Performance Assessment of Residential Cogeneration Systems in Southern Italy

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

Annex 42 of the
International Energy Agency
Energy Conservation in Buildings and Community Systems Programme
First published: October 2007

AUTHORED BY:
Maurizio Sasso and Carlo Roselli (Università degli Studi del Sannio, Italy)
Sergio Sibilio and Raffaello Possidente (Seconda Università di Napoli, Italy)

ANNEX 42 OPERATING AGENT:
Ian Beausoleil-Morrison (Natural Resources Canada)

ANNEX 42 SUBTASK C LEADER:
Viktor Dorer (EMPA, Swiss Federal Laboratories for Materials Testing and Research)

CITATION

Maurizio Sasso and Carlo Roselli (Università degli Studi del Sannio, Italy), Sergio Sibilio and Raffaello Possidente (Seconda Università di Napoli, Italy). Performance Assessment of Residential Cogeneration Systems in Southern Italy. A Report of Subtask C of FC+COGEN-SIM The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems. Annex 42 of the International Energy Agency Energy Conservation in Buildings and Community Systems Programme. (52 pages).

Copies of this report may be obtained from the Annex 42 web site at: www.cogen-sim.net or from the IEA/ECBCS Bookshop at: www.ecbcs.org.

Participating countries in ECBCS:

Australia, Belgium, CEC, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Israel, Italy, Japan, the Netherlands, New Zealand, Norway, Poland, Portugal, Sweden, Switzerland, Turkey, United Kingdom and the United States of America.

ISBN No. 978-0-662-48049-5

Catalogue No.: M154-14/10-2008E-PDF

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)

Acknowledgements

This report of Subtask C of Annex 42 was reviewed by:

Viktor Dorer (Empa, Swiss Federal Laboratories for Materials Testing and Research)
Alex Ferguson (Natural Resources Canada)

Marco Citterio (ENEA, National Agency for New Technology, Energy and the Environment)
Morad Atif (National Research Council)

The assistance of the other participants of Annex 42 in producing this report is also gratefully acknowledged.

Viktor Dorer
Subtask C Leader

CONTENT

1 INTRODUCTION

During the last decade, small-scale combined heat and power systems have become a viable alternative to conventional power supply and boiler-based heating system in many types of applications. In the domestic sector the use of combined generation on micro scale is currently relatively uncommon, but the market availability of gas-fuelled generating equipment, together with a significant number of current R&D projects, confirms the large potential for micro-CHP, which was until now limited to niche applications. Cogeneration technology is also available for small-scale applications: about thirty years ago FIAT group built TOTEM, a gas fuelled cogenerator (15 kW_{el}, 34 kW_{th}) based on a 903 cm^3 internal combustion engine; since 1981 a district heating system based on 31 TOTEMs has operated in Vicenza in the North of Italy.

Since 1995, an Italian research group has been active in R&D projects on Micro Cogeneration and MCHP (Micro Combined Heat and Power) applications in residential and light commercial fields. The activity is the result of a cooperation among the Università di Napoli Federico II, the Seconda Università di Napoli (UNapoli2), the Università del Sannio (USannio), the Napoletanagas Clienti Spa (Natural gas distributor), the Bruno srl (Standby unit industry) and is also strongly supported by an European supplier of MCHPs and of Gas engine driven Heat Pumps (Tecnocasa) and by a grant from Regione Campania (Legge 41/1994).

The aim of this research is to analyze the energetic, economic and environmental implications related to the use of micro-CHP ($\leq$ 15 kW_{el}) to supply heat and power to small scale end-users. Attention is paid to the problems derived by the transfer of this technology to small-scale applications (such as matching the unit's output to the load profiles of end-users).

To test small cogenerators in actual operating conditions, a test facility has been built with some residential appliances, such as a dishwasher, washing machine, and water heaters that are used both in their traditional configuration (electric driven) and in more efficient configurations (thermal and electric power driven) with electric resistances and internal coil heat exchanger for thermal recovery of the MCHP hot water. The simulation system is designed to satisfy a variable electrical load, 0÷10 kW, and a thermal load, 0÷30 kW, Fig. 1.

Fig. 1. Internal view of test facility.

Detailed investigations were performed on reciprocating internal combustion engine micro-cogenerators (1.67, 3 and 6 kW_{el}), one of which is available on the Japanese and European markets.

Furthermore, a Micro Combined Cooling Heating and Power system (MCCHP) consisting of a MCHP driving an Electric air-to-water vapor compression Heat Pump (EHP) has been tested. The heat pump can be considered thermally activated (by MCHP). In this configuration the system acts as polygeneration system to satisfy electric and thermal (heating and cooling) energy requirements (4 kW_{el}, 12.5 kW_{th} in heating and 6 kW_{th} in cooling).

The typical 3-E (Energetic, Economic and Environmental) approach has been performed to compare the proposed energy systems, MCHPs and MCCHP, to the traditional one based on separate "production", that will be presented in the next chapters, in order to evaluate the potential primary energy saving and the environmental benefits of small-scale on-site energy conversion devices.

In order to optimize the match between a micro-CHP and the thermal and electric users, an analysis of residential appliances has been performed. Attention focused on domestic Electric Storage Water Heaters (ESWH), Washing Machines (WM), and Dish Washers (DW), because they contribute significantly to residential energy consumption and because they may use either electricity and heat to satisfy their energy requirements. Finally, to evaluate the energetic, environmental and economic feasibility of domestic cogeneration in Italy, an analysis of energy demand profiles of a 120 m^2 house has been performed and a simulation, based on a spreadsheet, of a micro-CHP system has been developed. In order to identify the right application for cogeneration in the domestic sector, the 3-E analysis has been performed varying some parameters, such as number of dwellings, operating mode and reference systems. As the intention was to evaluate only the most important parameters affecting cogeneration in residential sector, a simplified spreadsheet based tool, which did not include the detailed models developed in Annex 42, has been developed.

2 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.

2.1 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 cogen 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 as a measure for the assessment 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.

2.2 Abbreviations and indices

Energy terms, symbols and indices see § 2.3

Abbr./index	Description
AS	Alternative system
BAT	Best available technology
Bsim	Building Simulation (with the building and system simulation tools used within A42)
Build	Building
CC	Combined cycle (gas and steam power plant)
CGU	Cogeneration device (cogen unit)
CHP	Combined heat and power (= cogeneration)
CCHP	Combined cooling heat and power (= tri- or polygeneration)
DHW	Domestic hot water
DW	Dish Washer
El	Electric, electricity
El-Grid	Electricity supplied from the grid
El-NetGrid	Net amount of electricity exported to grid or delivered from grid
ERFA	Energy reference floor area
ESWH	Electric Storage Water Heater
Fuel	Delivered fuel
GB	Gas boiler, gas boiler system
GHG	Green house gases
GWP	Global warming potential
ICE	Internal combustion engine
LHV	Lower heating value
MCHP	Micro-combined heat and power
MFH	Multi-family house
NG	Natural gas
NPV	Net present value
NRE	Non-renewable energy
NRPE	Non-renewable primary energy
OC	Operating cost
PA	Performance assessment
PES	Primary energy savings
RE	Renewable energy
SPB	Simple pay-back period
SFH	Single-family house
SH	Space heating
SC	Space cooling
Th	Thermal
TS	Traditional system
ΔCO_2	Equivalent CO_2 emissions avoided
ΔOC	Operating cost difference between traditional and alternative system

2.3 Energy terms

All energies are based on LHV. See also § 3.2, for further description of energy terms.

No See Fig. 2	**Term**	**Description**
1	Energy demand	Energy needed to fulfill 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. cogen system) may contribute as internal gains.
3	Net energy	Part of the energy demand which is provided by the HVAC system (including RE 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 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 PE

8	Primary energy equivalence for locally generated renewable energy	Represents savings in non-renewable PE and in GHG emissions due to the on-site generated renewable energy (electric or thermal energy provided on site by PV, solar collectors, wood stoves, etc.). The same conversion from PE to DE as for (7) to (4) must be considered. Electric/thermal energy provided by power plants fuelled by renewable sources (solar, geothermal, hydro, wind, photovoltaic, biomass fuelled station etc.) is accounted for as renewable PE in (7) and reflected in the respective primary energy factors or emission factors
9	Primary energy (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 § 3.2.1 and also Fig. 4.

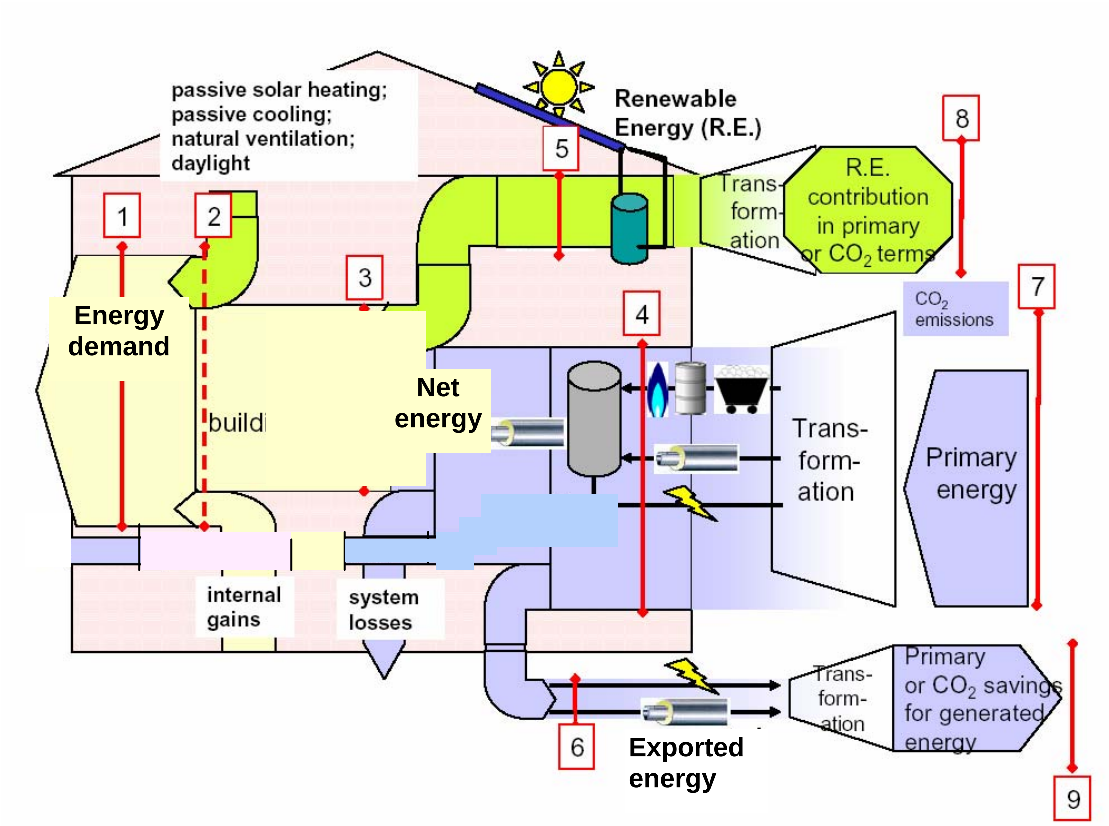

Fig. 2 Energy conversion processes and energy terms, as exemplified by residential building supply (Source: CEN/BT WG 173 EPBD N 27 rev)

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

Symbols for energy parameters and related factors

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

Parameters starting with a capital letter refer to amounts of energy, parameters starting in lower case represent energy amounts per reference area.

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 §3.2.

Energy values are based on LHV. Electricity input and output as used (normally AC, as electricity from and to grid).
See also § 2.3 for further description of energy terms.

Symbols	Description	Unit
BE	Non-HVAC energy, often related to the building design (Energy type No 2 in Fig. 2)	kWh
DE	Delivered energy (No 4)	kWh
NE	Net energy (No 3)	kWh
OE	Energy output of cogen unit or reference energy system	kWh
PE	Primary energy (No 7)	kWh
RE	Renewable energy generated on the building premises (No 5)	kWh
XE	Exported energy (No 6)	kWh
pef	Primary energy factor (ratio of primary energy to delivered energy)	-
ηrpef	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 exported to grid or delivered from grid
El-CGU	Electric energy output of cogen unit
Fuel	Fuel
H	Heat
NRE	Non-renewable
NRPE	Non-renewable primary energy
NG	Natural gas from grid
PE	Primary energy
SH	Space heating
SC	Space cooling
Th	Thermal
Th-CGU	Thermal energy output of cogen unit

Examples (parameters starting with a capital letter refer to amounts of energy, parame-

	ters starting in lower case represent energy amounts per reference area)	
pE_{NRE}	Non-renewable primary energy usage per energy reference floor area of building	kWh/ m^2
$PE_{El\text{-}Grid}$	Primary energy usage for electricity from grid	kWh
NE_{El}	Net electricity demand	kWh
$XE_{El\text{-}NetGrid}$	Net amount of electricity exported to the grid (total exported minus re-delivered)	kWh
OE_{Th}	Thermal energy output of cogen unit	kWh
$nrpef_{NG}$	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	-

