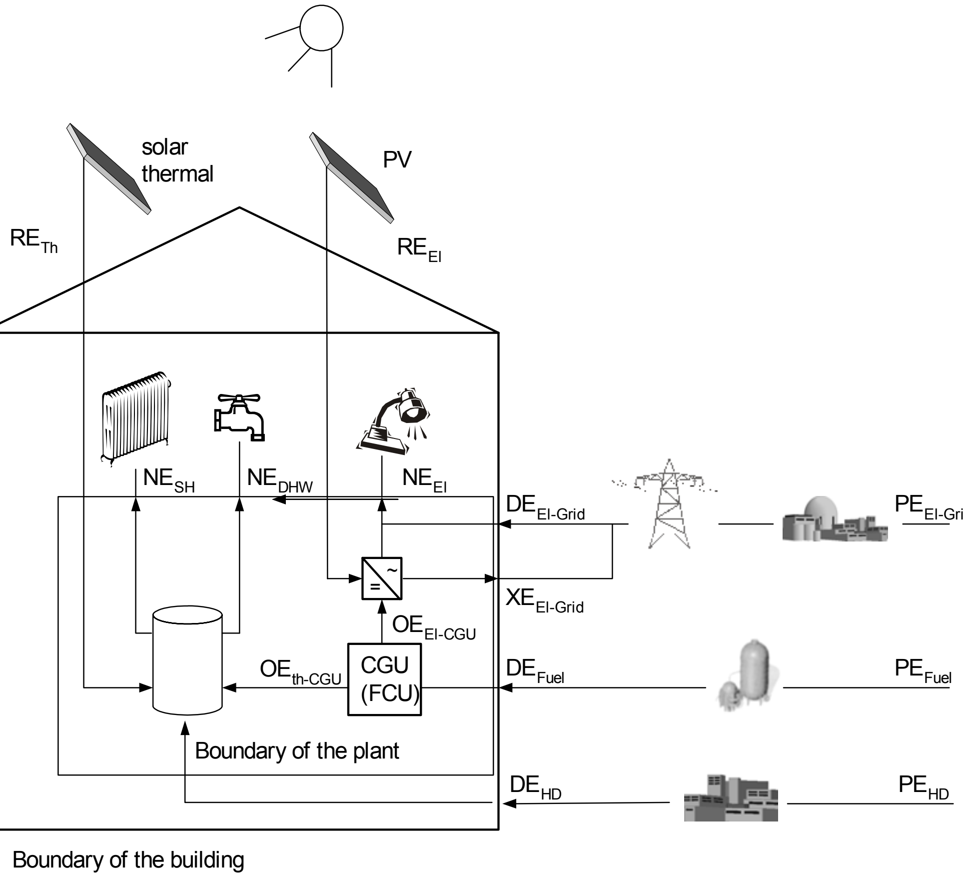


Fig. 5 Control volumes and related energies

4.2.4 Amendments to energy definitions

<u>Net energy demand for space heating and cooling, and for domestic hot water</u>

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} (per reference floor area). Energy for space cooling is determined accordingly.

Distribution losses for space heating may be considered, if they are displayed separately, in order to increase the comparability of the different cogeneration systems analysed.

For domestic hot water, it is assumed that the heat demand equals the net energy for hot water (no distribution losses assumed).

Referring to § 3.3 Energy terms and Fig. 4, the following comments and clarifications apply in respect to the definition of "net energy demand":

No (Fig. 3)	Topic	Comment
2, 3	Parasitic losses of system	A part of the parasitic losses of the cogeneration system (radiative and convective skin losses incl. venting of heat from individual cogeneration 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 such cases, this ought to be considered in the simulation. However, the useful amount of the parasitic heat loss may not be considered neither as an increase of the thermal output of the cogeneration device ($OE_{th\text{-}FCU,\ CGU}$) nor as an increase of the thermal efficiency of the system.
2, 3	Distribution losses within building for heat/cold and electricity	Basically, losses in the distribution system for space heating/cooling and DHW are to be accounted for on level 3 (net energy provided by the system). However, as A 42 deals with the performance assessment of cogeneration systems (and not of distribution systems), it is suggested to consider no losses for DHW and electricity distribution within the building, see below, or to account for them separately (and not as a part of the cogeneration system performance).
3, 5	Combined hot water storage for cogeneration and solar system	In this case the net energy output of the system "cogeneration device and storage" includes already the contributions from the RE system (5). The system ought be evaluated by energy ratios as NE to DE or to PE. System efficiency evaluation should focus on non-renewable energies or emissions. In addition, the percentage of NE supplied by the renewable energy system can be 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

For cogeneration systems, a split of pollutant emissions and costs between the two energies produced has frequently been practised in comparative analyses between systems. The allocation of the energy consumption and the emissions to the product energy forms (heat and electricity) may be based on physical or on cost and market oriented parameter.

In the literature, several types of allocation methods, adapted to the evaluation topics and the scenarios studied, are presented [Ménard et al. 1998, Gantner et al. 2000, Lucas 2000].

a) Equivalent consideration of heat and electricity:

   The energy consumed and the emissions released are considered in total for both the electricity and the heat generated, without any weighting.

b) Bonus or credit methods:

   - If electricity is the product of main interest, the energy consumption and the emissions (and cost) are allocated to the generated electricity, with credits for the heat generated
   - If heat is the product of main interest, the energy consumption and the emissions (and cost) are allocated to generated heat, with credits for the electricity generated.

c) Exergetic allocation:

   The energy consumed and the emissions released are allocated in relation to the exergies generated, that means to the exergy of the generated heat and to the exergy of the generated electricity.

In the Annex 42 STC work, method a) is basically used. However, for the consideration of the electricity produced locally and delivered to the net, elements of the bonus/credit method may also be considered.

Bonus or credit methods b) are also applied as an optimization goal or objective for PE optimal control [Lamon et al. 2006, Gähler et al. 2007]. In order to evaluate the system performance with the optimization objective implemented in the control algorithms, for compliance reasons, the same objective is used as a performance criteria in the performance assessment of the system. However, for comparison with other systems, it may be necessary to additionally apply method a). The application of allocated criteria may lead to differences to the results gained with method a), due to the different basis for comparison, see example given in the Appendix of this report.

For boundary conditions and reference systems see §6.

Non-renewable / renewable energies

For hybrid systems which use non-renewable and renewable energies (e.g. a natural gas driven cogeneration system combined with a solar thermal system), it is proposed 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. Such, 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.

4.2.6 Energy performance factors

General

In order to evaluate how efficiently delivered or primary energy is utilized by the analyzed building and its cogeneration system to cover the annual electricity and net heat demand in the building, dimensionless energy performance factors η_{DE} and η_{PE} are defined, as a ratio of the net energy demand of the building to consumed delivered energies (η_{DE}) or to consumed primary energies respectively (η_{PE}).

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

The energy performance factor by itself is not a measure for the effectiveness of a CHP unit, but a measure how effective the demand of the building is covered by the energy system, consisting of CHP system and other energy converters, and the external supply (see Fig. 5). 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 which 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.

Basically two approaches are possible to consider $XE_{El\text{-}NetGrid}$:

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 (see Fig. 3 No. 9, and § 6.7.3). Thus, the amount of energy consumed by the system (delivered energy or primary energy) to cover the net demand is reduced by $DE_{El\text{-}Displaced}$ or $PE_{El\text{-}Displaced}$.

$$DE_{El-Displaced} = XE_{El-NetGrid}$$

$$PE_{El-Displaced} = pef_{El-Grid} \cdot XE_{El-NetGrid}$$

The primary energy factor considered may be related to the average grid generation mix, to marginal power generation technology or to an end-use related mix, see § 6.7.3.

For time dependant primary energy factors, $PE_{El\text{-}Displaced}$ has to be determined as an integral of primary energy values per simulation time step.

For both approaches the respective definitions of the performance factors are given below. Both methods have its advantages and disadvantages, the method to be used has to be selected in accordance with the aims and the purpose of the individual performance assessment study.

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 is identical to the electric efficiency of the cogeneration unit, with method b) however, the factor becomes zero. On the other hand, with method b), performance factors > 1.0 may result for cases where electricity is exported and a high pef_{Grid} applies.

Energy performance factors

Approach a) Additional demand

The energy performance factors for delivered and primary energy respectively are defined as

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

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

using annual net energy consumption *NE*, annual delivered energy *DE*, primary energy *PE*, in conjunction with indices for electricity (*El*), space heating (*SH*), domestic hot water (*DHW*), net amount of electricity from (DE) or to grid (XE) (*El-NetGrid*), the fuel (*Fuel*) and district heat (*HD*) (see also § 3.3 and especially Fig. 4).

<u>Note 1</u>: As mentioned above, due to the different energy qualities, the evaluation should be made on the level of primary energy whenever possible. The definition of η_{DE} is given mainly for reason of completeness.

<u>Note 2</u>: For a specific case, either $PE_{El\text{-}NetGrid}$ *(and* $DE_{El\text{-}NetGrid}$*) or* $XE_{El\text{-}NetGrid}$ is equal to zero, see definitions in § 3.3.3

<u>Note 3</u>: 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

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

Approach b) Substitution principle

The energy performance factors for delivered and primary energy respectively are defined as

$$\eta_{DE} = \frac{NE_{El} + NE_{SH} + NE_{SC} + NE_{DHW}}{(DE_{El-NetGrid} - DE_{El-Displaced}) + DE_{Fuel} + DE_{HD}}$$

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

with

$$DE_{El-Displaced} = XE_{El-NetGrid} \qquad PE_{El-Displaced} = pef_{El-Grid} \cdot XE_{El-NetGrid}$$

4.2.7 System comparison approach

Another way to evaluate the energy performance of a system is to compare the primary energy demand of the system directly with a reference system, for a given electric demand and a given heat demand for space heating and domestic hot water, see Fig. 6. Such a case, but with increased complexity, with auxiliary burner and with net electricity feedback from the CHP unit to the grid, is exemplified in [Lamon et al. 2006].