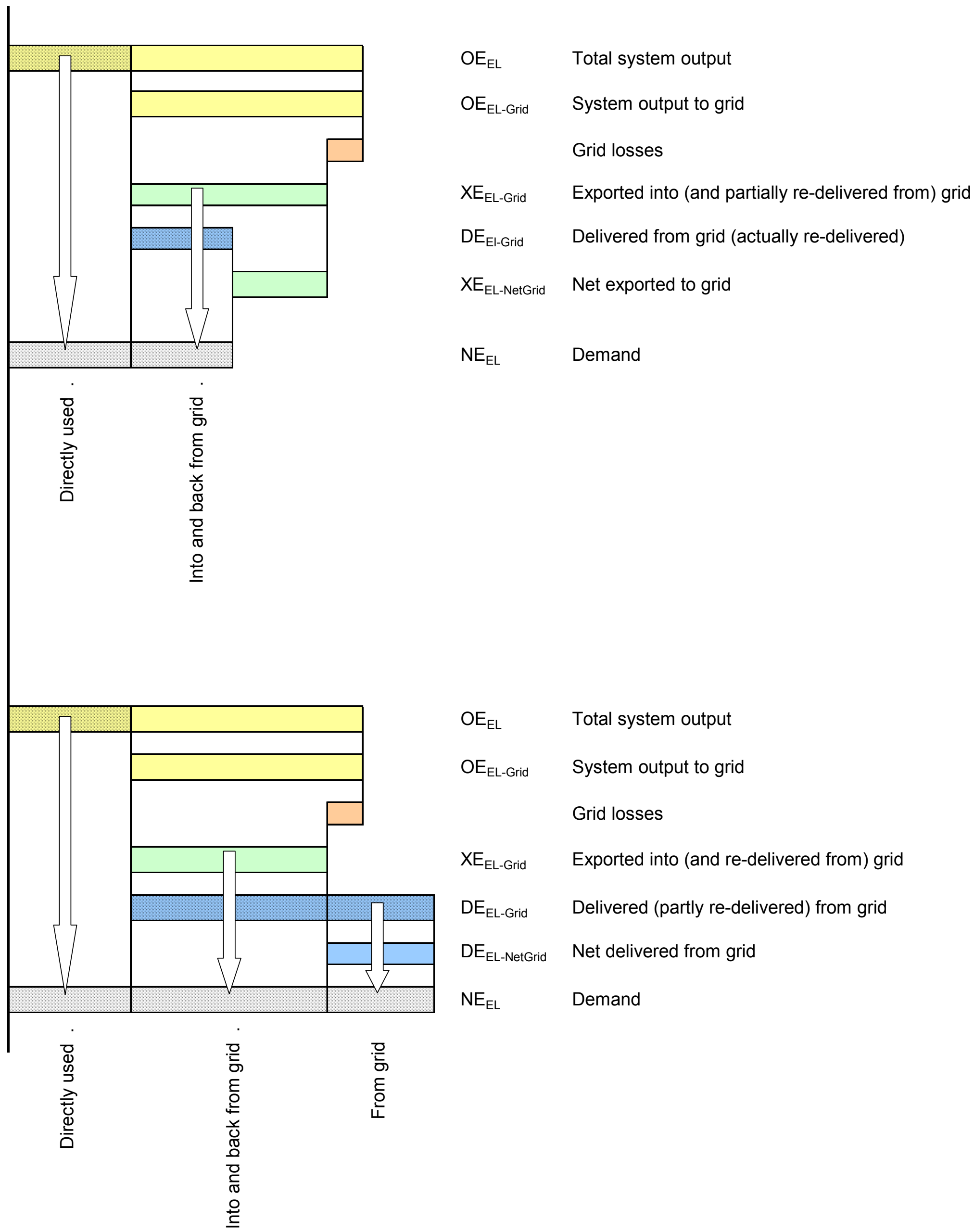

Fig. 3. Energy terms for electricity.

3 Performance assessment procedure

3.1 Performance assessment

3.1.1 Types of performance assessments

The following analysis (3-E analysis) has been carried out, using a spreadsheet, within this ST C study for an annual simulation:

- Energy analysis;
- Environmental analysis;
- Economic analysis.

3.1.2 Performance assessment procedure

The following steps were made in the energy analysis procedure:
1) The building's energy demands, and system's capacity to satisfy the end-user were analyzed, starting from data available for Italian domestic user considering hourly time-step;
2) The dwelling's primary energy consumption was derived, based on the calculated values for the net energies;
3) Starting from these values, energetic analysis was undertaken to compare alternative and traditional system performance;
4) Environmental impact was estimated by calculating equivalent CO_2 emissions, based on the energy demand values;
5) Economic analysis was undertaken using prices of delivered energy flows.

In the following chapters, details to these individual steps are given.

3.2 Energy analysis

3.2.1 Energies considered

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

- Net energy demand (energy demanded from the HVAC and the cogeneration to cover the demands for space heating and cooling, for domestic hot water, and for electricity).
- Primary energy: non-renewable primary energy (NRPE);

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

Net vs. primary energies are used for system efficiency assessments.

3.2.2 Reference and units for energy values

In this ST C analysis, net and primary energies are also related to the energy reference floor area (ERFA) of the building. The energy values are thus expressed in kWh and kWh/a for annual period.

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

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

The following types of boundaries or control volumes and types of balance analysis could be applied (see Fig. 4):
a) analysis of the cogen device in terms of power oriented assessments;

b) analysis of building energy supply system (cogen device and other HVAC components) in terms of net power;
c) analysis of the building in terms of primary 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 energy, for the whole simulation period (normally one year).

This study focuses mainly on analysis type (c) (net and related primary energy demand), however, analysis type (b) may be applied for choosing the best size of components.

For analysis type (c), the control volume 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 energy and energy conversion from primary to net energy are considered by factors in the study results. In particular, in this case study renewable energy supply is not considered.

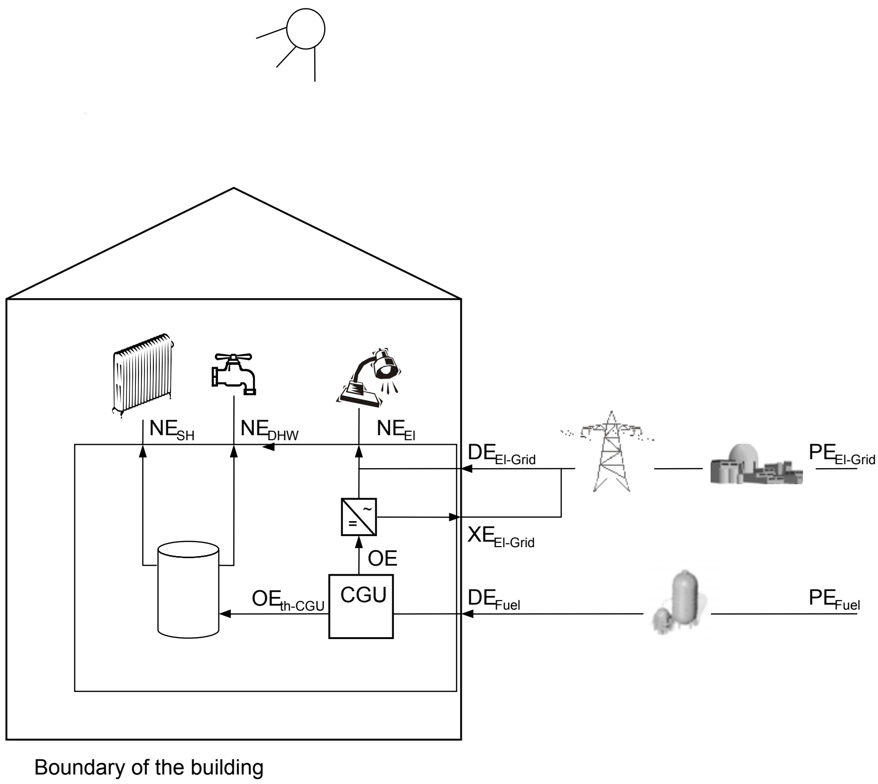

Fig. 4 Control volumes and related energies

3.2.4 Amendments to energy definitions

Distribution losses
Distribution losses for space heating are not considered. For domestic hot water, it is assumed that the heat demand equals the net energy for hot water (no distribution losses assumed).

Parasitic losses of system
A part of the parasitic losses of the cogen system (radiative and convective skin losses incl. venting of heat from individual cogen system components for cooling purposes) may contribute to the internal heat gains of the building and thus reduce heating load or increase cooling load. In

such cases, this is considered in the simulation. However, the useful amount of the parasitic heat loss is not to be considered neither as an increase of the thermal output of the cogen device (OEth-FCU, CGU) nor as an increase of the thermal efficiency of the system.

Electricity demand

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

4 PERFORMANCE CRITERIA

4.1 Energy performance criteria

4.1.1 NRPE demand

Performance criterion for the primary energy demand is the non-renewable primary energy demand used during the considered period by:
a) the cogen system;
b) the other devices able to satisfy energy demand;
c) the production chain for grid electricity (depending on the electricity generation mix; emission factors are described in § 5.3.3).

4.1.2 Energy performance factors

<u>General</u>

In order to evaluate how efficiently delivered or primary energy is utilized by the system to cover the annual electricity and net heat demand in the building, dimensionless energy performance factors ηDE and ηPE are defined, as a ratio of net energy output to consumed delivered energies (ηDE) or to the primary energies respectively (ηPE).

Electric and heat energy values are added in this approach.

<u>Energy performance factors</u>

The energy performance factor for primary energy respectively is defined as:

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

Using annual net energy consumption *NE*, primary energy *PE*, in conjunction with indices for electricity (*El*), space heating (*SH*), space cooling, *(SC)*, domestic hot water (*DHW*), net excess of electricity produced locally and delivered back into the grid (*El-NetGrid*), grid electricity (*El-Grid*) , the fuel (*Fuel*) and district heat (*HD*) (see also § 2.3 and especially Fig. 3). In the particular system considered in this case study, no electricity is exported to the grid and there is no district heating network. So the energy performance factor can be modified as:

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

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:

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

4.2 Emissions analysis

The emissions performance criterion is the amount of CO_2 equivalent gases emitted during the considered period by:
a) the cogen system;

b) the other devices able to satisfy energy demand;
c) the production chain for grid electricity (depending on the electricity generation mix; emission factors are described in § 5.3.3).

CO2 equivalents are used to compare the emissions of 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 / CO_2 (100 years)
Carbon dioxide	CO_2	1
Methane	CH_4	23
Nitrous dioxide (protoxyde)	N_2O	298
Perfluorocarbons	C_nF_{2n+2}	6 500 to 8 700
Hydrofluorocarbons	$C_nH_mF_p$	140 to 11 700
Sulfur hexafluoride	SF_6	23 900

4.3 A simplified approach

According to a typical 3-E (Energetic, Economic and Environmental) simplified approach, the performances of the alternative system (AS = cogen 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 cogen devices with hot water storage tank, or combined cooling, heating and power to satisfy also cooling demand.

In section 5.4.3 of this report the primary energy performance factor will be 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:

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

The environmental impact is really important when choosing a technology, and the simplified approach quantifies this impact by evaluating the emissions of equivalent CO_2 from the compared energy systems. A suitable parameter for comparison is the avoided greenhouse gas emissions:

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

Fig. 5 shows the energy flows of the two compared systems.

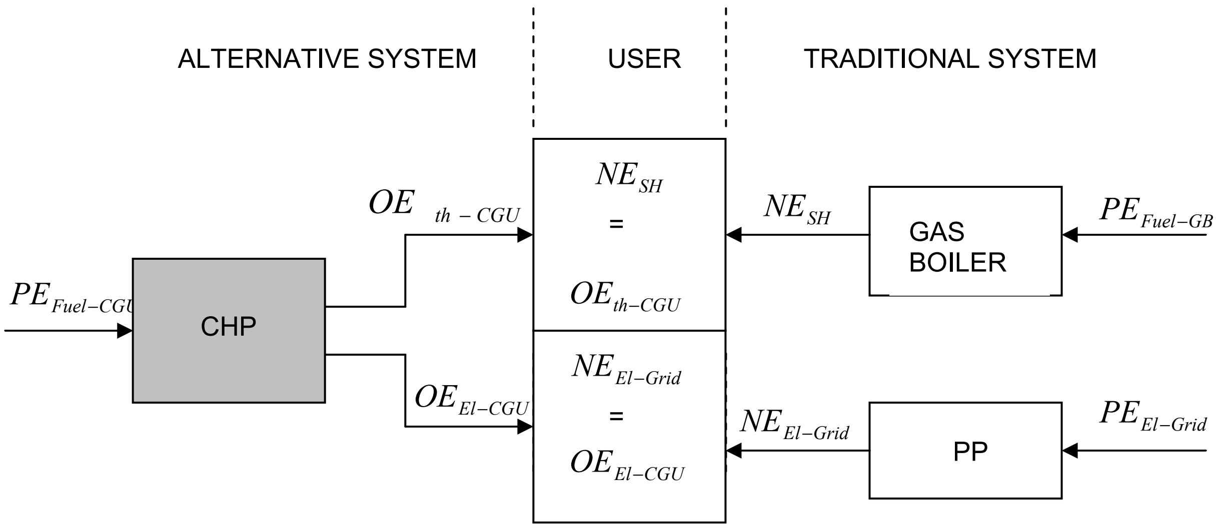

Fig. 5 Energy flows of the two compared systems

4.4 Economic criteria

4.4.1 Economic analysis

Economic analysis focuses on the comparison of total cost for the different systems, and on the influence of electricity and fuel prices on the optimization of the system in terms of size, control and operation.

4.4.2 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. While numerous criteria are available, the ones most often used to determine whether to reject or to accept a project are the net present value (NPV), internal rate of return (IRR) and payback period (PP).

To complete the analysis of small scale cogeneration in domestic sector, it is necessary to evaluate the economic performance indices. In fact, cogeneration technology must demonstrate a short pay-back period if it is to be broadly adopted. However, the number of the variables, that we have to take into account, does not permit to obtain homogeneous results depending, above all, by the different conditions in the various countries. Therefore there are a great number of subjects involved in the definition of the economic variables including the institutional sectors and the private sectors (gas utilities, manufacturers, …). For example, government grants, along with attractive rates for electricity export may significantly encourage MCHP market penetration.

However, in the following, in order to give general indications, the Simple Pay Back (SPB) and Net Present Value (NPV) of MCHP will be evaluated.