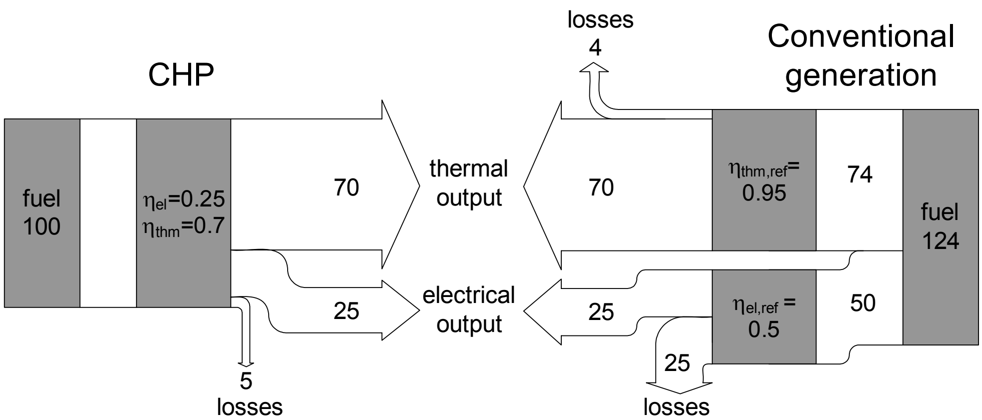


Fig. 6 Comparison of thermal and electrical outputs between a CHP engine and a conventional system where the thermal output is generated by a burner and the electricity by a power plant, see [Lamon et al. 2006]

This approach yields a consistent set of criteria for both the assessment of the CHP system as well as for the optimization of its operation strategy.

For PE optimized control, the relative savings, $PE_{REF} - PE_{CHP}$, are maximized.

For performance assessment, primary energy performance indicators Ind_{PE} may be defined, relating the difference of the primary energy demand of the two system to (a) the primary energy demand of the reference system

$$Ind_{PE} = \frac{PE_{REF} - PE_{CHP}}{PE_{REF}}$$

or (b) by relating the primary energy demand difference to the primary energy demand for heat generation only.

$$Ind_{PE,Heat} = \frac{PE_{REF} - PE_{CHP}}{PE_{REF,SH+DHW}}$$

With approach (b), PE savings achieved by CHP devices can be directly compared to the savings achieved by other measures, for example better isolation of the building envelope.

For further details see the Appendix, with a gas boiler and grid electricity as the reference system. Such performance indicator may also be used as an optimization goal or objective for PE optimal control, see e.g. [Lamon et al. 2006, Gähler et al. 2007].

Systems comparisons may also be included in the results presentation sections of the study reports, see §7.2.1.

4.3 Environmental impact analysis

Concerning environmental impact, the PA studies performed within ST C focus on the evaluation of GHG emissions, based on the primary energy demand, and the respective life cycle analysis, considering the whole life cycle of the cogeneration device or system.

Other pollutants and the respective environmental impacts (as e.g. acidification, eutrophication, or photo-chemical smog) are not considered within ST C.

4.3.1 Emissions analysis

Performance criteria are the emission of:

- CO_2
- CO_2 equivalents, considering the most relevant green house gases (GHG)

As for the energies, also for the emission the fuel production chain must be considered for assessments on the basis of primary energy.

Emission values may be given in absolute figures, or normalized to the same energy reference floor area value as used for the presentation of the energy figures.

Whenever possible, GHG emissions shall be determined. In particular methane, associated with natural gas production and transportation/distribution, must be considered.

<u>CO_2</u>

- Amount of CO_2 emitted during the simulation period ([kg], [kg/a] or [kg/m^2/a]) by
  a) the cogeneration system
  b) the production chain for fuel (emission factors see Table 2 in § 6.7.3)
  c) the production chain grid for electricity (depending on the electricity generation mix).

<u>CO_2 equivalents</u>

- Amount of CO_2 equivalents emitted during the simulation period ([kg], [kg/a] or [kg/m^2/a]) by
  a) the cogeneration system
  b) the production chain for fuel (emission factors see Table 2 in § 6.7.3)
  c) the production chain for grid electricity (depending on the electricity generation mix).

CO_2 equivalents are metric measure used to compare the emissions from various greenhouse gases 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 / CO2 (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

4.3.2 Life cycle analysis (LCA)

Life cycle analysis is an analytical tool to assess the environmental impact of a process or a product, considering the whole life cycle from raw material extraction, manufacturing, shipping, installation, operation, to the final waste disposal.

Several methods are available for environmental analysis, see e.g. [ecoinvent 2005] and [Pehnt 2003a, 2003b] or the IEA Annex 42 ST C State of the art report [Dorer 2007].

The Research Institute for Energy Economy (FfE) presented an approach based on the Cumulative Energy Demand which states the entire demand, valued as primary energy, which arises in connection with the production, use and disposal of an economical good (product or service) or which may be attributed respectively to it in a causal relation. This energy demand represents the sum of the Cumulative Energy Demands for the production, for the use and for the disposal of the economic good. It has to be indicated for these partial sums which preliminary and parallel stages are included.

However, in the frame of Annex 42, the participants did not perform LCA studies considering comprehensive assessments of environmental impacts or the synthesis of e**m**ergies (embodied energies). Also the Research Institute for Energy Economy only considers the operation period of the system life cycle.

4.4 Economic analysis

Economic analyses focus on the comparison of total cost for the different systems, and on the influence of time-dependant pricing of purchased electric energy and fuel on the optimization of the system in terms of size, control and operation.

Only a very limited amount of economic assessments are performed within ST C. It is difficult to put much emphasis on system costs since A42 deals with technologies that are still under development. However, some treatment of the economics is critical, especially in relation to energy costs. However, also energy cost structures become increasingly complex, and the supply industry is in an unprecedented state of flux.

Information on first and on operation and maintenance (O&M) costs for small scale cogeneration unit based on reciprocating internal combustion engine are available due to the availability of this devices on the Japanese and European market. Stirling engine MCHP units are limited available in other country (UK) too. University of Sannio and Second University of Napoli have carried out economic analysis considering first and O&M costs of ICE MCHP systems.

4.4.1 Economic criteria

In general, economic cost models for the assessment of a cogeneration system incorporate both the investment costs and operating costs of the system [Hawkes et al. 2006], [Marechal et al. 2005]. Although there are numerous criteria available, virtually the only ones used to determine whether to reject or to accept a project have been the net present value (NPV), internal rate of return (IRR) and payback period

(PP). [Biezma & SanCristóbal 2006] give a description of the uses and limitations of many different economic evaluation techniques and shows how these methods are applicable to cogeneration plants.

In the frame of IEA Annex 42, the Research Institute for Energy Economy (FfE) has adapted and extended a tool for economic assessment of residential cogeneration, based on the German standard [VDI 2067].

For ST C it is assumed that in most studies the economic performance analysis is rather of relative then of absolute nature, showing the influence of certain parameters on cost in comparison to base or reference cases.

Analysis of real manufacturing and market prices certainly is beyond the scope of this Annex. It is also be beyond the scope of ST C work to detail the production cost of future products, extrapolating from present pre-series units by assuming scale factors and "learning curves" and respective cost reductions.

Externalities are not included in the economic assessment, as environmental criteria are separately treated.

Below different cost parameter are listed which might be used in the performance assessment of cogeneration systems. However, within ST C, the emphasis of economic performance assessment focused on the comparison of systems, thus on cost related to the energy output of the cogeneration system (specific cost).

<u>Specific (electricity) costs</u>
Any type of cost, normalized to the electric energy output of the system. Nominal (e.g. cost per kWe installed) or effective energy output values (cost per kWh generated) may be considered.

<u>Investment cost (= first cost)</u>
Cost of device and/or system, including direct and indirect cost for installation and also cost for commissioning.

<u>Operating / Running cost</u>
Energy costs for delivered energy (imported fuels and electricity, minus revenue from electricity export, and possibly heat/cold) and maintenance costs, but no taxes, insurance and planning costs.

<u>Total cost</u>
Total cost = investment cost + operating cost

<u>Maximum allowable investment cost</u>
Another investment cost parameter is the maximum allowable investment cost in comparison to a reference system, as an investment cost threshold, above which the equivalent annual cost for the investigated system are higher than those of the reference system

<u>Net present value (NPV) of cogeneration system or devices</u>
The NPV is a value calculated in cost benefit analysis. The NPV discounts all the cash outflows (payments for investment and operation cost) and inflows (revenue from electricity or heat exported to the grid) over the life of the project to their present day value. The choice of discount rate reflects the cost of capital.

<u>Equivalent annual cost (EAC)</u>
The equivalent annual cost consists of equivalent annual capital costs, annual maintenance costs, annual fuel costs for the cogeneration unit and, if applicable, the supplementary boiler, annual electricity import costs minus annual revenue from electricity export.

<u>External cost</u>
External costs accounting for environmental impacts and for embodied energies are covered by life cycle analysis (LCA), see respective chapter above. External cost are not considered in ST C work.

4.5 Technological analysis

4.5.1 Criteria

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

In ST C, the focus is on criteria which have a relation to or an impact on the energy, emissions and economic performance criteria set out above, such us:

- Number of equivalent full load operation hours
- Demand coverage (in stand-alone configuration)
- System efficiencies

A technological analysis may also comprise the evaluation of technical issues in regard to energy, emissions and cost. Such issues might e.g. be to determine the influence of:

- 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 (especially for PEMFC)
- Flow rates in water heat exchange system

Other topics, such as installation requirements (e.g. supply gas pressure), pollutants emission data, or acoustic performance data, are to a limited extend included in the ST A state of the art report on cogeneration systems [Knight & Usurgal, 2007], but are not dealt further within ST C.

4.6 A simplified approach

University of Sannio has proposed a simplified approach for the performance assessment of residential cogeneration [Possidente et al. 2006] . A short outline is given below.