The first economic index considered, SPB, is defined as:

$$SPB = \frac{IC}{\Delta OC} = \frac{IC}{OC_{TS} - OC_{AS}}$$

where IC (Investment Cost) represents the increase, in comparison with traditional system based on separate energy production, of the investment cost connected to the introduction of microcogeneration unit in the alternative system; while OC (Operating Cost) represents the yearly operating cost connected to AS and TS considering only fuel (natural gas) and electricity.

Using Net Present Value (NPV) index, defined as:

$$NPV = \sum_{k=1}^{N} \frac{\Delta OC_k}{(1+a)^k} - \text{IC}$$

it is possible to evaluate the amount of money that it is possible to earn using the AS considering an operating life of cogenerator equal to 10 years (N=10) and a discounting back factor equal to 5% (a=5).

The MCHP considered has a first cost of about 2500 €/kWel (first cost equal to 15000 €), evidently too high, compared to the market cogeneration standards. According to the Italian market, an electric energy price of 0.17 €/kWh and a natural gas price of 0.55 €/Sm^3 have been assumed.

It is evident that only very peculiar conditions, characterized by an intensive use of CHP, allows acceptable SPB. Then, the SPB has been estimated in presence of economic action to support this technology. So, it has been considered a contribution equal to 20% (2000 €/kWel: first cost equal to 12000 €) on the first cost (by Institutions, manufacturers, gas utilities, …) and a reduction of the natural gas price for cogenerative use (0.35 €/Sm^3) in the following analysis.

5 BUILDINGS, LOADS AND EXTERNAL FACTORS

The utilization and wide diffusion of MCHP is strongly related to the characteristics of final users (i.e. to the load profiles or electrical, thermal and cooling requirements that have to be matched by the MCHP output).

To illustrate this key-point in MCHP utilization, consider its application in an Italian dwelling. Space heating is required for only a third to half of the year. Even during the heating season the heating system is often operating for short periods of the day, and the electrical demand profile is not always well matched to that of heat. For example, a residence may require maximum thermal output during a cold winter night while electrical demand may be minimal or maximum electrical output may be required for residential cooling during hot summer day when there is little or no need for thermal energy.

To best match the MCHP's output to building loads, we first considered the energy requirements of those domestic appliances that can use either electricity or hot water to meet their energy requirements (that is, water heaters, dish washers, and clothes washers).

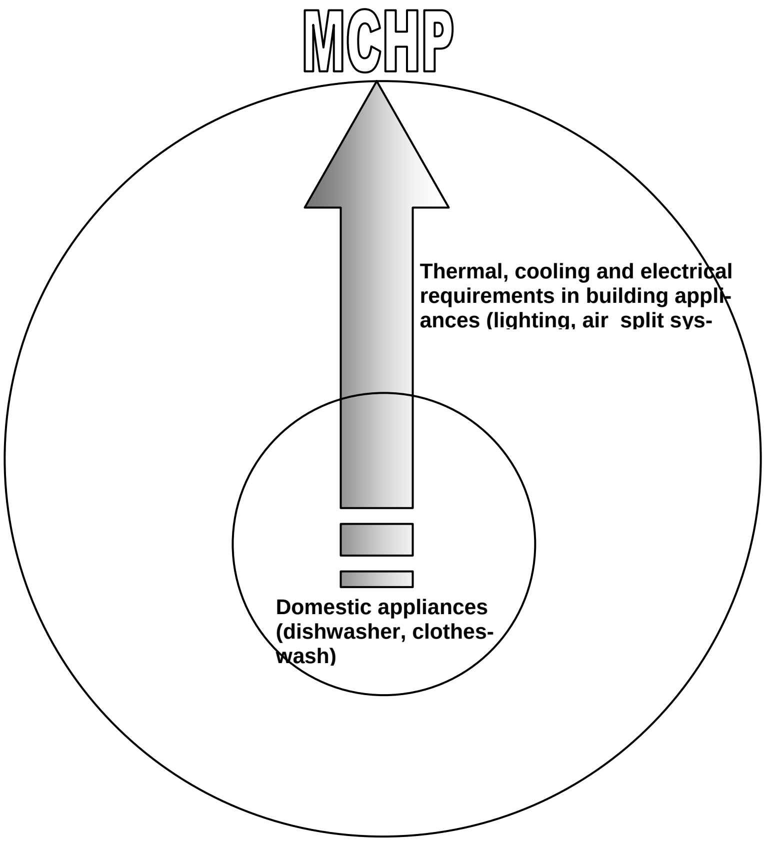

Fig. 6. MCHP applications.

5.1 Domestic appliances

In order to optimise the match between the micro-CHP and the thermal and electric users, an analysis of residential appliances has been performed. Attention focused on domestic electric storage water heaters, domestic washing machines, and finally on household dish washers, for two reasons:

a) they consume a significant part of household electricity. The energy efficiency of ESWH, WM and DW is analysed by manufacturers, research groups, national and international energy authorities that are studying the technologies to reach the optimum balance between energy consumption and overall working performance;
b) they permit shifting the energy requirements from electricity to thermal energy: in fact the energy supplied to ESWH, WM and DW systems is mainly used to produce hot water, usually by means of electric resistance heaters. There are commercially-available equipment that are both thermally- and electrically-driven and therefore can be linked to alternative energy suppliers such as boilers and/or micro-CHP.

Referring to topic (a), the total European Union electricity consumption by ESWH systems in 1997 was 87 TWh, and about 15% is due to household units. About 30% of the 142 million EU households use this equipment. The energy consumption of the estimated 120 million WMs installed in EU amount to about 38 TWh, which is approximately 2% of the total EU electricity consumption. In Italy, ESWH, WM and DW systems are responsible for about 45% of the average annual household energy consumption. It is important to underline that about 70% of the total energy consumption of household appliances is covered by ESWH, WM and DW systems. In the USA, WM and DW systems that meet the standards set in the National Energy Conservation Act consume about 30% of total annual energy consumption of typical domestic appliances.

Referring to topic (b), it can be noted that, for a ESWH, the energy supplied less the stand-by losses, is used to heat the water. Starting from cold water at 10 °C, in order to supply 100 litres of hot water at 60 °C, the average European citizen consumes 36 litres of hot water each day, that is about 6 kWh of energy. However, during a whole 24-hour period, average stand-by losses range from 1 to 2.5 kWh, depending on insulation thickness, thermal conductivity of insulation material, geometry of the ESWH. In a WM typical wash cycle (at 60 °C) about 85% of the total energy requirement is used to heat water and only 15% to other electric devices**.** For a bio cycle of a DW, 55/65 °C, only 10% of the energy supplied is not used to hot water production.

In order to evaluate the potential energy savings of thermal and electric appliances, market-available WMs and DWs were tested in both traditional and hybrid operation mode (that is, powered by the electric network, and with electric input in addition to hot water feed at 45 °C). For the DW, no restrictions were placed on the temperature level of input hot water and each appliance was linked to the hot water pipe instead of cold pipe to avoid water heating by electric resistance. For the WM, the water temperature must be controlled, and therefore appliances are available with two pipes for water inputs. Table 2 shows the energy balances for dish washers and washing machines when activated by different energy sources.

Table 2. Energy balance for electric and heat activated dish-washer and washing –machine for different energy sources starting from measurement data.

Appliance	**DW**		**WM**	
Energy Source	ELECTRIC	ELECTRIC + THERMAL	ELECTRIC	ELECTRIC + THERMAL
Net Electric Energy [kJ]	5447	2859	3460	2701
Net Thermal Energy [kJ]	-	2571	-	560
Total Net Energy [kJ]	5447	5430	3460	3261

5.2 Buildings

5.2.1 Buildings type

The building types considered is multi-family house, MFH (4-12 dwellings).

5.2.2 Building energy demand levels

The energy demand levels, identical for the SFH and MFH building types, are derived from experimental data acquisition as follows:

a) Electricity demand. Report of the Politecnico of Milano based on measurements on-site of the electric consumptions in the Italian residential sector within the SAVE EURECO and MICENE projects;

b) Space and hot water heat demand. Report of the Snam Rete Gas based on measurement on-site of domestic hot water and space heating for 500 flats located in Naples area (Italy).

From the monitored data, as well as existing literature, we know that domestic non-HVAC electrical energy and thermal energy consumption is primarily dictated by the following factors:

- floor area of the dwelling;
- number of occupants;
- geographical location;
- occupancy patterns;
- seasonal and daily factors;
- ownership level of appliances.

The final profiles produced and the related energy consumption therefore are derived considering a standard usable floor area (120 m^2) with four occupants located in Southern Italy in climatic Zone C; the grid electric power supply is fixed at 3 kW.

There are no specifications on buildings envelope characteristics so they can be assumed from typical building arrangement.

The occupant-driven energy demand profiles were adapted such that the energy demand values given in Table 3 were met.

Table 3. Energy demands per m^2 energy reference floor area.

	SFH
Space heating [kWh/(m^2 a)]	77.3
DHW [kWh/(m^2 a)]	35.0
Electricity [kWh/(m^2 a)]	19.1
Electricity (including HVAC in hot season) [kWh/(m^2 a)]	25.2
U-value exterior walls [W/m^2K]	1.93

5.2.3 Building geometry

The geometric layout of a MFH is an extention of the SFH type building geometry. All dwellings have the same usable floor area (120 m^2) and the same assumption considered for table 1.

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

Heat distribution is performed by water-based radiators while cooling is provided by an electric-driven split system with air cooled condensing unit; it is noteworthy that in southern Italy split systems are used to in portions of the living spaces (i.e. bedroom, dining room) comprising 25%

of total volume. The rate of natural ventilation through open windows is assumed to be 1.5 $m^3/h/m^2$.

5.3 Occupancy related loads

5.3.1 Space heating and DHW demand profiles

Data for SFH and MFH

A report from Snam Rete Gas provides data for domestic hot water and space heating for 500 flats located in Naples area (Italy). Available data describe:

- period from 1998 to 2002 (December);
- gas consumption in Sm^3/h for each flat;
- acquisition interval: 60 minutes.

A high standard demand level of 200 litres per day was assumed for each house. With regards to space heating and DHW tree periods of the year corresponding to standard climatic conditions were considered:

- cold season, Fig. 7;
- cool (intermediate) season, Fig. 8;
- hot season, Fig. 9.

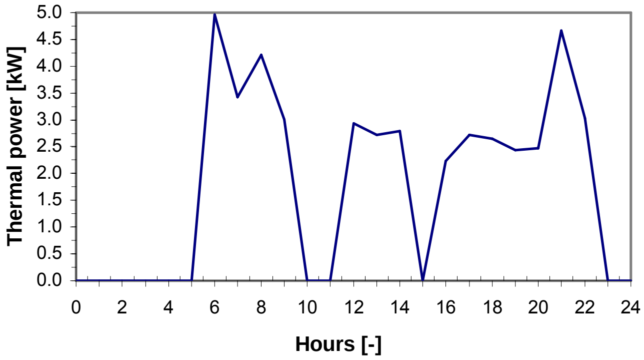

Fig. 7 Cold Season Daily SH and DHW Demand in Southern Italy for SFH

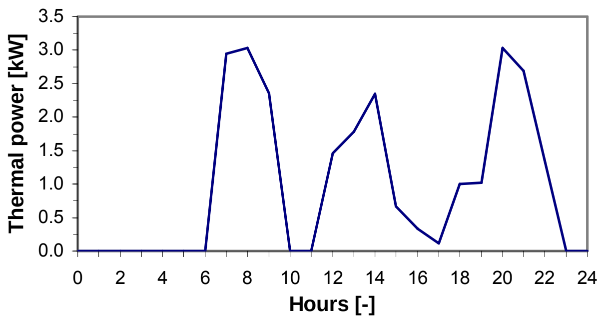

Fig. 8 Cool Season Daily SH and DHW Demand in Southern Italy for SFH

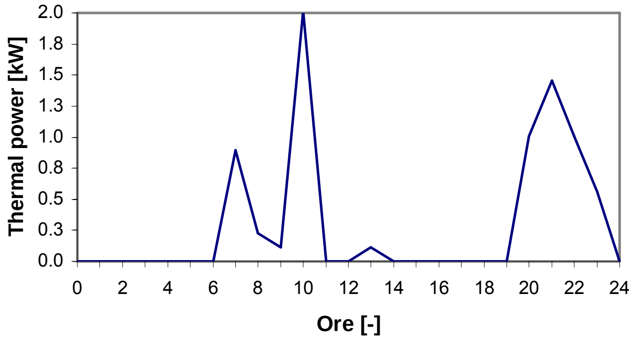

Fig. 9 Hot Season Daily DHW Energy Consumption in Southern Italy for SFH

5.3.2 Electricity demand profiles

Data for SFH and MFH

The Italian domestic electrical non-HVAC dataset is derived from on site measurements of the electric consumptions in the Italian residential sector. The report provides 10-minute data for:

- 110 flats located in 5 Italian regions analyzed for 3 years;
- the monitored electrical energy consumption and electric power demand of the total household appliances and lighting systems;
- electric energy consumption and electric power demand of each flat and of the whole building.

The data provided describe the total electricity demand values, including the demand of appliances (refrigerator, standby loads of electronics, lighting, household appliances, and IT devices), but exclude any demand for electric heating.

It is noteworthy that during hot season the electrical load includes the energy consumption of electric air conditioners.

Superposition of several SFH profiles provides the following 12-dwelling MFH load profiles for each period of the year:

- Cold season, Fig. 10;
- Cool (intermediate) season, Fig. 11;
- Hot season, Fig. 12.