According to a typical 3-E (Energetic, Economic and Environmental) simplified approach the performances of the alternative system (AS = cogeneration unit) are usually compared to that ones of the traditional energy system based on separate "production" (TS = electric grid and gas boiler). Both alternative and conventional systems have to satisfy the electric and the thermal (heating and domestic hot water production) end user requirements (see Fig. 6). Obviously this approach could also be used to analyse more complex energy systems, such as cogeneration devices with hot water storage tank, or combined cooling, heating and power to satisfy also cooling demand.

In § 4.2.6 the primary energy performance factor has been introduced. According to scientific literature and European Directive [COM 2004/8/EC] to compare the alternative energy system able to satisfy the same user, it's important to evaluate the Primary Energy Savings (PES) defined as

$$PES = \frac{(PE_{Fuel-GB} + PE_{El-Grid}) - PE_{Fuel-CGU}}{PE_{Fuel-GB} + PE_{El-Grid}} = 1 - \frac{\eta_{NRPE}^{TS}}{\eta_{NRPE}^{AS}}$$

The environmental impact is really important by choosing a technology and a simplified approach is based on the evaluation of the emissions of equivalent CO_2 of the compared energy systems. The parameter that could be used is the avoided greenhouse gas emissions defined as:

$$\Delta CO_2 = \frac{(CO_{2,Fuel-GB} + CO_{2,El-Grid}) - CO_{2,Fuel-CGU}}{CO_{2,Fuel-GB} + CO_{2,El-Grid}} = \frac{CO_2^{TS} - CO_2^{AS}}{CO_2^{TS}}$$

Figure 20 in § 7.2.4shows an example of the PES and of the ΔCO_2 of different MCHP systems as a function of the supplied electric power.

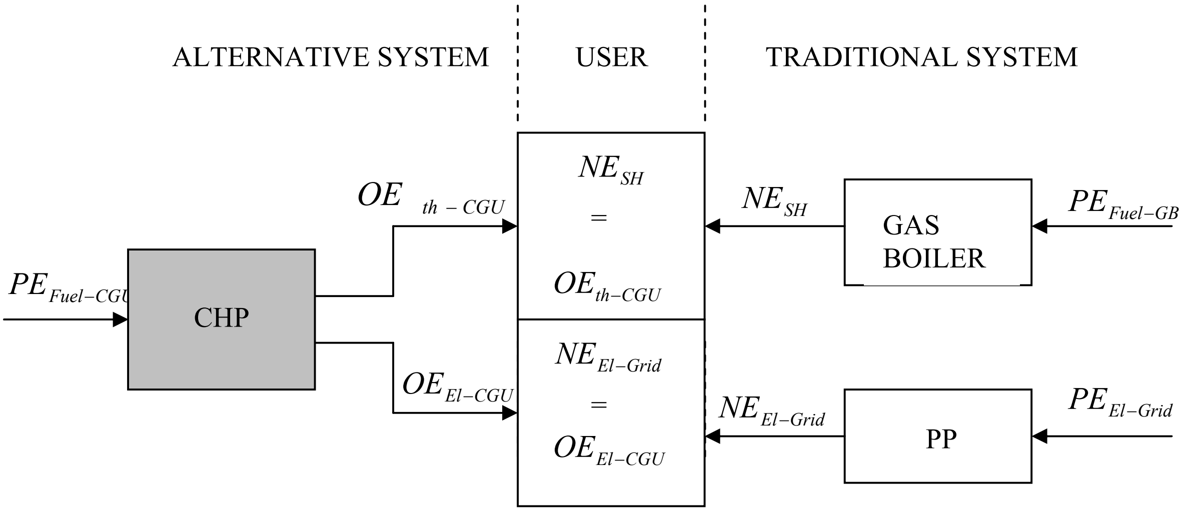


Fig. 7 Energy flows of the two compared systems

5 PERFORMANCE ASSESSMENT METHODS

5.1 Deterministic method

5.1.1 Performance of individual cases and configurations

Assessment of the performance of individual system in respect to selected parameter or performance criteria and respective time period (see § 4.1.3).

5.1.2 Comparison between cases and configurations

Comparison between cases and configurations for selected performance parameters and respective time period. This method will be applied in many studies. Mostly, the performance values are compared with those of a reference system or base case. Such reference system may also be an empirical evaluation case. For reference cases see § 6.3

5.1.3 Performance bound methods

In order to define a performance bound, cases with assumed optimal control may be analyzed and then be used as benchmark case(s). Such optimal control may be based on the advance knowledge of boundary conditions (loads, climate), which is available in the simulations, but not in real conditions.

5.2 Sensitivity analysis

Sensitivity analysis is applied for

- the determination of critical parameters for a given situation (case/configuration)
- the indication of errors bands /confidence intervals in the presentation of simulation results.

5.2.1 Single parameter sensitivity

By single parameter sensitivity analysis, a clear indication can be gained of the first order influence of this parameter on the system performance in respect to the selected criteria.

Therefore, it is proposed to apply this method in cases, where the aim of the study is to gain basic knowledge on system behaviour, and to determine the influence of individual parameters.

For single parameter analysis, (at least) three different values (or profiles, or data sets) should be analysed (Fig. 7)

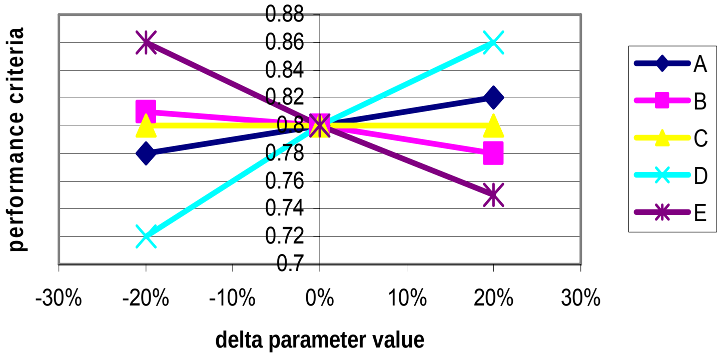


Fig. 8 Base case and effects of variations for parameter A-E on the performance

5.2.2 Multiple parameter sensitivity

With multiple parameter sensitivity analysis, a good general picture of the system performance in the selected parameter range can be gained. However, it is more difficult to derive conclusion in terms of parameter optimisation and to identify most influencing parameters.

Fractional factorial design

Multi parameter sensitivity can be derived by applying multi-factorial test design methods for the definition of the individual cases and configurations to be analysed. For each of the investigated parameter, a mean value (0), a low value (-1), and a high value (+1) is defined. With optimal test design theories, the necessary number of individual combinations to be considered is minimized, see e.g. [NIST e-Handbook] or [Box et al. 1978].

5.3 Probabilistic and stochastic approach

5.3.1 Monte-Carlo methods

For a probabilistic approach, Monte-Carlo methods may be applied. For some of the simulation codes considered in this Annex, specific tools are available.

For a Monte Carlo analysis, dominant parameters have to be identified, and probability distributions have to be defined for these input parameters. The results of a Monte Carlo analysis are probability distributions and indications of error bands/ confidence intervals of the performance criterion parameter analysed.

The results of a probabilistic analysis gives a good overall picture of the performance of a system. However, it is difficult to identify the influence of specific parameters, and therefore also difficult to derive conclusions in regard to system optimization and system dimensioning.

As one of the goals of ST C is to identify most relevant parameters, it was suggested not to use Monte-Carlo methods.

5.4 Single-objective optimization

This type of optimisation focuses on the optimisation of a single criteria (or result or cost) function, which itself of course can be a function of many independent (or free or decision) variables.

A typical generic optimisation tool for such types of optimisations is the GenOpt® tool [Wetter 2004]. GenOpt is an optimization program for the minimization of a cost function that is evaluated by an external simulation program, such as EnergyPlus, TRNSYS, ESP-r, SPARK, IDA-ICE or DOE-2. It has been developed for optimization problems where the cost function is computationally expensive and its derivatives are not available or may not even exist. GenOpt can be coupled to any simulation program that reads its input from text files and writes its output to text files. GenOpt has not been designed for linear programming problems, quadratic programming problems, and problems where the gradient of the cost function is available. For such problems, as well as for other problems, special tailored software exists that is more efficient.

The use of optimization in control was demonstrated by [Lamon et al. 2006, Gähler et al. 2007] for cost and primary energy (PE)-optimal operation of a CHP building energy system.

5.5 Multi-objective assessment and optimization

The goal of an optimisation is to find the set of optimal points in regard to the criteria or objectives functions in the space of the decision variables. To overcome the problem of solving a mixed integer non-linear programming problem, multi-objective evolutionary algorithms are developed.

EPFL-LENI has recently developed new clustering evolutionary multi-objective optimizers (MOO) [Leyland 2002]. In the frame of IEA Annex 42, Maréchal presented the application of these methods for the thermo-economic optimization of cogeneration (and trigeneration) systems, see [Maréchal et al. 2005, Weber et al. 2006]. These evolutionary algorithms have proven to be robust and effective for the resolution of non-linear, non-continuous and mix real integer problems, such as those encountered when dealing with integrated energy systems.

This not only allows to identify optimum solutions, but also the shape of the search space as Pareto frontier (see Fig. 10). For a given range of cases and configurations, Pareto curves from MOO simulations could be specified for two criteria. Systems which meet certain threshold criteria may then be described in more detail.

Also ENEA made multi-objective assessments using evolutionary algorithms [Deb 2001].

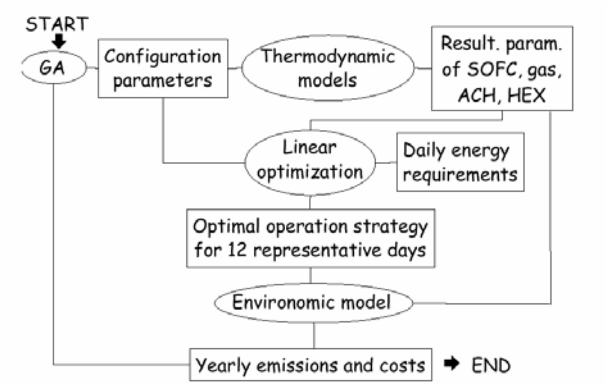


Fig. 9 Resolution strategy for MOO analysis
(Source: Maréchal EPFL)

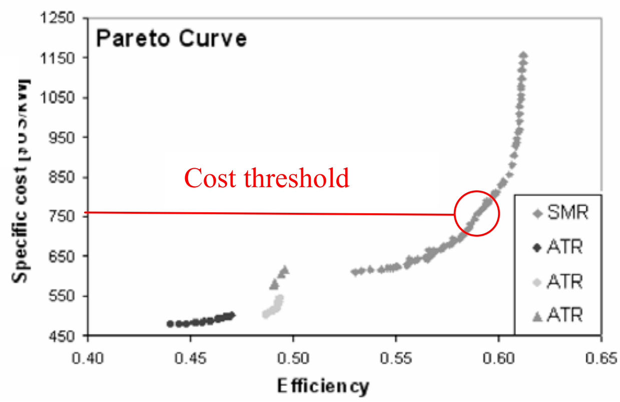


Fig. 10 Pareto curve from MOO analysis
(Source: Maréchal EPFL)

6 CASES, CONFIGURATIONS AND INPUT PARAMETERS

This chapter gives an outline and recommendations on how and what types of cases are selected, and some details on possible variations.

It would have been best if the performance analysis studies could have been treated on the basis of a standard set of cases. However, many Annex 42 participants were only in the position to have funding for the assessment of national cases.

In order to be able to draw any generally applicable conclusions from the individual performance assessment studies, it was suggested to rely as much as possible on a standard set of parameters also for the national studies, and/or to relate the results to generalized loads and system parameter.

The influence of system parameters and external parameters on the selected assessment criteria is 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, it was proposed to define a base case, from which then a variation in terms of lower/higher or less/more is defined. However, the aim of the PA task is to identify the most influencing parameters. Therefore, the question of what range / how many options to be considered in regard to the boundary condition parameter, is related to the cases studied and the assessment method applied.

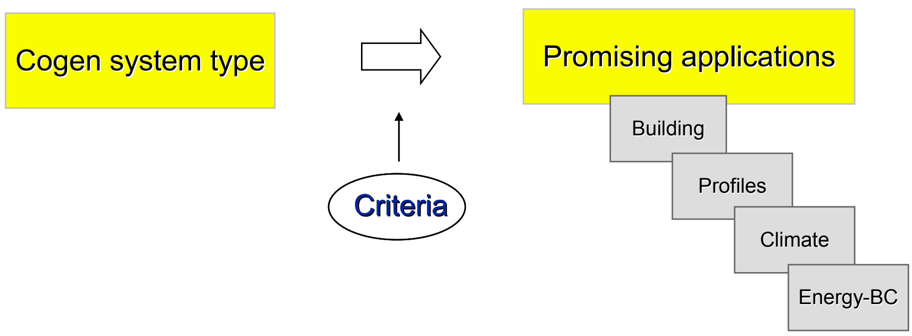
Optimizations of system parameters is performed for a selected number of cases, and a limited number of system parameter, applying different optimization methods.

6.1 Starting point for the definition of cases

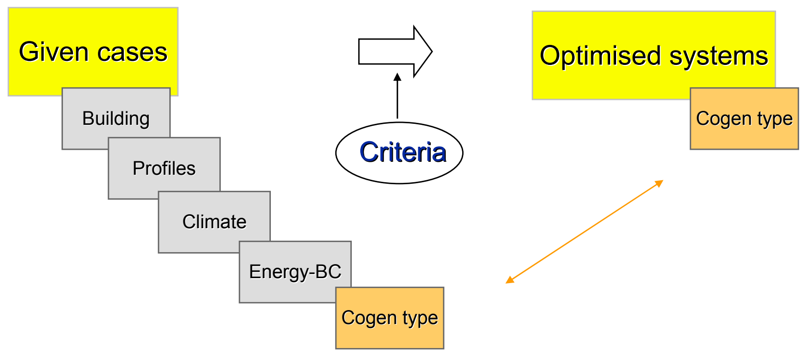
For the selection and variation of cases, the definition of the starting points and the order of parameter are essential.

In this respect of priority in parameter variation, two approaches can be distinguished:

- The definition of cases relies on existing cogeneration devices and systems in regard to performance levels and performance characteristics. The purpose of the study is to define the most suitable application environment (in terms of building type and size, loads, climate) for a given cogeneration system type or cogeneration unit.



- The definition of cases starts with given boundary conditions in terms of buildings, load profiles, etc. The purpose of the study is to define which system devices size in terms of performance levels and characteristics would be most appropriate for the selected case.



6.2 Cases in the individual studies

The cases analysed by the individual participants are shortly described in the Annex 42 Summary Report [Beausoleil-Morrison et al. 2008]

6.3 Reference cases

Reference cases should be defined on the basis of

1. a reference energy generation and supply system
2. a reference building with reference heat distribution and ventilation system
3. a reference set of occupant related loads

Preferably, and where applicable, the reference system should be based on the same primary fuel source (e.g. NG).

It is important, that the reference case is simulated and analysed in the same way as the case with the co-generation system. Therefore, any reference case must be simulated using

- the same model for the building and the respective heat/cold distribution and ventilation system
- the same level of detail considering e.g. parasitic and distribution losses.
- the same DHW and electric load profiles
- the same weather files

More details on input parameters (also for reference cases) are given in § 6.9.

6.3.1 Reference system for comparison

The cogeneration cases analyzed are compared to benchmark or reference cases with systems which are based on traditional and widely used supply technology.

The following system was suggested as reference energy system:

- 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.
- cold generation by an electric compression chiller
- electricity supply from the electric grid

Part load efficiencies must be considered in an adequate manner as applied for the evaluation of the co-generation system.

6.3.2 Reference buildings

There are several options for the definition of a reference building:

- one of the buildings used in the empirical evaluations, namely the CCHT building (Canada).
- a virtual building unit which is scalable from a single family house to a multifamily house or a cluster of houses, and which could be set up with different insulation levels (energy levels). This approach is applied in [Dorer et al. 2005].
- a building which already has been used in cogeneration evaluation studies (and building description and input files would be available).
- a set of buildings which spans the application range for residential cogeneration: from new SFH with low energy demand to minor insulated MFH with high energy demand.

6.4 System types

6.4.1 Micro cogeneration device types and characteristics

The set of systems selected for the individual studies may comprise data of:

- devices/systems tested in the frame of Annex 42
- other 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 are preferred for initial consideration, However, alternate system configurations or dimensions are considered, e.g. systems which lead to significantly improved performance, or systems with expected improved performance characteristics due to the replacement of prototype components with top state of the art components or due to technology developments. Such analysis may lead to recommendations to the manufacturers.

Therefore, whenever possible, system descriptions are extrapolated to consider similar devices that (i) are larger or smaller and (ii) more efficient than systems presently available today. It is recognized that the modelling approach used in the Annex 42 models may make such extrapolations challenging.

A list of cogeneration devices used in the performance assessment studies is given in the IEA Annex 42 Summary Report [Beausoleil-Morrison et al. 2008].

6.4.2 Auxiliary heater

- according individual system
- condensing gas burner/boiler (as default)

6.4.3 Cooling system

- thermally driven absorption or adsorption chiller
- desiccant cooling

6.4.4 Additional energy systems (solar thermal, PV, heat pump, etc.)

Combined cogeneration – solar system will be considered as follows:

- solar collector for DHW supply during summer period
- solar collector for DHW supply and for solar cooling during summer period

PV system

- according to specific case

Heat pump

- according to specific case. Electric heat pump may be directly driven by the electricity produced by the cogeneration system (total heat energy module).
- absorption heat pump driven by thermal power supplied by cogeneration system

6.4.5 Heat storage types and configurations

- size of storage
- mixed / stratified
- storage only for DHW / Combined storage for space heating and DHW
- long-term storage (phase change materials, chemical storage, seasonal ground storage)

6.4.6 Electric storage

- local electricity grid
- electricity storage (batteries, H_2 system)

6.4.7 Control and energy management

Many strategies, methods and algorithms may be investigated:

- strategies: heat demand following / electric demand following / minimised cost following / minimised total primary energy demand following …
- methods: deterministic, probabilistic, adaptive, predictive, fuzzy, neural network, ….

Several approaches may be defined for the sensitivity analysis and the performance assessment:

- control optimised in respect to the investigated criterion (energy, cost, etc.)
- control algorithms fixed throughout the assessment of a specific system
- control includes an optimizer

It is suggested to evaluate control methods separately.

6.5 Building types

For the individual studies, participants use building models representative of their local housing stock. Here, guidance is provided on what types of houses are to be studied (e.g. typical houses, low-energy homes, best-practice construction, new and retrofit cases).

Building types ought to be selected according to the following classifications:

Building size

- SFH / MHF / row of houses (terraced houses)

Building energy level (envelope)

- building according average housing stock of country or region
- building complying to minimum and/or target requirements as set out in the present national building standards and codes, or in the frame of the new EPBD (European Directive on Energy Performance of Buildings).
- building complying to low energy standards or labels (e.g. German Passive House standard, Swiss Minergie standard, Canadian R2000 standard)
- building of “best construction practice” or “best available technology (BAT)”

Building construction type

The construction type has an influence on the transient room temperatures and thus on the heating or cooling loads.

- heavy / lightweight construction

Distribution system for space heating and cooling; ventilation system

The influence of the heating system type on the performance of the cogeneration system is mainly related to the temperature level of the distributed heat and the type of heat distribution. Three system types are proposed:

1. low temperature floor heating
2. medium to high temperature radiator/convector system
3. air heating

Ventilation system

Only the influence of the ventilation on the space heating and cooling load is considered. Three cases are considered.