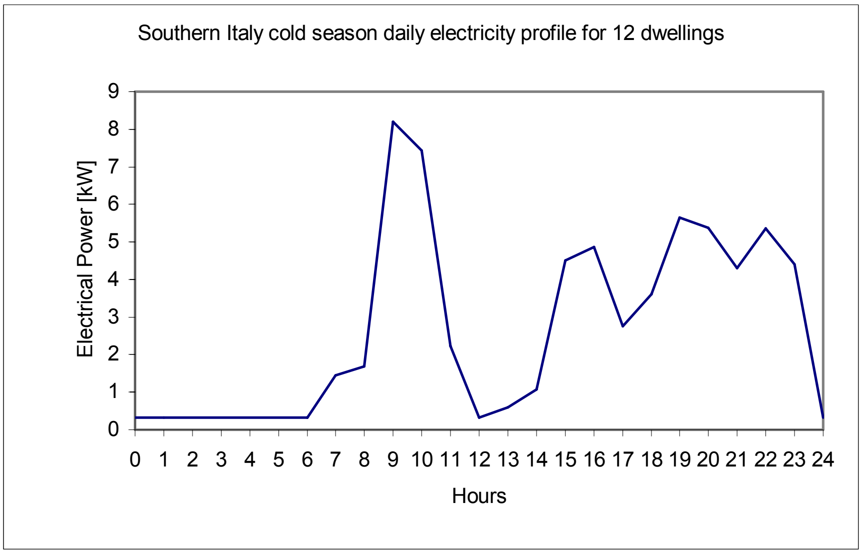

Fig. 10. Cold season electric consumption for MFH.

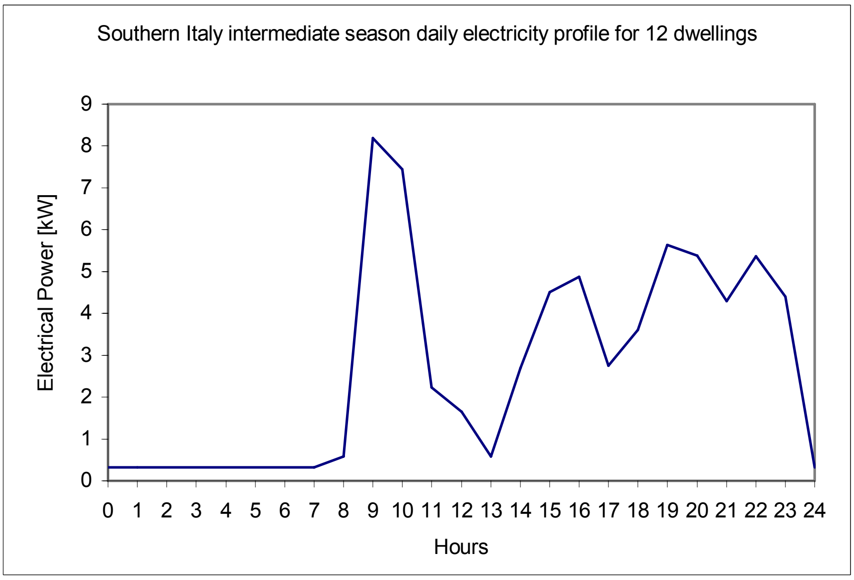

Fig. 11. Cool (intermediate) season electric consumption for MFH.

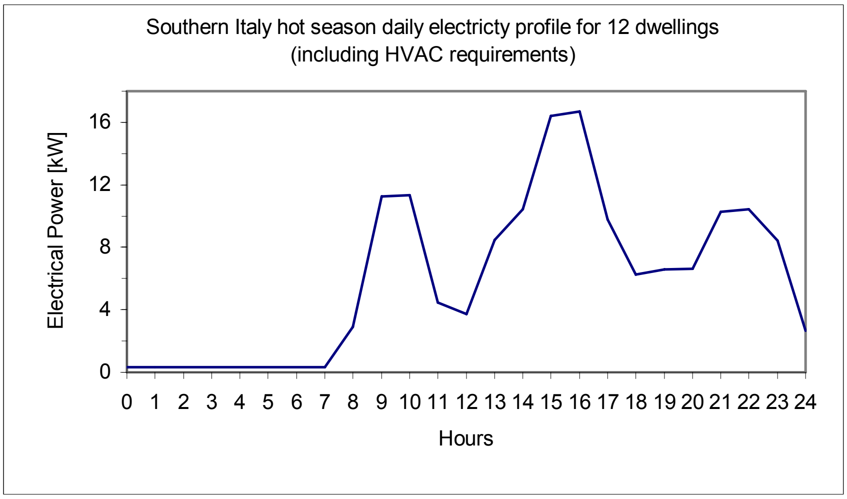

Fig. 12. Hot season electric consumption for MFH.

5.4 External factors

5.4.1 Outdoor climate

Italy is classified into climatic zones that are independent from their geographic location; all results correspond to regions in Southern Italy designated as climate zone "C", with the characteristics noted in table 4. In particular for climate of Naples the value of degree-days is 1034..

Table 4. Climatic data.

zone	Degree-days	Heating Period	Heating Hours/day
C	from over 900 to 1400	15 November - 31 March	10

5.4.2 External energy supply (delivered energy)

Energy sources

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

- Fuel: Natural gas;
- Electricity: Grid electricity with different generation mix.

Natural gas

Lower heating value: 34.524 kJ/m^3 (LHV).

The following composition was assumed for natural gas:

Mol (%)	CH_4	91.01%
Mol (%)	Others	8.99%

5.4.3 Generation mix for electricity and other delivered energy carriers

The different system configurations were evaluated in terms of the annual non-renewable primary energy demand and the related CO_2 emissions.

A factor was applied to allow for the distribution losses of natural gas, as the supplied energy source. For grid electricity, the NRPE demand and respective CO_2 emission rates depend on the electricity mix.

Two electricity mixes were considered:

a) Italian average;

b) state-of-the-art gas and steam combined cycle power plant (CC power plant), BAT.

Given the wide range of possible electricity mixes, the CC power plant is best chosen as the reference, as it uses the same fuel as the cogeneration system (mostly natural gas); it is clearly identifiable by its working cycle; and it is another innovative substitution technology. The energy ratios used are shown in Table 5.

Table 5. Primary energy factors (primary to delivered energy ratios) and CO_2 emission factors.

	Electricity mix for low-voltage electricity supply		Natural gas supply
	Italian MIX	CC power plant	
Primary energy factor pef (based on LHV) [MJ primary/MJ end energy]			
Non-renewable energy	2.56	1.94	1.13
CO_2 factor [kg/MJ delivered energy]	0.192	0.111	0.0556

They include a 11.5% distribution loss factor in the electric grid. The Italian mix mainly comprises fossil fuel power plants, therefore, the CO_2 emission factor and the non-renewable energy factor are both high. For the CC power plant, an electrical efficiency of 58% (in relation to the LHV of NG fuel) and a factor of 11.5% for grid distribution losses were assumed without considering for NG distribution losses..

Two reference heating systems were considered: (a) a gas fired boiler with an efficiency equal to 85 % (based on LHV) and (b) a condensing gas-fired boiler with an efficiency equal to 95 % (based on LHV).

6 DESCRIPTION AND CHARACTERISTICS OF SYSTEM COMPONENTS

6.1 Cogenerator characteristics

The CGU unit used in this study (see Fig. 13), has a nominal rated output of 6 kW electric and 13.5 thermal power with a total efficiency at full load equal to 86 % (based on LHV of the fuel). This unit is available on the European market and its rated characteristics are shown Table 6. The reciprocating internal combustion engine also used with the GHP (Gas Heat Pump), has three cylinders with a total displacement of 952 cc. Thermal energy is recovered from the exhaust gases and engine coolant liquid.

Table 6. Cogenerator characteristics.

Electric efficiency	[%]	**26.5**
Thermal efficiency	[%]	**59.5**
Overall Efficiency	[%]	**86.0**
Rated Output	[kW]	**6.00**
Exhaust heat Recovery Rate	[kW]	**13.5**
Output hot water temperature	[°C]	60 - 65
Fuel gas type	-	Natural gas, propane gas

Fig. 13. Cogenerator considered in the case study.

This cogenerator can modulate its electric output between a minimum value of 1 kW and a maximum of 6 kW; Fig. 14 shows its electric and total efficiency as a function of fuel input.

A back-up boiler (see § 6.2) was assumed to cut in automatically if additional thermal power was needed, depending on the temperature of water inside the heat storage.

The generated electricity was directly used in the dwellings. The electric grid was used also to cover peak demand or in case of the cogenerator was off.

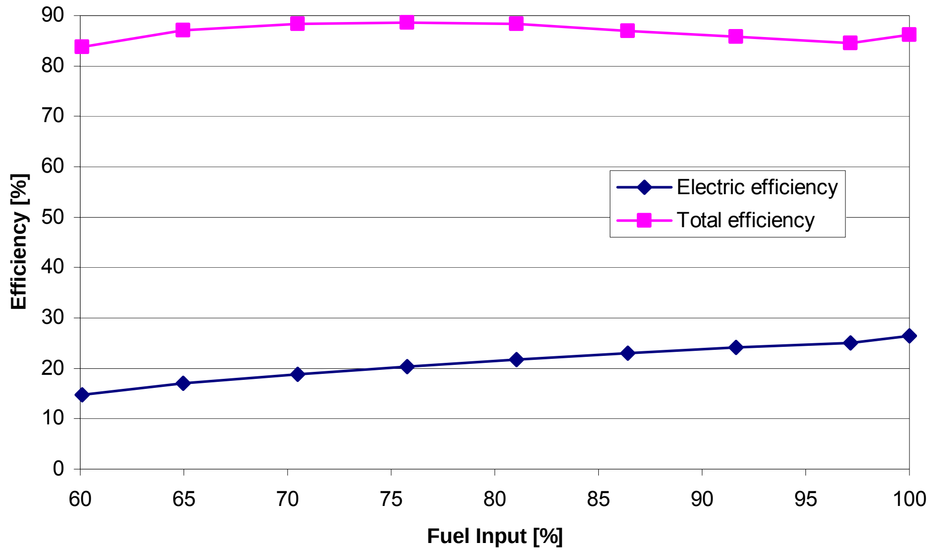

Fig. 14. Electrical and total (thermal and electrical) efficiency performance characteristics for cogenerator. Efficiencies are in relation to the lower heating value of the fuel.

No dynamic effects were considered within the operating range.

6.2 Reference and auxiliary heater

6.2.1 Condensing gas boiler/boiler

Two reference systems were considered in order to satisfy energy demand for space heating and DHW:

a) gas-fired boiler;
b) condensing gas-fired boiler.

In the two configurations, gas-fired boilers were used both as reference system and as back up heaters. The thermal efficiency considered for case (a) is 85% (based on LHV) and 95% (based on LHV) for case (b).

6.3 Hot water storage tank

For all systems a single cylindrical, stratified storage tank was assumed for the space heating and domestic hot water. The size was 500 l for the analysis.

6.4 Electric storage – grid connection

No electric storage is considered in this study. The cogen unit does not supply electric energy to the grid. Instead, the cogenerator is connected in parallel with the grid, and the grid satisfies electric requirements both in peak load period and when the MCHP can not operate.

6.5 Electric Heat Pump (EHP)

The cooling equipment used is a simple air to air electric driven heat pump. The heat pump uses split indoor and outdoor units with direct expansion of the refrigerant. In Fig. 15 the electric power required by EHP during a typical hot day is shown.

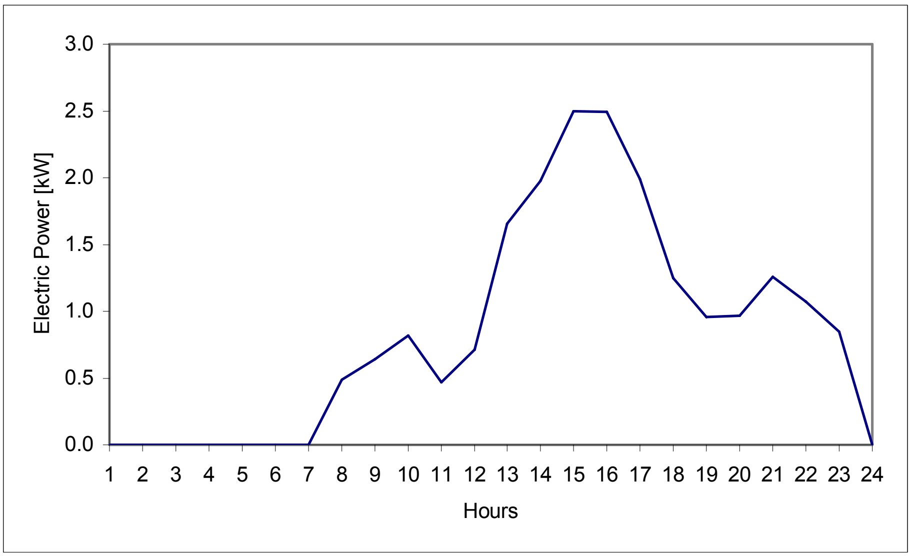

Fig. 15. Daily electric power required in hot season.

7 DESCRIPTION OF SYSTEMS

7.1 Domestic appliances

In order to evaluate the potential energy saving of thermal and electric activated appliances, market-available WMs, DWs and heat storage tank were tested in both traditional mode (heated by electricity) and hybrid operation mode (heated by thermal and electrical energy supplied by MCHP), Fig. 16.