1. outdoor air flow rates according indoor air quality requirements (e.g. 10 dm^3/sec and person) without heat recovery
2. outdoor air flow rates according indoor air quality requirements (e.g. 10 dm^3/sec and person) with heat recovery
3. ventilation system with air heating

New / retrofit

Both new and retrofit buildings are to be considered, however not as a separate building type classification, but by means of the respective combination of the selected building characteristics, namely the energy performance level of the envelope, the building transient behaviour due to building mass, the distribution system for heating (and cooling) and the ventilation system.

6.5.1 Internal and external heat gains

The amount of heat which contribute to the internal heat gains has to be defined for electrical appliances, lighting, occupants, and from cooking and washing. External loads are calculated by the building model of the BSim code used.

For the definition of the external heat gains, the amount of solar protection applied has to be defined. Solar protection may also be defined with due consideration to the daylighting requirements.

Excessive indoor air temperatures in summer may be reduced by increased natural ventilation.

6.5.2 Space heating and cooling loads

The basic link between building and the cogeneration system is given by the time dependant heating (cooling) load of the building. Therefore, buildings are basically to be considered and specified according to the energy demand level for space heating (and cooling), thus to the energetic performance of building envelope (average/low energy), and the size of the building (number of storeys, floor area).

Within IEA Annex 42, the influence of the building design on passive gains (solar, day-lighting, use internal gains) is not a topic of investigation. Therefore, the net heating (or cooling) demand is the decisive parameter, determined by the dynamic building model within the actual simulation. This allows to fully consider the interaction between building, HVAC and cogeneration system, heat distribution system and the time varying boundary conditions.

Especially for the cooling load, the transient thermal behaviour of the building due to building mass has to be considered.

6.6 Occupancy related loads

6.6.1 DHW demand profiles

Standard Annex 42 profiles

The DHW consumption profiles for use in the modelling undertaken in Annex 42 have been produced at 1 minute, 5 minute and 15 minute intervals. All the demand profiles are given for the whole building. Details for the profile data are given in the Annex 42 ST A report on Load Profiles [Knight et al. 2007].

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 – 77 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 user should alter the volume of DHW provided in the profiles by using the following correction:

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

This correction normally is done in each simulation time step.

The 5 minute and 15 minute profiles have been produced by simply aggregating the 1-minute profiles of the IEA SHC Task 26 model [IEA Task 26 2001] over the longer time intervals.

Other issues to be aware of in the supplied data are given in the A42 ST A Report.

Standard profiles shall be considered in each performance assessment study, in order to facilitate the comparison of results. The following three standard demand levels provided by ST A are applied in the studies (demand per building/dwelling):

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

For MFHs, directly the profiles for higher demands, produced using the IEA SHC Task 26 profile generator, are used (e.g. 800 litres per day as the moderate demand for a 4-family house). With the IEA SHC Task 26 profile generator, profiles for a period of one year can be generated by superposition of original profiles, which are generated for 1 min, 6 min and 1h intervals [IEA Task 26 2001], [Jordan & Vajen 2001].

The suggestion is therefore that the Annex 42 work uses the 200 litres/day modelled annual profiles for the European DHW profiles (corresponding to around 140 litres of water from the DHW storage tank) and the 300 litres/day modelled profile data for the Canadian DHW profiles (corresponding to around 210 litres of water from the DHW storage tank).

Individual profiles

In addition to the standard profiles, individual profiles may be considered.
Hot water supply for dish washing and laundry machine may be assumed

a) from central hot water tank
b) local electric heating

6.6.2 Electricity demand profiles

The Annex has provided two different sets of domestic electrical energy consumption profiles in regard to geographic allocation [Knight et al. 2007]:

- European domestic electrical energy consumption data profiles
- electricity demand profiles for Canada

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

- appliances (refrigerator, stand by loads of electronics)
- occupant related additional loads (lighting, household appliances, IT devices)

but not including figures for

- electric heating
- HVAC components (pumps, fan, control)

European domestic electrical energy consumption profiles

The three sets of actual annual load profiles from three homes, typical for low/medium/high electric energy consumption, as provided by the Annex 42 & Knight Kreutzer 2006, Knight et al. 2007], were used.

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

6.6.3 Coherence between DHW and electric loads

Coherence between occupancy related DHW and electric loads in regard to weekday and vacation absence must be established as much as possible.

6.7 External factors

6.7.1 Outdoor climate

As all studies performed in STC are based on national conditions, also the climate data are defined country specific.

6.7.2 External energy supply (delivered energy)

Fuel types

- natural gas
- renewable energy carriers (bio gas, wood)
- analysis of hydrogen fuel will be limited to studies of hydrogen-based renewable energy storage systems (i.e. the manufacture and distribution of hydrogen by a central utility will not be considered)

Electricity supply

- public grid with feedback possibility
- stand-alone system

Heat/cold supply from district network

- to be considered depending on the cases to be analysed

6.7.3 Generation mix for electricity and other delivered energy carriers

Annex participants do not use a standard reference generation mix when calculating primary energies and emissions. Instead, participants select mixes appropriate for their country/region, and justify their choices accordingly. Dynamic grid mixes and energy prices are modelled where appropriate.

In relation to the energy related assessment criteria (primary/fossil/renewable energy) and to emissions, the generation mix (fossil gas/oil etc., nuclear power, renewable hydro/wind/PV, etc.) and the respective primary energy and emission factors have to be considered.

The electricity mix defines the

- primary energy factor / fossil energy factor / non-renewable (or renewable) energy factor
- emission factors
- grid loss factors

The generation mix may considerably vary within the country. Average mixes are meaningless in such cases.

In [prEN 15203 /15 315, 2006] three types of primary energy factors for grid electricity are distinguished:

Average factor or coefficient: The average factor or coefficient reflects the annual average impact of all plants delivering energy (directly or indirectly) to the building. It is calculated by estimating the total impact (primary energy use, CO_2 production) during a year and divided by the total energy delivered.

Marginal factor or coefficient: If energy consumption is reduced (or increased), not all power stations are affected equally: the operation of "base load" stations is unchanged - the change in demand is met by reduced operation of other plants. The marginal factor or coefficient takes into account only production units that are affected by the change in energy demand. For example, the marginal new plant factor or coefficient relate to a new plant that should be built if the energy demand increases.

End use factor or coefficient: Different end-uses produce demands at different times - lighting, heating, air-conditioning, for example, each having very different demand patterns - and this might justify the use of specific demand-weighted factors for different end-uses.

Canadian approach

Canada analyzes the GHG emissions considering "on-margin" fuel mix to determine the displaced emissions. In general, this determination needs to be performed at each time-step as the on-margin fuel mix of the grid changes over the year and over the day. This same philosophy applies to the calculation of the primary energy demand. However, to calculate improvements in PE in this PA task, NRCan used standard cases to compare: a coal fired power plant and a NG fired CC.

European approach

Considering the liberalisation of the electricity market, and the respective transport and exchange of electricity between countries and industrial centres, an European mix according to UCTE is widely accepted and has been used in many European studies.

Reference generation mix for grid electricity

For grid electricity, the NRPE demand and respective CO_2 emission rates depend on the plant mix of electricity generation. Facing the wide range of possible electricity mixes, the CC power plant is proposed 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.

As an example, Table 2 gives energy ratios for a) European average (UCTE) (first column in the table), and b) an energy ratio for a state-of-the-art gas & steam combined cycle power plant (CC power plant) (middle column).

They include a factor for the distribution of primary energy to the electric power plant plus a factor assuming 11.5% distribution losses in the electric grid. For the CC power plant, an electrical efficiency of 58% (in relation to the LHV of NG fuel), a factor of 1.2 for primary energy to plant input according to the PE factor of natural gas and the electricity grid distribution loss of 11.5% of the delivered electricity were assumed.

An electricity grid distribution loss factor may also be applied for the home-generated electricity delivered into and re-supplied from the grid (see Fig. 3).

Table 2 Energy factors (primary to delivered energy ratios) and CO_2 emission factors (Source: [ecoinvent 2005])

	Electricity mix for low-voltage electricity supply		Natural gas supply
	UCTE/ECOINVENT	CC power plant	Typical for Switzerland
PE factor *pef* (based on LHV) [MJ primary/MJ delivered energy]			
Renewable energy	0.28	0.004	0.0021
Non-renewable energy	3.25	2.31	1.20
CO_2 factor [kg/MJ delivered energy]	0.142	0.120	0.0074
CO_2 factor, including combustion [kg/MJ end energy]			0.0624

Facing the wide range of possible electricity mixes, for the ST C performance assessment task, it is suggested to take a reference mix which is related to an electricity generation which

- is based on the same fuel as the cogeneration systems analyzed (thus mostly natural gas)
- is clearly identifiable by its technical processes
- represent an innovative but accepted and proven technology

Therefore, a mix according to a natural gas fired combined cycle (gas and steam turbine) power plant with the following characteristics is suggested:

▪ primary energy factor for natural gas	1.20	MJ primary per MJ delivered energy
▪ electric efficiency of plant	58 %	of plant input (LHV)
▪ electricity grid distribution losses	11.5%	of delivered energy
▪ total primary energy factor	2.31	MJ primary per MJ delivered electric energy (this factor results from the efficiency and losses given above)
▪ CO_2 emission factor	0.12 kg	CO_2/MJ delivered energy

For comparison and sensitivity analysis, the following other mixes may be considered:

- mainly GHG emission neutral generation (hydro, nuclear)
- mainly fossil based generation
- mainly generation based on renewable energy sources
- UCTE mix [UCTE]
- mix according to national or local grid
- Canada: evaluation based on displaced emissions determined by "on-margin" fuel mix [IFC Consulting 2003]

<u>Primary energy factor for natural gas</u>

Example primary energy factors and emission factors for natural gas are given in Table 2 above (last column).