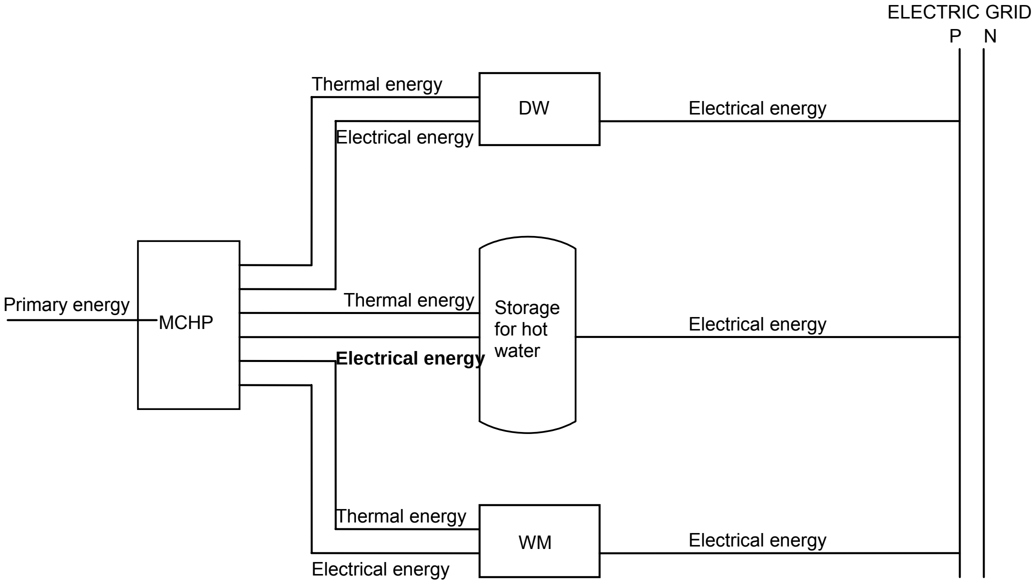

Fig. 16. Energy flows of TS (El-Grid) and AS (MCHP) able to supply dish washer, washing machine and DHW.

7.2 Systems

The system considered in this study consists of a combined storage for space heating and domestic hot water, as well as a boiler. The alternative system (AS) adds a MCHP unit in parallel with the boiler. Fig. 17 and Fig. 18 present the schematic of the alternative system, AS:

- grid connected CHP device with gas boiler as auxiliary heater, in heating mode (cold and intermediate season), Fig. 17;
- grid connected CHP device with gas boiler as auxiliary heater, and EHP (for cooling load), in cooling mode (hot season), Fig. 18

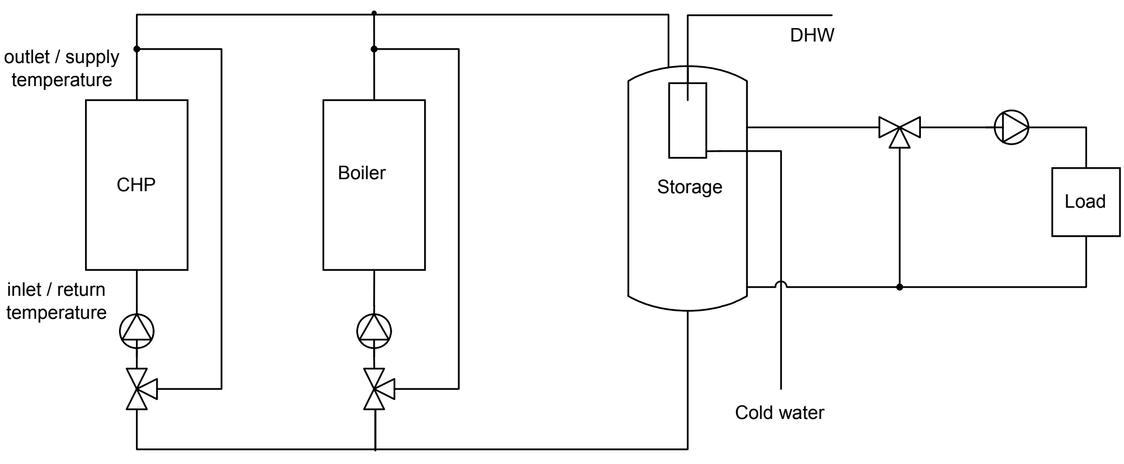

Fig. 17. Schematic of the DHW and space heating system for AS.

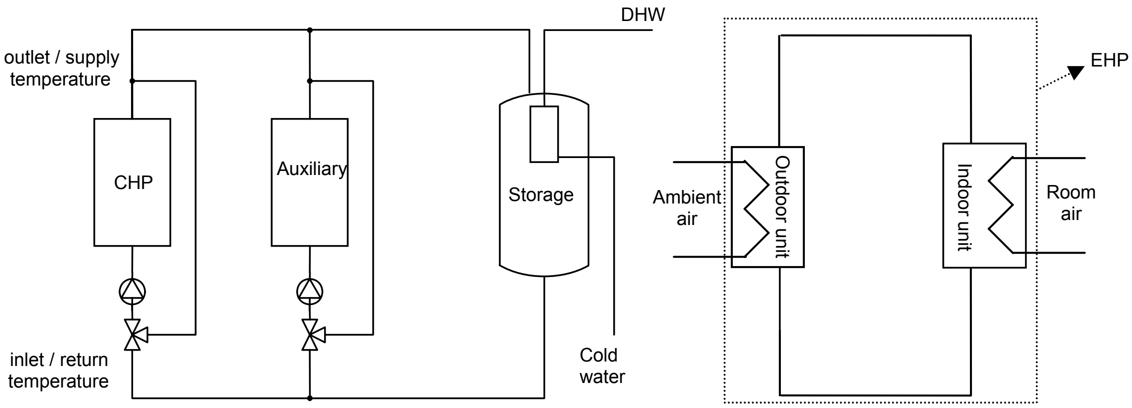

Fig. 18. Schematic of DHW and space cooling system.

Fig. 19 and Fig. 20 depict the schematic of the reference system:

1. heating mode: gas boiler as heat generator (space heating and DHW); electric grid;
2. cooling mode: electric heat pump (space cooling), gas boiler (DHW); electric grid.

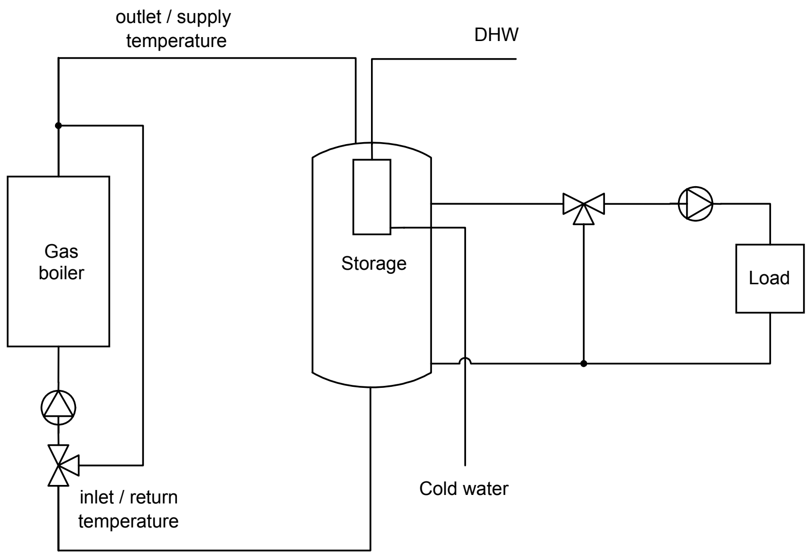

Fig. 19. Schematic of the DHW and space heating system for TS.

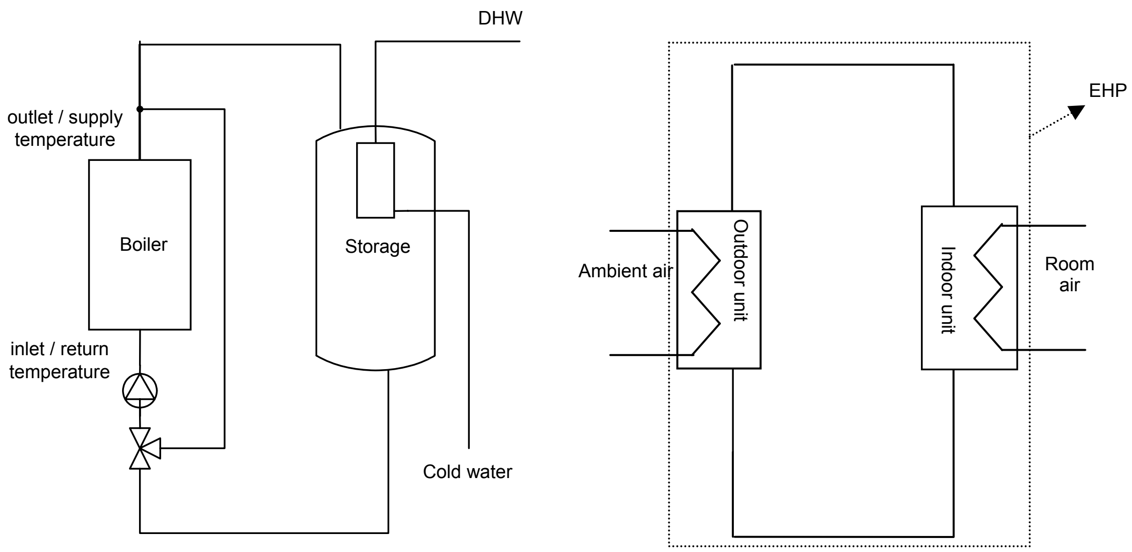

Fig. 20. Schematic of the DHW and space cooling system for CS.

According to a typical 3-E (Energetic, Economic and Environmental) simplified approach, the performance of the alternative system (AS = cogen unit) are usually compared to that 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. Fig. 21 and Fig. 22 show the energy flows of the two compared systems in heating (cold and intermediate period) and cooling mode (hot period).

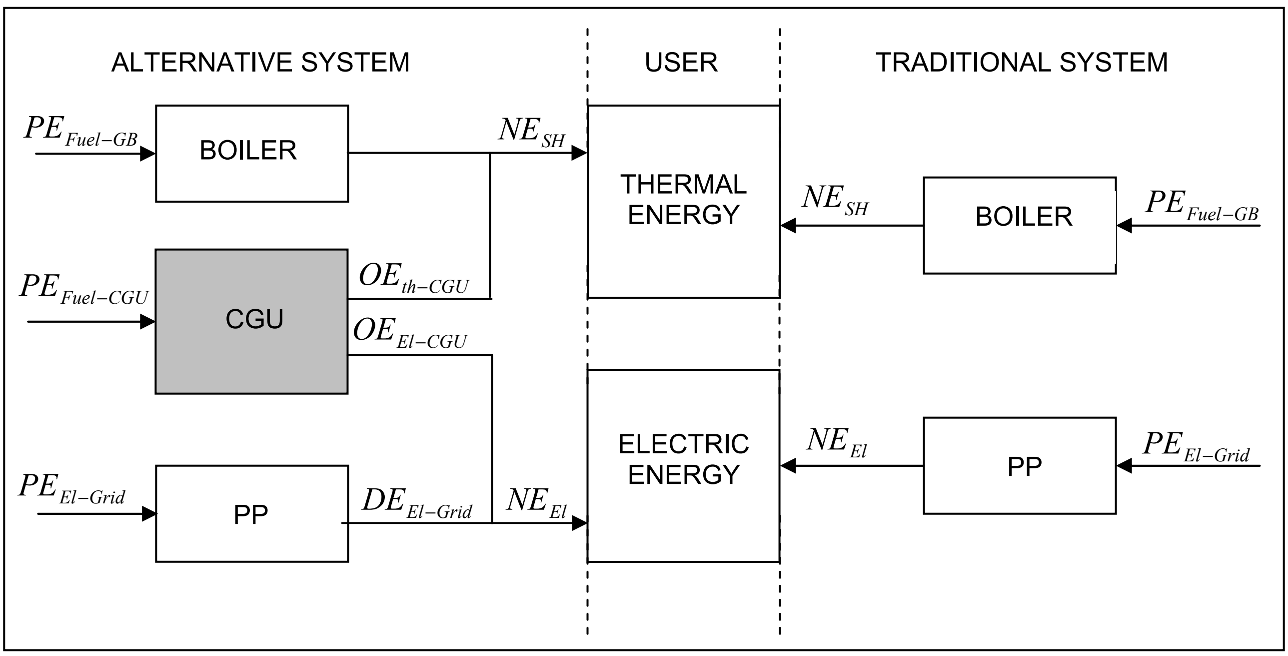

Fig. 21. Energy flows of the two compared systems in heating mode (cold and intermediate period).