6.8 Costs

The following cost elements may be considered in the economic analysis:

6.8.1 Energy costs

<u>Fuel price</u>

- fixed price

Electricity

- fixed prices, but with different values for
  - day time / night time , week day / weekend, etc.
  - costs for electricity supplied form grid to home and revenue price for electricity delivery back into the public grid.
- time variable prices, both for electricity purchased from the grid and sold to the grid (dynamic pricing):
  Dynamic pricing may influence the system design : i.e. the pricing strategy influences the performances of the system and the sizes of the equipments, therefore dynamic pricing has to be considered in a holistic way.

6.8.2 System component costs

In the economic assessments within ST C not much emphasis can be put on system costs since the Annex is dealing with technologies and systems that are mostly still under development. However, some treatment of the economics is critical, especially in relation to energy costs. However, also energy cost structures become increasingly complex, and the supply industry is in an unprecedented state of flux.

6.9 Input Parameters

The parameters are distinguished in

a) decision parameters, for which a range of values is investigated, and
b) state parameters, which are fixed for the analysis of the case.

Basically, five topical types of parameters can be distinguished:

a) cogeneration system parameters (cogeneration device, auxiliaries, storage, control)
b) building parameters (type, size, heat distribution and ventilation system)
c) occupancy related parameters (DHW and electric loads)
d) external factors (climate, energy generation mix, energy supply situation, energy prices)
e) economic parameter

7 REPORTING

7.1 Description of cases, configurations and input parameter

7.1.1 System description and parameters

It is suggested to make a graphical outline of the system set up (Fig.11) and describe the individual components in a clearly structured way.

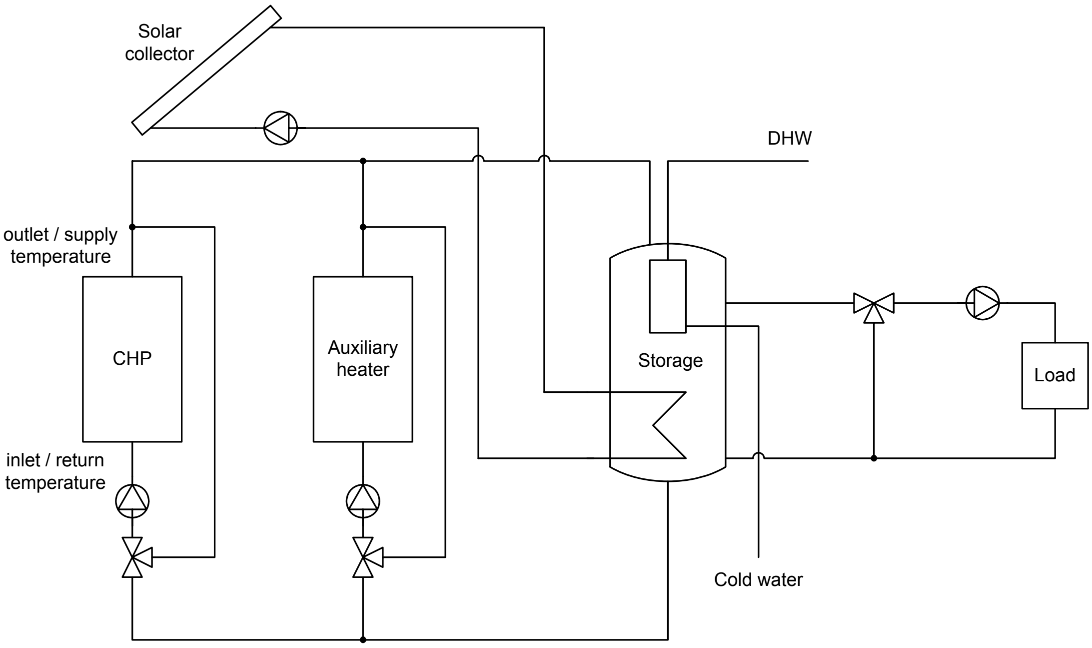


Fig. 11 Example schematic of a system

The input data needed for the system description depend of course heavily on the type of models and the type of BSim tool used.

In the following an outline for the description of the individual system components is given:

Cogeneration device

Depending on the type of cogeneration device the following data are to be given where applicable and as far as available:

- type of the cogeneration device
- fuel type and composition
- nominal ratings of thermal and electric outputs
- modulation range
- performance characteristics as electrical and thermal or total efficiencies (in relation to the LHV of the fuel) in function of the modulation ratio (ratio of actual to nominal fuel input). For the given thermal or total efficiency characteristics also supply or return flow temperatures and the mass flow should be specified (ICE and SE) (examples see Fig. 12 and Fig. 13)
- maximum rate of power output change
- thermal time constant or thermal mass
- restrictions for the number of start/stop cycles

- start/stop cycle time
- losses from cooling after shutdown
- fuel/electricity demand for start-up
- degradation parameters

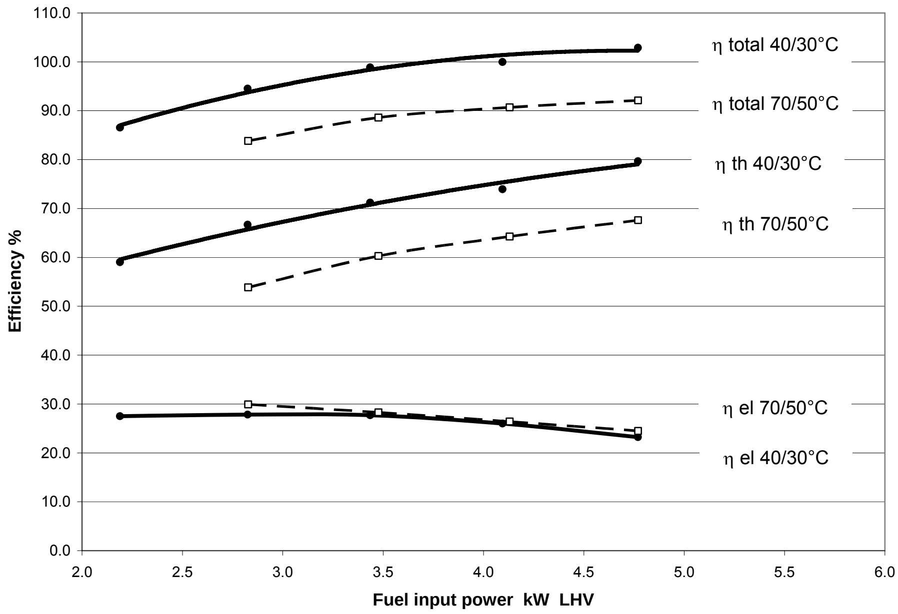


Fig. 12 Example for electric, thermal and total efficiency performance characteristics of a fictitious FC unit in relation to the power input of the fuel (lower heating value), for two different sets outlet/inlet flow temperatures

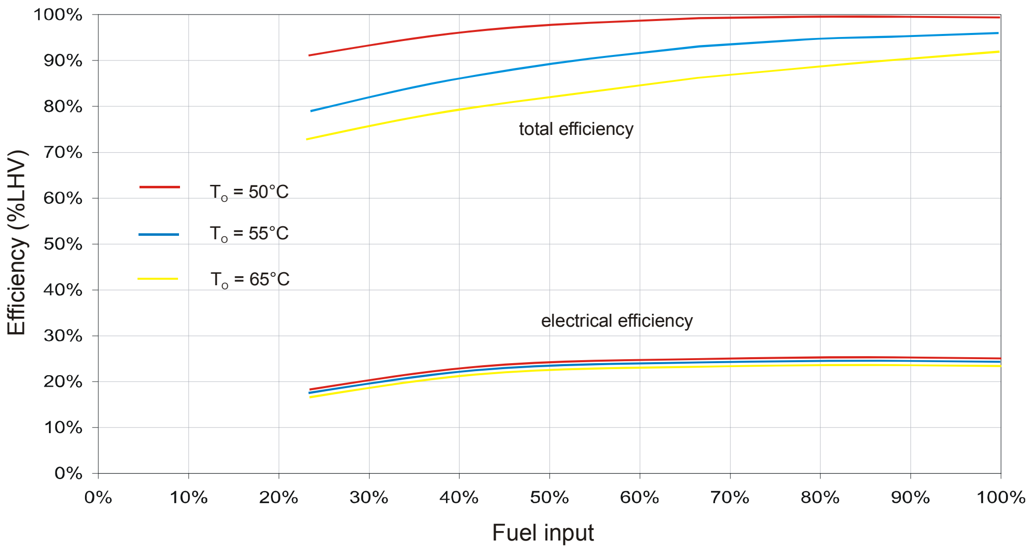


Fig. 13 Example characteristics of a Stirling engine cogeneration unit [SOLO, 2003]
(T_o = CHP water outlet temperature)

Auxiliary heater (condensing gas burner/boiler)

- type of the auxiliary heater
- fuel type
- nominal rating of thermal output
- modulation range
- performance characteristics as thermal efficiencies (in relation to the LHV of NG fuel) in function of the modulation ratio (ratio of actual to nominal fuel input) and return flow temperature Fig. 14
- cool-down losses

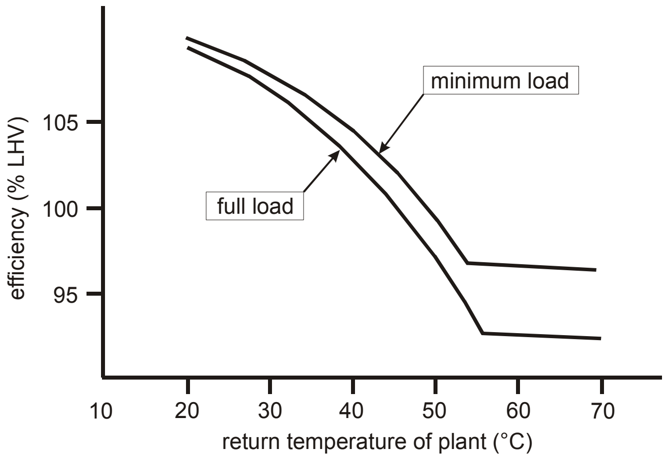


Fig. 14 Example efficiency curve of a condensing gas boiler

Hot water storage tank

The following information about the storage tank has to be specified:

- storage type
    - mixed / stratified
    - only for DHW / combined storage for space heating and DHW
    - long-term storage (phase change materials, chemical storage, seasonal ground storage)
- geometry
- insulation (thickness, thermal conductivity)
- power and position of electric resistance auxiliary heating elements
- control strategy for the auxiliary heating elements

Cooling system

- type of cooling system
    - Thermally driven absorption or adsorption chiller
      (rated conditions: typically 30°C inlet cooling water temperature and 7°C chilled water setpoint according to [ANSI/ARI Standard 560])
        - rated cooling capacity (W)
        - rated COP
        - (characteristic of capacity and COP in function of fraction of load, chilled water set point temperature, entering cooling water temperature and inlet hot water temperature)
    - Desiccant cooling:
      description of the system, cooling capacity and COP for the envisaged operating range

Solar collector

- collector type
- collector area
- efficiency coefficients a_0, a_1, a_2
  $\eta = a_0 + a_1 \cdot \Delta T/G_k + a_2 \cdot \Delta T^2/G_k$
  - ΔT: difference between mean collector and ambient temperature
  - G_k : irradiation
- angle factors longitudinal and transversal at 50°
- orientation and tilt

PV

- cell type
- module area (m^2)
- electrical characteristics per module under standard test condition (STC)
  - P_{mp} maximum power (W)
  - V_{mp} operating voltage (at maximum power point) (V)
  - I_{mp} operating current (at maximum power point) (A)
  - V_{oc} open-circuit voltage (V)
  - I_{sc} short-circuit current (A)
  - current temperature coefficient (A/K)
  - voltage temperature coefficient (V/K)
  - power temperature coefficient (W/K)
- number of modules in series and parallel
- orientation and tilt

Heat pump

- heat pump type
- heat source
- heating power (W) and COP at conditions according to [EN 14511], [ISO 13256] or other appropriate standard
- COP

Electric storage

- battery type
- capacity (J)
- charge efficiency (-)
- discharge efficiency (-)
- maximum rate of charging (W)
- maximum rate of discharging (W)

Power conditioning unit

- efficiency characteristic

Control strategy and methods

Descriptions of the performance assessment cases and configurations do also include a concise description of the control strategy used. Schematics of the control principle and algorithm are recommended, see [Kelly 2006].

Here the description of a PI control system is given as an example:

A target value for the storage loading, established on the basis of the heating curve of the building and the 24 h averaged outside air temperature, is used by a PI controller with anti-wind-up functions to define the actual modulation rate for the fuel cell or the gas boiler system. An additional P-controller is used to ensure the DHW temperature in the top storage segment.

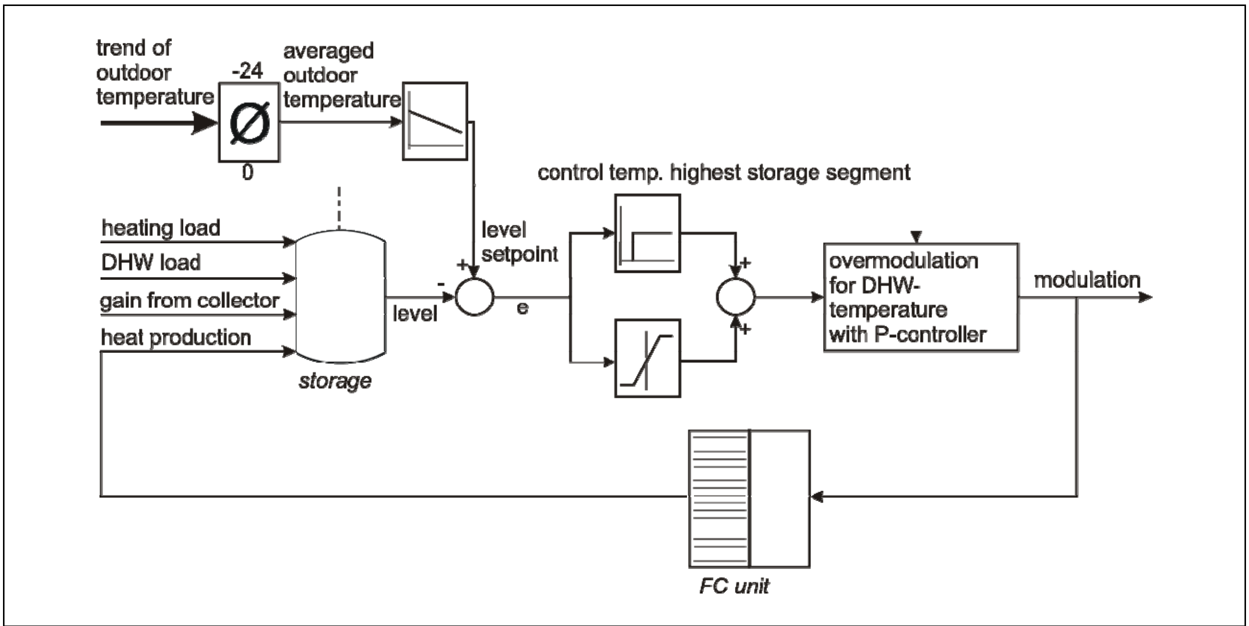


Fig. 15 Example schematic of PI-control

7.1.2 Building related factors

The building type has to be described in terms of size, use (MFH, SFH), energy level and construction type. Also the distribution system for space heating and cooling and the ventilation system has to be described (see § 6.5).

The following parameters have to be specified for each building:

- energy reference area (m^2) (see § 4.2.2)
- space heat demand ($MJ/m^2/a$)
- DHW heat demand ($MJ/m^2/a$)
- electricity demand ($MJ/m^2/a$)
- cooling load ($MJ/m^2/a$)
- total heat gains per useable floor area ($MJ/m^2/a$)
- U-value exterior walls ($W/m^2/K$)
- U-value roof ($W/m^2/K$)
- U-value glazing ($W/m^2/K$)
- overall averaged U-value ($W/m^2/K$)
- g-value glazing (-)
- description of solar protection (i.e. fixed overhang shadings, controlled blinds for no direct solar radiation)

- H heat loss coefficient according to ISO 13790 (W/K)
- C heat capacity according to ISO 13790 (J/K)

Building geometry and orientation can be shown with a simple graphic as shown as an example in Fig. 16.

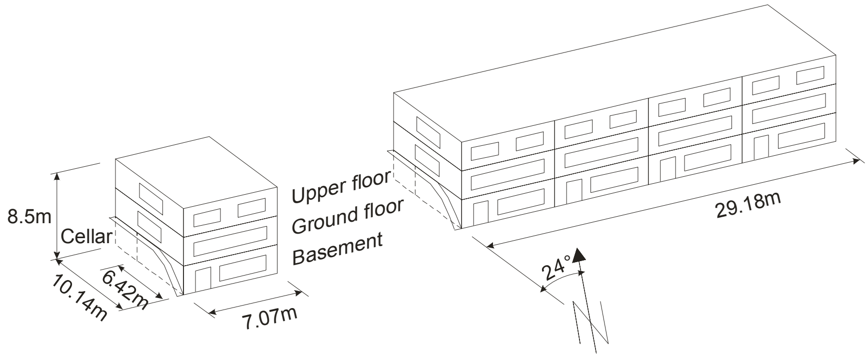


Fig. 16 Geometry and orientation of SFH building (left) and MFH building (right)

7.2 Results data presentation

This paragraph contains only some general suggestions and gives some examples for the presentation of results. As this report acts as a reference for the individual performance assessment studies, the examples shown were taken from earlier studies (not from the STC performance assessment studies). Most examples are adapted from [Dorer et al. 2005].

7.2.1 Comparison of cases

In order to draw conclusions, results in terms of a given performance assessment criteria P for a selected case or configuration are presented in relation to a given reference case. Results are given as table values and graphics, as well as in form of a relative performance *p* (see also § 4.2.7 System comparison approach).

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

If combination of systems are studied, relative comparisons of the different systems might also be of interest.

Example set of cases:

-	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)

besides p_I and p_{II}, the incremental changes from the System I or II (SOFC or GB&SC) to system III (SOFC&SC) are of interest. Thus, p_{III-I} and p_{III-II} have to be presented:

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

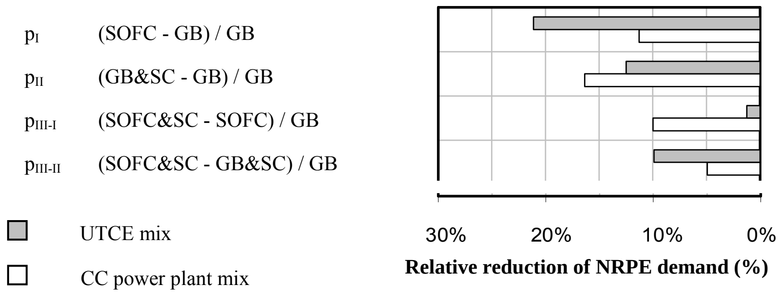


Fig. 17 For a MFH of "Passive House" type, comparison of different systems without and with solar collectors ("& SC") in terms of NRPE demand, expressed as percentage of NRPE demand reduction in relation to standard gas boiler system without solar collector (GB), for two electricity generation mix.

Example: "(SOFC&SC- SOFC)/GB" is NRPE demand reduction for SOFC system with solar collector (SOFC&SC) compared to SOFC system without solar collector (SOFC), in relation to demand of gas boiler system (GB).

7.2.2 System parameter

The evolution in time of system parameters like temperatures, mass flows, fuel consumption etc. is presented using the data from the individual time step (normally 1 h). Data may be presented for one day, one week, or a number of weeks.