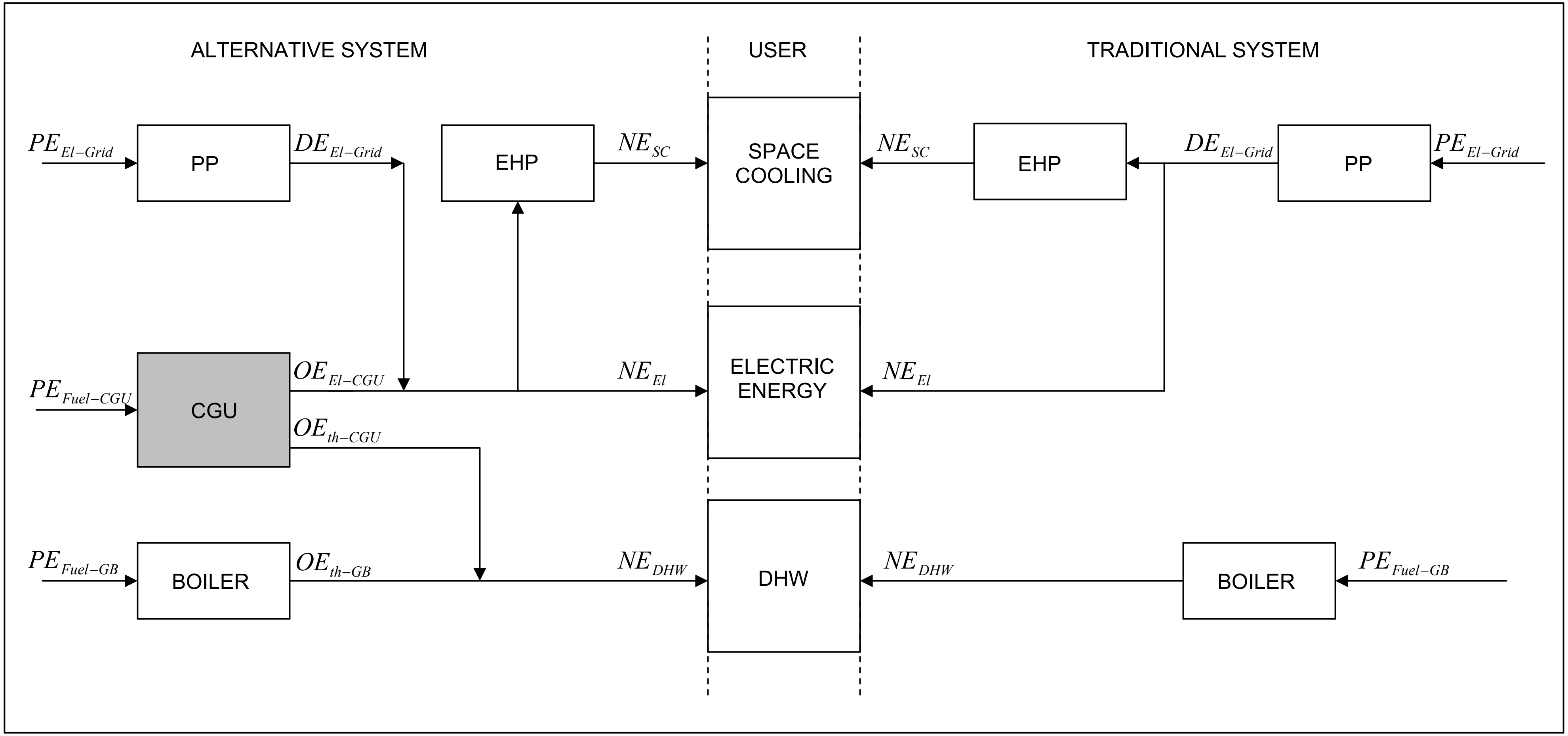

Fig. 22. Energy flows of the two compared systems in cooling mode (hot period).

8 SYSTEM CASES AND CONFIGURATIONS

Starting from the energy loads of some appliances (see § 5.1) and thermoelectric load profile (see § 5.2) available for an Italian user a simplified 3-E (Energetic, Economic and Environmental) approach has been performed to compare the proposed energy system, MCHP, to the conventional one based on separate "production".
In order to identify the right application for this technology in the domestic sector, the 3-E analysis has been performed while varying some parameters, such as number of dwellings, operating mode and reference systems.

8.1 Description of evaluation cases

The parameters and configurations considered in this study are briefly outlined in Table 7 and described in more detail in the next section.

Table 7. Parameters and configurations considered in this study.

Building	
Building type	MFH
Dwellings	4-12
Building energy level	Average energy building
HVAC system	Heating: Hydronic (fan coil) Cooling: air to air EHP
Boundary conditions	
Climate	Naples
Occupant type	Average (mixture of working and familiar types)
DHW demand	Four person/family per house
Electricity demand	Four person/family per house (seasonal profiles)
Domestic hot water demand	Seasonal profile
Micro-cogeneration unit	Reciprocating internal combustion engine (6 kWel)
Additional heat generation	(a) gas-fired boiler and (b) condensing gas-fired boiler
Hot water storage size	500 l
Control options	(a) Pure electricity-led and (b) Optimized electricity-led
Operational options for micro-cogeneration unit	(a) Modulation range and (b) start/stop options
Cogenerator data	From manufacturer
Fuel	Only natural gas is considered
Electricity mix	Non-renewable primary energy demand for generation of grid supplied electricity (a) Italian average mix and (b) state-of-art combined cycle power plant

First, we suppose that all dwellings have an electrically driven air conditioning system to satisfy space cooling loads, and a gas-fired boiler for space heating and domestic hot water loads. Using the data available from the manufacturer of the cogenerator an *analysis* was carried out in order to determine the minimum number of dwellings that guarantee satisfactory performance from an economic point of view. This analysis was conducted while varying the number of dwellings from 4 to 12, using the same energy loads for each dwelling.

8.2 Reference cases

The reference cases established on the following basis:
1. the external parameters and the buildings analyzed are identical;
2. the reference energy systems are:
   (a) typical Italian generation mix for electricity supply from the electric grid and gas boiler (efficiency equal to 85%) for SH and DHW;
   (b) combined cycle gas turbine (electricity) and condensing gas boiler(efficiency equal to 95%) for SH and DHW.

8.3 Cases selected and operating strategy

This section defines the two parameters that were varied during the energetic, environmental and economic performance assessment:
1. dwellings number;
2. operating strategy.

The number of dwellings was increased in increments of two (that is, 4, 6, 8, 10, 12), while assuming for each dwelling the same energy loads at the same time.

8.3.1 Operating strategy

For all cases, the cogeneration unit's electric output was matched to the electric load (that is, the unit was electricity-led), and no electricity was exported to the grid. A 500 l storage tank of was used for thermal recovery.
In particular, two operating strategies were considered:
1. Fixed start-up value (actual MCHP operating mode);
2. Variable start-up.

Fixed start-up value strategy
In the first approach, for the fixed start-up value, MCHP starts automatically when the electrical load is greater than a minimum fixed value, which varies by season and number of dwellings: this value is chosen in order to obtain the best economic performance (maximum ΔOC ensuring a positive PES). It is clear that this strategy, depending on load profiles of the user, gives different energetic and economic performances as a function of minimum electric load at which MCHP starts,

In Fig. 23 are reported the PES, ΔCO_2 and operating cost (ΔOC) savings in a typical day during the cold season as a function of the fixed start-up value (the minimum electric power at which the MCHP is switched on) when the MCHP provides heat and power to 12 dwellings. In this way the figure represents an example to point out the variability of the three parameters as a function of fixed value start-up.

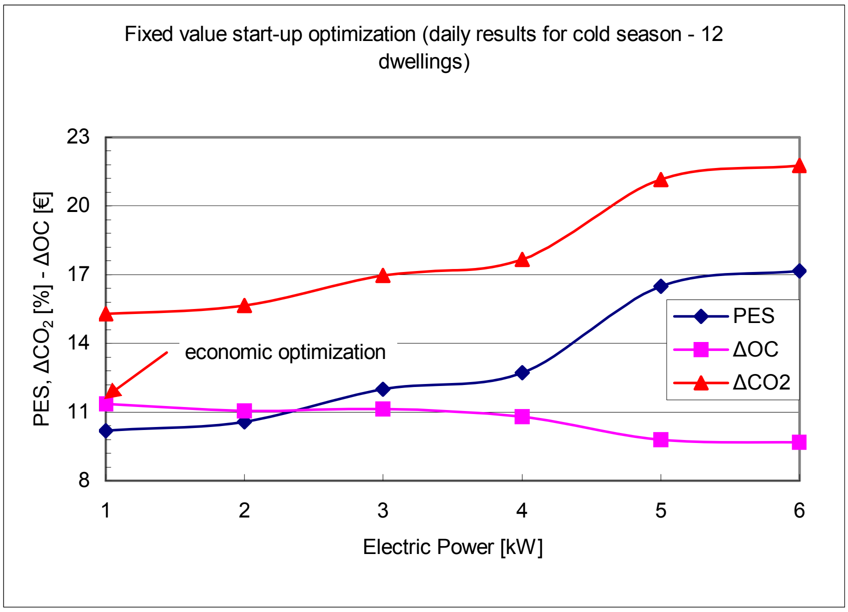

Fig. 23 PES, ΔCO_2 and operating cost (ΔOC) savings in a typical day during cold season for 12 dwellings application

It is important to observe that:

- The maximum operating cost savings is obtained for a fixed electrical power of 1 kW because, in this configuration:
  1. the MCHP runs for the maximum possible number of hours;
  2. all thermal energy output delivered by MCHP is useful for the users (12 dwellings)

- The maximum PES and ΔCO_2 savings are obtained for an electric power of 6 kW because, in this configuration:
  1. The MCHP operates at its highest efficiency..

In Fig. 24, he PES, ΔCO_2 and operating cost (ΔOC) savings are plotted for a typical day during the hot season as a function of fixed start-up value (that is, the minimum electric power at which the MCHP is switched on).

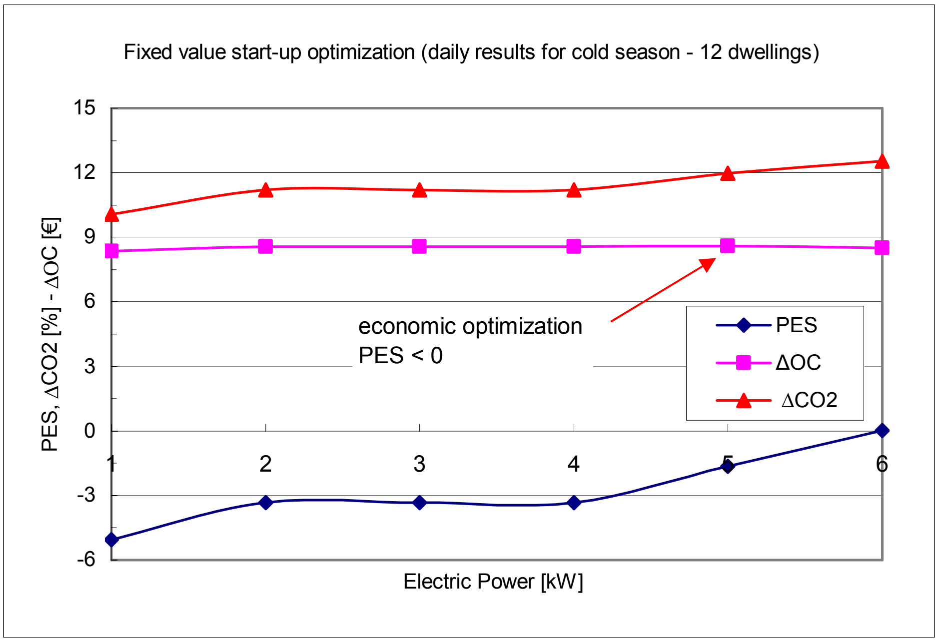

Fig. 24. PES, ΔCO_2 and operating cost (ΔOC) savings in a typical day during hot season for 12 dwellings application.

It is important to observe that the operating cost savings are quite constant and reaches a maximum when the start-up value is 5 kW; at the same time the PES results with negative value of -1,65%. Consequently, the fixed start-up value was adjusted to 6 kW, yielding a very low, but positive (0,02%) PES.
This approach (PES≥0, ΔOC maximum) was then performed for each combination of number of dwellings and season. The optimal fixed start-up values are presented in Table 9.

Table 8 Minimum value of electrical power to start automatically MCHP

Number of dwellings	Hot	Intermediate	Cold
4	5 kW	2 kW	1 kW
6	5 kW	2 kW	1 kW
8	6 kW	1 kW	1 kW
10	6 kW	1 kW	1 kW
12	6 kW	1 kW	1 kW

Variable start-up value strategy
Once we fix the start-up value to get the maximum ΔOC (and at the same time ensuring positive PES), it is necessary to improve the MCHP's energetic performance (PES optimization).

One possibility is to optimize usage of the thermal storage (i.e. reduce the number of hours during which the thermal load is satisfied by an auxiliary boiler).

This approach is hampered by the following two conditions:

1. The MCHP does not start for electric requirements of less than 1 kW (manufacturer's restriction);
2. The optimal start time depends on the thermal load requirements of the subsequent hours.

An example for the intermediate season is presented in the Fig. 25 and Fig. 26.

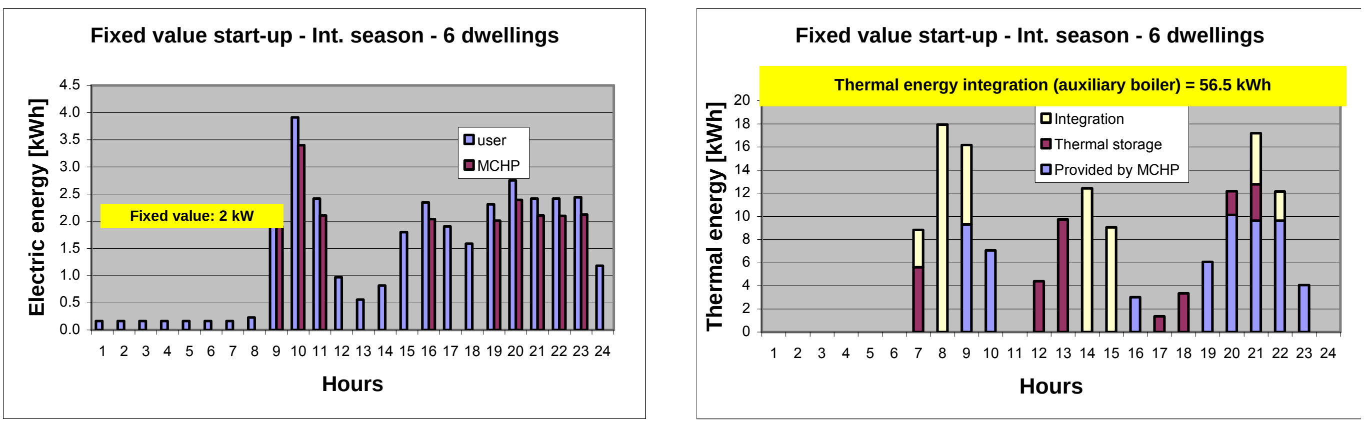

Fig. 25. Thermal energy integration with auxiliary boiler for fixed value start-up strategy (intermediate season, 6 dwellings).

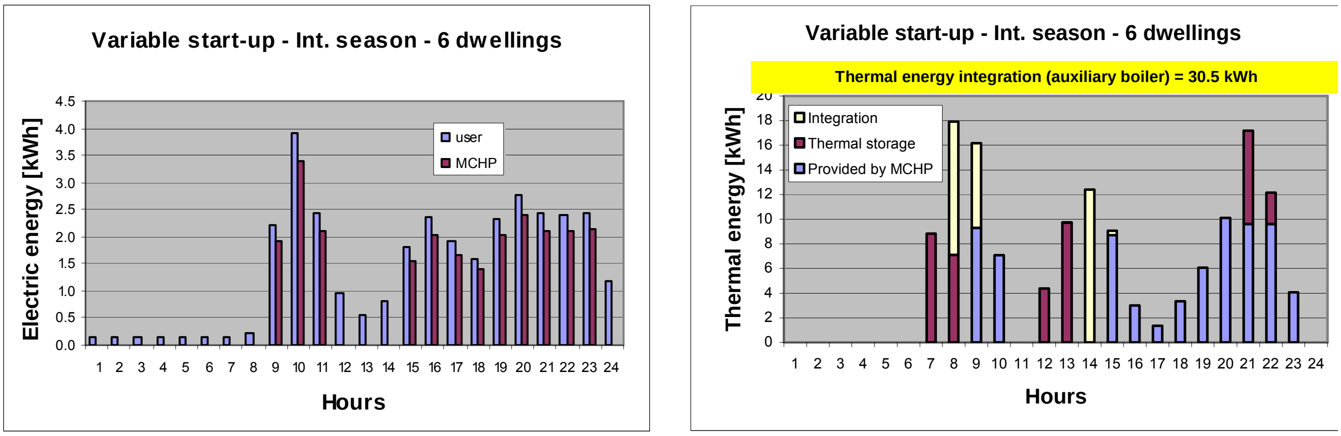

Fig. 26. Thermal energy integration with auxiliary boiler for variable value start-up strategy (intermediate season, 6 dwellings).

It is noteworthy that (i) the MCHP does not start in the first 8 hours of the day because the electric demand is less than 1 kW and (ii) that the MCHP also operates from hours 17 to in variable start-up strategy (it does not operate during this time in the fixed start-up value strategy) with the intent of charging the thermal storage for the subsequent hours: in this case thermal energy supplied by auxiliary boiler is reduced from 56.5 kWh/day (first operating strategy) to 30.5 kWh/day (second operating strategy), equivalent to a reduction of 46%.

Another example for the hot season is presented in Fig. 27.

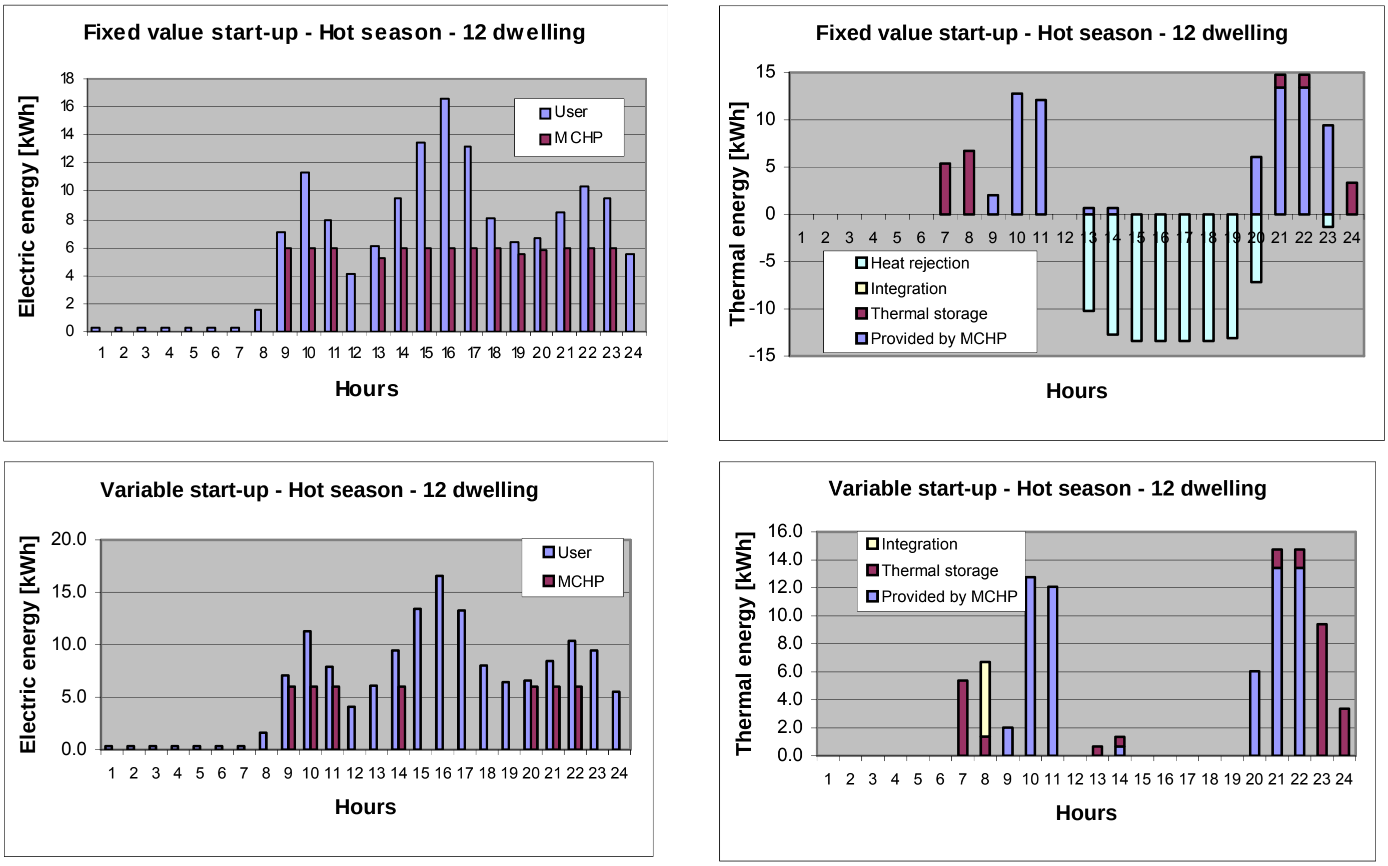

Fig. 27. Hot season: reduction of thermal waste caused from MCHP running (12 dwellings).

During hot season, the variable start-up strategy attempts to reduce the number of MCHP running hours in order to avoid thermal waste, contrary to its operation during the cold and intermediate seasons: from hours 15 to 19 o'clock and at hour 13 o'clock the MCHP does not run in order to avoid thermal dissipation (heat rejection).

9 RESULTS

In this section, we report the results obtained for preliminary analysis, starting from available data of micro-cogenerator manufacturer.

9.1 Domestic Appliances

Table 9 and Table 10 present the results of the comparison between two different energy systems (MCHP and TS). For TS has been considered a system, typical of Italian condition, and a second reference system based on BAT (see § 8.2), used to supply the energy requirements related to a cycle of the DW, a cycle of the WM and to the production of 80 litres of hot water at 60 °C. It has been considered for MCHP electrical and thermal efficiency performance respectively equal to 0.20 and 0.80 (based on LHV).

Table 9. Energetic, economic and environmental results respect to first reference system.

SYSTEM	Electric Grid	MCHP
Primary energy [kJ]	57579	27800
Delivered energy [kJ]	22456	22240
Efficiency [-]	0.39	0.800
PES [%]	51.7	
ΔOC [€]	73.4	
ΔCO_2 [%]	64.6	

Table 10. Energetic, economic and environmental results respect to second reference system (BAT).

SYSTEM	Electric Grid	MCHP
Primary energy [kJ]	43604	27800
Delivered energy [kJ]	22456	22240
Efficiency [-]	0.515	0.800
PES [%]	36.2	
ΔOC [€]	73.4	
ΔCO_2 [%]	38.1	

The results show that there is little difference in economic performance (□OC) between the two operating strategies because in this case they are not function of energy performances of the reference system..

The PES reduction is 15.5 % (from 51.7% for first reference system to 36.2% for second reference system). The reduction of CO_2 avoided emissions is 24.1 % (from 64.1% for first reference system to 38.1% for second reference system).

9.2 Influence of building size

9.2.1 Fixed start-up value strategy

The following table provides the final results of the simplified analysis parameters obtained by varying the number of dwellings for the fixed start-up value strategy.

Table 11. Fixed start-up value strategy: results for the simplified approach (grid electricity generation mix: typical Italian conditions)

	Dwellings				
	4	**6**	**8**	**10**	**12**
PES [%]	6.0	9.0	11.9	11.5	10.6
SPB [year]	20.0	6.9	4.4	3.6	3.1
NPV [€]	-5.76E+03	6.10E+03	1.62E+04	2.27E+04	2.87E+04
ΔCO_2 [%]	7.8	14.6	18.1	18.5	18.2
hours per year	1165	3225	4635	5000	5570
hot period [hour]	95	475	665	950	1330
int. period [hour]	190	1710	2850	2850	3040
cold period [hour]	880	1040	1120	1200	1200

The PES is positive for every configuration and ranges between 6% and 12%; for 8 or more dwellings PES > 10%.

The predicted avoided emissions of CO_2 are also encouraging; they range between 8 and 18%, with values greater 10% for 6 or more dwellings.

It is evident that acceptable SPB values (less than 5 years) are realized for only 8 or more dwellings, which are characterized by intensive use of the MCHP (4600 running hours). The SPB is more sensitive than the other indices the number of dwellings: it is as low as 3 years for 12 dwellings.

9.2.2 Variable value start-up strategy

In the following table are shown the final results of the simplified analysis parameters obtained with the considered strategy for each number of dwelling analyzed.

Table 12. Variable value start-up strategy: results for the simplified approach.

	Dwellings				
	4	**6**	**8**	**10**	**12**
PES [%]	10.0	10.8	12.0	12.9	12.7
SPB [year]	10.0	6.1	4.6	3.7	3.2
NPV [€]	4.95E+02	8.30E+03	1.49E+04	2.15E+04	2.70E+04
ΔCO_2 [%]	13.9	16.4	17.4	18.5	18.5
hours per year	2780	3795	4350	4620	4905
hot period [hour]	190	475	380	570	665
int. period [hour]	1710	2280	2850	2850	3040
cold period [hour]	880	1040	1120	1200	1200

The PES is positive for every analyzed configuration and it is included between 10% and 13%. In hot season variable start-up strategy suggests to reduce the MCHP running hours in order to improve energetic conversion performance avoiding thermal dissipation (REP<0). SPB (less than 5 years) is acceptable only for 8 or more dwellings, with MCHP running hours of 4300; it is 3 years in the case of 12 dwellings.

Avoided emissions of CO_2 are included between 14% and 18%, with values greater 10% starting from 6 dwellings.

9.2.3 Fixed and variable value start-up strategy: comparison

Fig. 28,Fig. 29 and Fig. 30 compare the environmental, economic and energetic performance of the fixed and variable start-up value strategy;

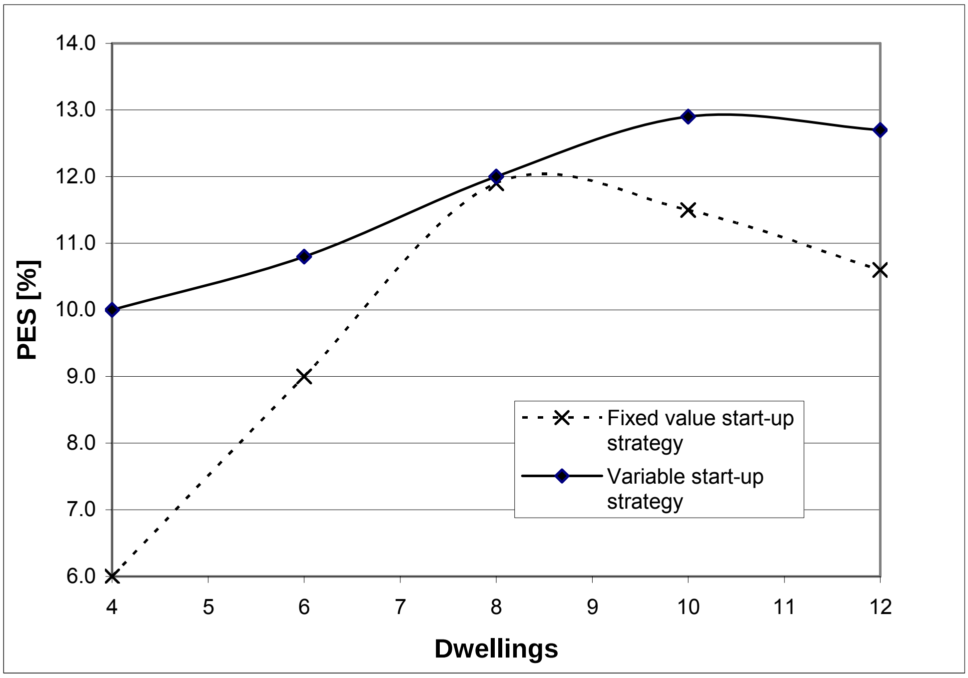

Fig. 28 Annual PES for varying number of dwellings.

It is noteworthy that the variable start-up strategy provides greater PES values than does fixed value start-up strategy, which is consistent with the goal of improving the system's energetic performance.