Example:

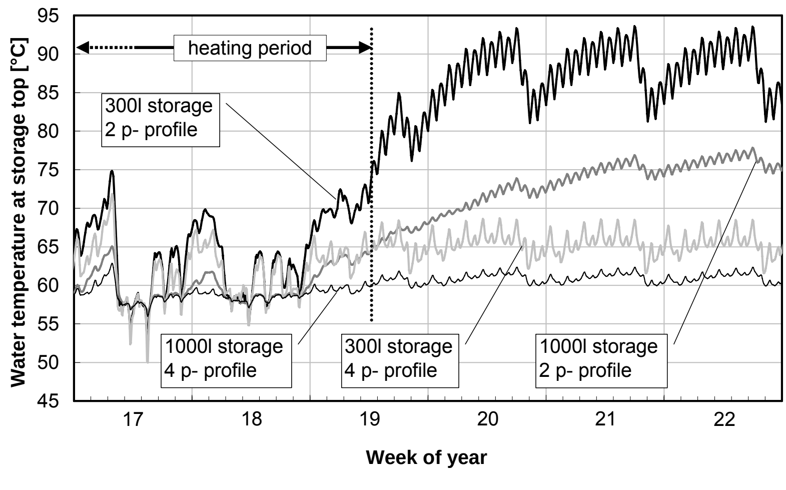


Fig. 18 Typical sequence of water temperature at top of hot water storage for a few weeks in the summer period, considering two demand profiles and two storage sizes. SFH building type with SOFC system.

7.2.3 Energies

PA results in terms of energy show specific energy demands in terms of delivered or primary energy demand. If possible, the individual forms of delivered energy are distinguished (fuel, grid electricity, district network heat), see Fig 19.

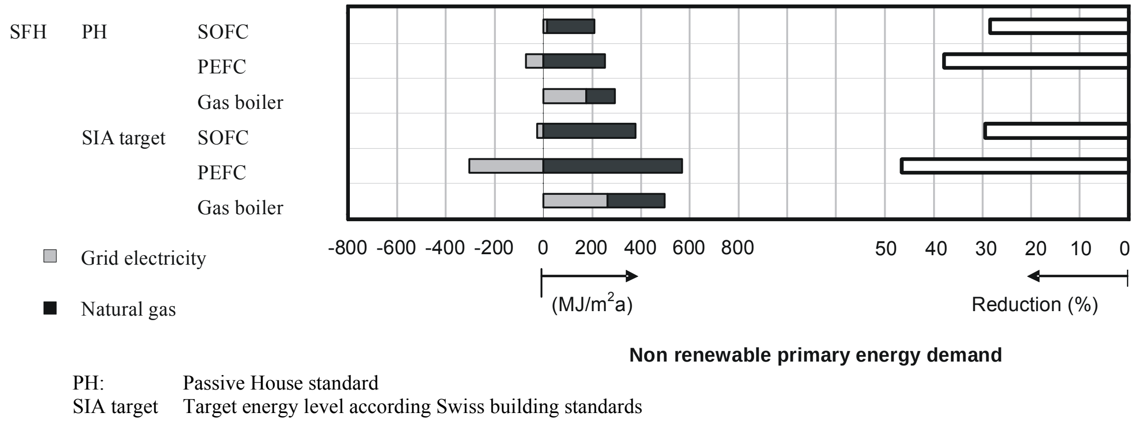


Fig 19 Example for data presentation of simulation results:
Annual non-renewable primary energy demand (MJ per energy reference floor area) for two types of SFH, equipped with SOFC, PEMFC and gas boiler (left). Negative values account for the grid electricity which is substituted by the net amount of electricity supplied by the cogeneration device back to the grid. Reduction of demand compared to the gas boiler system (right).

7.2.4 Simplified approach

Fig. 20 gives an example results for the simplified approach, see § 4.6

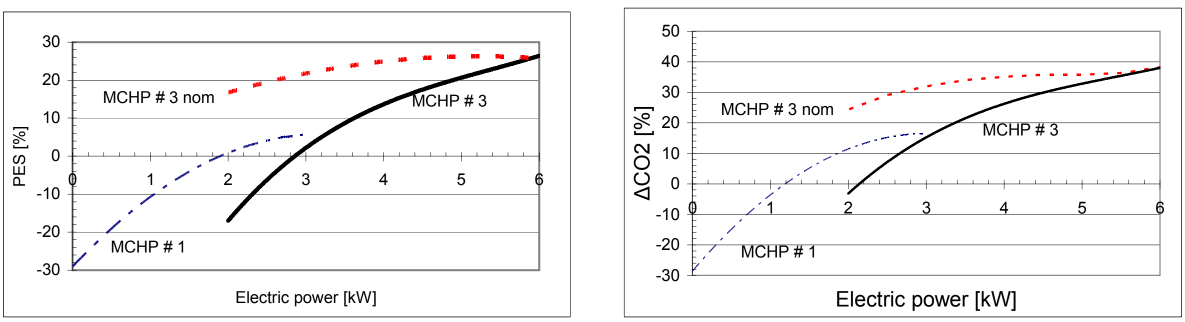


Fig. 20 PES (left) and ΔCO_2 trend (right) vs. the supplied electric power

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For a more comprehensive literature list on cogeneration performance assessment see the Annex 42 ST C report [Dorer 2007].

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9 APPENDIX

Example: Allocation of PE consumption to generated electricity and to generated heat

Method (a) Heat and electricity generation (no allocation)

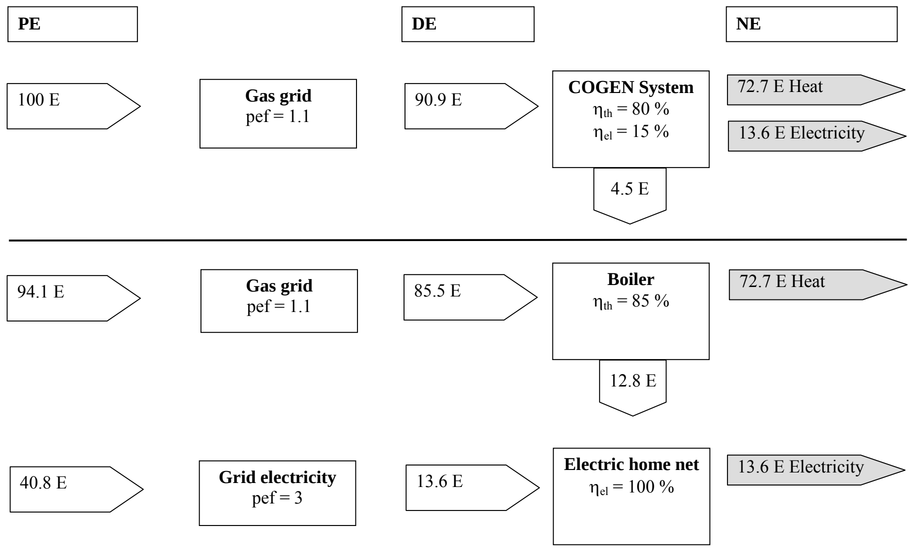

Fig. 21 : Comparison of primary energy efficiency of cogen system compared to uncoupled system.

Method (b.2) Heating (bonus for electricity)

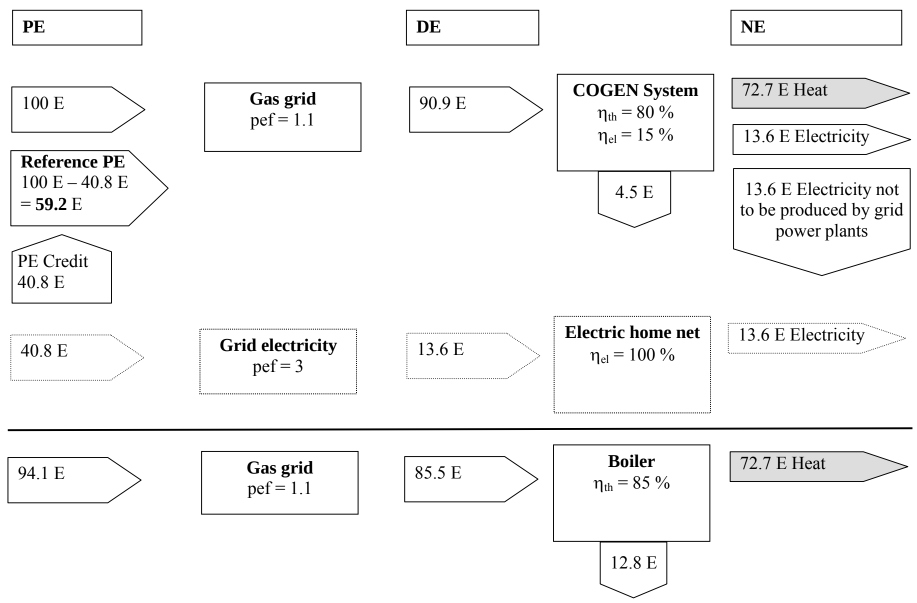

Fig. 22 : Comparison of primary energy efficiency of cogen system compared to boiler, assessing heating only

Table 3 Computation of relative PE savings ($Ind_{PE,Heat}$ as defined on page 22)

Method	**System**	**PE Consumption**	**Percentage**
Method (a), §4.2.5	Boiler and Grid Cogen system	94.1 + 40.8 = 134.9 100.0	100 % 74 %
	Reduction	35.2	26 %
Method (b) Heat, §4.2.5	Boiler	94.1	100 %
	Cogen system	100 – 40.8 = 59.2	63 %
	Reduction	34.9	37 %
Method (b), §4.2.5 Alternative represen-tation	Boiler	94.1	100 %
	Grid	40.8	43 %
	Boiler and Grid Cogen system	94.1 + 40.8 = 134.9 100.0	143 % 106 %
	$Ind_{PE,Heat}$	= (134.9-100)/94.1	37 %