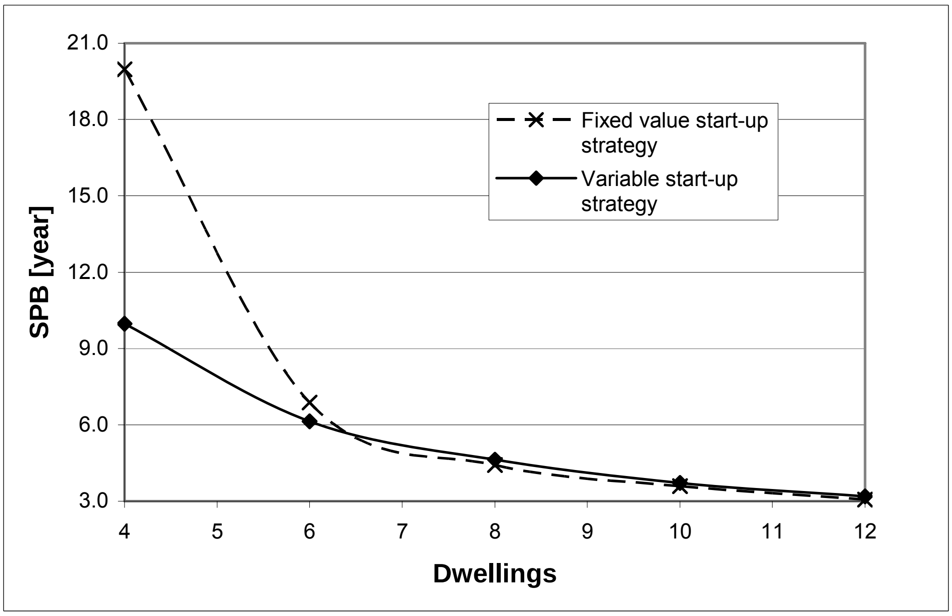

Fig. 29 SPB for varying number of dwellings

There are not many differences in the SPB index between two operating strategies when the number of dwellings exceeds 6.

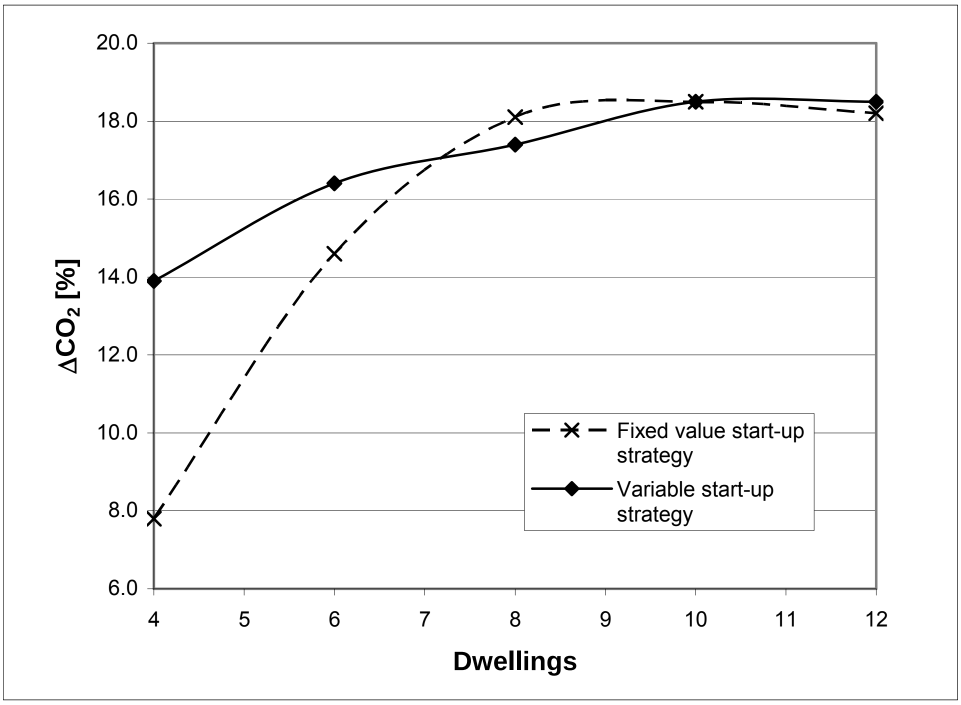

Fig. 30 Annual ΔCO_2 for varying number of dwellings.

Again, the two operating strategies provide similar environmental benefits when the number of dwellings increases above 7.

9.2.4 Results for 12 dwellings considering BAT

In the following table are shown the final results of the simplified analysis parameters obtained from the comparison with Best Available Technology (BAT) for 12 dwellings.

Table 13. Fixed and Variable value start-up strategy: results for the simplified approach (12 dwellings).

	Fixed value start-up strategy	Variable value start-up strategy
PES [%]	0.6	4.8
SPB [year]	3.4	3.5
NPV [€]	2.44E+04	2.32E+04
ΔCO_2 [%]	1.3	5.4
hours per year	5570	4905
hot period [hour]	1330	665
int. period [hour]	3040	3040
cold period [hour]	1200	1200

The results in Table 13, based on BAT (TS), show a considerable reduction of the PES and ΔCO_2 with respect to the first reference system (Italian generation mix and boiler efficiency equal to 85%) both for the fixed and variable value start-up strategies. The SPB is acceptable because it is less than 4 years.

10 CONCLUSIONS AND RECOMENDATIONS

An efficient power supply system, such as a cogenerator, is attractive in residential and light commercial markets because of the contribution of these sectors to the total energy consumption of developed countries. In Italy, commercial and residential sectors were responsible for 35.6% of the national energy consumption in 2005 (in 1999 these sectors contributed about 30% to the total value). In 1999 a potential energy savings of about 200,000 toe (ton of oil equivalent) per year, about 16% of the total national energy requirement, was estimated if 500,000 micro-CHP units were to replace the usual energy-supply equipment in Italy.

Furthermore, about 71 million European houses are supplied with natural gas. The European Commission recognises the advantages of cogeneration and have made increased cogeneration capacity a key part of its CO_2 reduction strategy.
Our study shows that, with some limitations, cogeneration is promising for powering both for domestic appliances and whole building loads.

For domestic appliances, MCHP systems provide significant energetic, economic and environmental savings due to the great importance of thermal recovery in electric driven appliances.

For domestic building applications, at least 8 dwellings are the minimum target size for application of the 6kW MCHP device in the south of Italy. This choice is based a simple pay back period of less than five years, which is deemed acceptable to domestic users. The results also show an increase of in the number of dwellings leads reduces the SPB, and the SPB is not influenced by MCHP operating strategy in buildings with 8 or more dwellings.

But the operating strategy does influence energy savings; variable start-up provides additional savings of as much as 13%. When deployed in a building with 8 or more dwellings, the equivalent CO_2 emissions reduction is not influenced by operating strategy and the related increase with the number of dwellings is negligible.

When compared to the second reference system (BAT), the MCHP's performance is not as favourable. In this case, both the PES and equivalent CO_2 emissions achieved with MCHP are substantially lower than those related to the first reference system (typical Italian generation mix).

It is well known that legislative initiatives play an important role in supporting very efficient technologies, such as MCHP and MCCHP. At the moment, the Italian government has received European directives that can strongly contribute to the diffusion of small scale cogeneration and/or polygeneration systems, such as that one-on emission trading on electricity and gas and finally on the energy performance of building. Further policies have been set forth by the Italian government to establish for micro scale the same benefits of large equipments, such as:

- low tax rates on gas;
- carbon tax exemption;
- dispatch priority in the transmission grid;
- "white certificate", an economic instrument to support high energetic efficiency systems.

Furthermore, the need for high quality power supply, the congestion and vulnerability of the transmission and distribution lines are key motivators to the development of distributed generation and polygeneration energy conversion systems, moving from the traditional centralized scenario based on separate "production" to the incoming decentralized one.

11 REFERENCES AND LITERATURE

For more comprehensive literature list on cogeneration performance assessments and methodology see [A 42 STC SoA 2007] and [IEA A42 STC PAM 2007].

A42 STA. 2006. "Residential Cogeneration Systems: European and Canadian Residential non-HVAC Electric and DHW Load Profiles", IEA Annex 42 Subtask A Report, November 2006.

CECED. 1997. "Voluntary commitment on reducing energy consumption of domestic washing machines", Final report.

CECED. 1999. "Voluntary commitment on reducing energy consumption of household dishwasher", Final report.

Dentice d'Accadia M, Sasso M, Sibilio S, Vanoli R. 1998. "La microcogenerazione diffusa", Proc. of Workshop ENEA: Le innovazioni Tecnologiche e gli effetti sugli scenari futuri nell'industria del gas, Roma, (In Italian), 10 September 1998.

Dentice d'Accadia M, Sasso M, Sibilio S, Vanoli R. 2001. "Optimum operation of a thermal plant with cogeneration and heat pumps", ECOS 2000 from Thermo-economics to Sustainability, (Proc. ECOS 2000 Universiteit Twente, 5-7 luglio 2000, Olanda), Ed. G.G. Hirs, pp.1411-1423 ISBN 9036514665, Febodruk BV, Enschede, Olanda, 2000, then published in *International Journal of Applied Thermodynamics*, Vol. 4, N. 2, pp. 93-102, June 2001.

Dentice d'Accadia M, Sasso M, Sibilio S. 2001. "Cogeneration for energy saving in household applications", Energy Efficiency in Household Appliances and Lighting, Eds. P. Bertoldi, A. Ricci, A. de Almeida, Springer - Verlang, Berlino, ISBN 3-540-41482-7.

Dentice d'Accadia M, Sasso M, Sibilio S. 2000. "A test facility for technical assessment of Micro CHP feasibility in residential and light commercial applications", Proc. of V° International Conference on Industrial Thermal Engineering, renewable Energy and Environment COMEC 2000, Las Villas, Cuba, 8-10 November 2000.

Dentice d'Accadia M, Sasso M, Sibilio S, Vanoli R. 2002. "Micro-CHP in residential and light commercial applications", Proc. of 1st International Congress SITGAS, Napoli, Italy,14-17 November 2002.

Dentice d'Accadia M, Sasso M, Sibilio S, Vanoli R. 1996. "The future perspective of micro-CHP", Proc. of III° International Conference Energy and Environment Towards the Year 2000, Volume I, pp. 407-414, Capri, Italy.

Dorer V, Weber R, Weber A. 2005. "Performance assessment of fuel cell micro-cogeneration systems for residential buildings, *Energy and Buildings,* Volume 37, pp. 1132-1146.

Entchev E, Gusdorf J, Swinton M, Bell M, Szadkowski F, Kalbfleisch W, Marchand R. 2004. "Micro-generation technology assessment for housing technology", Energy and Buildings, Volume 36, Issue 9, 925-931.

eERG. 2006. "MICENE: MIsure dei Consumi di ENergia Elettrica nel settore domestico", http://www.eerg.polimi.it/micene.php.

IPCC. 2001. "Climate Change 2001: Working Group I: The Scientific Basis. Intergovernmental Panel on Climate Change", http://www.ipcc.ch/pub/online.htm.

Mc Mahon J, Pickle S. 1995. "Appliance efficiency standards", CBS Newsletter.

Official Journal of the European Union. Directive 2004/8/EC of the European Parliament and of the Council. 2004. "The promotion of cogeneration based on the useful heat demand in the internal energy market and amending Directive 92/42/EEC".

Possidente R, Roselli C, Sasso M, Sibilio S. 2004. "On site analysis of a gas driven microcogenerator incorporating heat pump", Proc. of International Gas Research Conference, Vancouver, Canada, 2-4 November 2004.

Possidente R, Roselli C, Sasso M, Sibilio S. 2005. "Analisi energetica, economica e di impatto ambientale di una pompa di calore alimentata da un microcogeneratore", Proc. of Congresso nazionale ATI, Rome, Italy, (In Italian), September 2005.

Possidente R, Roselli C, Sasso M, Sibilio S. 2005. "3-E analysis of a thermally activated heat pump", Proc. of ASME IMECE, Orlando, USA, 5-11 November 2005.

Possidente R, Roselli C, Sasso M, Sibilio S. 2006. "Gas drive microcogenerator incorporating heat pump for residential application", Proc. of IRHACE - Innovative Equipment and Systems for Comfort and Food Preservation, , Auckland, New Zealand, February 16-18 2006.

Possidente R, Roselli C, Sasso M, Sibilio S. 2006. "Gas Driven Micro-Cogenerator Incorporating Heat Pump: Exergetic, Economic and Environmental Analysis", Proc. of ESDA 2006, 8th Biennial ASME Conf. on Engineering Systems Design and Analysis, Torino, Italy, July 4-7 2006

Possidente R, Roselli C, Sasso M, Sibilio S. 2006. "Experimental analysis of micro-cogeneration units based on reciprocating internal combustion engine", *Energy and Buildings,* Volume 38, pp. 1417-1422.

Possidente R, Roselli C, Sasso M, Sibilio S. 2007. Assessment of micro-cogeneration potential for domestic trigeneration, *International Journal of Environmental Technology and Management*, Inderscience Enterprises, Volume 7, Issue 1/2, pp. 147-164.

Sasso M, Sibilio S, Vanoli L. 2003. "Energetic and environmental analysis of a domestic scale heat pump driven by a micro-cogenerator", Proc. of the EUROTHERM Seminar N. 72: Thermodynamics, heat and Mass Transfer of refrigeration Machines and Heat Pumps, Editors: J. M. Corberan, R. Royo, pp. 167-172, ISBN 84-931209-8-7, Valencia, Spain, March-April 2003.

Sasso M, Sibilio S, Vanoli L. 2003. "Micro combined heat & power (MCHP) in residential and light commercial applications", *Applied Thermal Engineering*, Volume 23, pp. 1247–1259.

SAVE. 1998. "Analysis of energy efficiency of domestic storage water heaters", EU SAVE Project Final Report.

Snam Rete GAS. 2002. "Riscaldamento e ACS per utenze domestiche", Final Report, (in Italian).

Tecnocasa srl. 2007. AISIN GECC60A1, see www.tecno-casa.com.