Experimental Assessment of Energy Performance and Emissions of a Residential Microcogenerator

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Abstract

Microcogeneration systems, if correctly sized, managed and operated, can guarantee sensible primary energy savings and greenhouse gas emissions reductions in the residential sector. In this paper, the results of experimental tests carried out on a microcogenerator (5.5 kW electric power and 14.8 kW thermal power) based on a natural gas fuelled internal combustion engine, integrated with a condensing boiler, have been analyzed. The tests were aimed at assessing the technical feasibility of the microcogeneration plant for residential applications, and at evaluating the possible energy and emissions savings it can achieve with respect to a benchmark scenario, based on separate "production" of electric and thermal energy. The tests have been performed at Institute for Energy Economy and Application Technology (IfE) of Technical University of Munich (Germany).

The test facility allowed to simulate the thermal energy requirements of a real residential application, represented by a Multi Family House consisting of 10 apartments, and to evaluate the energy flows of the conversion devices in actual operating conditions. Four type days, characteristic of Mediterranean climatic conditions, have been used to define space heating and domestic hot water user's requirements.

Experimental tests have been performed to implement energy and environmental analysis, comparing the system consisting of cogenerator and integration boiler with a reference system. Results showed that the former system can achieve a primary energy saving of about 6%, and CO_2 equivalent emissions reduction of about 12%.

Finally, the algorithm defined by the European Directive on the promotion of high efficiency cogeneration has been implemented; it demonstrated that the primary energy saving is well above the limit value prescribed by the Directive. Therefore the cogeneration plant can access support mechanisms which can help to achieve the economic feasibility of the system, besides energy and environmental benefits.

Keywords: microcogenerator, experimental assessment, energy, greenhouse gas emissions, residential sector

1. Introduction

Nowadays buildings represent about 30-40% of final energy consumption in industrialized countries, overtaking other sectors such as industry and transportation. In the residential sector, energy consumption is mainly related to air-conditioning requirements, both in summer and winter, domestic hot water (DHW) production, and electric loads (lights, office automation, etc.).

Cogeneration is an alternative technology to the conventionally adopted solutions, which are the external grid for electricity requirements, and centralized or autonomous fossil fuelled boilers, to provide thermal energy for space heating and DHW.

The installation of small scale cogeneration systems (MCHP, Micro Combined Heat and Power) in buildings is obviously more expensive than conventional technologies, therefore MCHPs have to achieve lower primary energy requirements and operating costs reductions to be competitive, as well as lower greenhouse gas (GHG) emissions, to be supported and incentivized by Governments.

The present trend to shift from the centralized production to the distributed generation scenario is attracting considerable R&D effort on experimental analysis and simulation of both MCHP (Roselli, Sasso, Sibilio, & Tzscheutschler, 2011) and MCCHP (Micro Combined Cooling Heating and Power) systems (Angrisani, Roselli, Sasso,

& Tariello, 2014), with electric power lower than 15 kW.

A key factor for distributed generation technologies, besides the high potential in reducing primary energy consumption and GHG emissions, is the decrease in energy losses related to: distribution of energy vectors over long distances (distributed generators provide energy on-site); operation at partial load of higher size equipment; use of intermediate equipment between generation and final use of energy. On the other hand, miniaturization of energy conversion devices often leads to an efficiency reduction (due to the so-called "size effect"), and this obviously has a negative effect on energy, economic and emissions performance of distributed generators (Angrisani, Roselli, & Sasso, 2012).

The most attracting sectors for MCHP and MCCHP systems are currently tertiary and light commercial applications (Piacentino & Cardona, 2008); nevertheless, in the brief-to-medium period, interesting market perspectives can be expected for residential buildings too (Pehnt et al., 2010), as the very high number of potential users and the on-going increase of available products could in few years determine cumulative installed powers much higher than in the tertiary sector.

For example in single family houses, the aim of R&D activities on MCHP is to gradually substitute natural gas boilers with devices having similar characteristics of safety, ease of use and installation, but which are capable of producing both thermal and electric energy; generally, technical feasibility can be achieved only if cogenerated heat is never dissipated and electricity is produced during peak hours, when the purchase cost from the grid is higher.

Nowadays, reciprocating internal combustion engine based systems represent the most widespread technology for small scale cogeneration, due to several advantages, such as small installation space, high electric and thermal efficiencies, quite low noise and vibrations, low maintenance cost, low specific investment cost and long life service. The Stirling engine, with respect to internal combustion engines, is not fully developed yet, and it is not widely used, due to low electric efficiency, high pressure level of working gas, high specific investment cost and quite long warm-up periods (Angrisani et al., 2012).

To achieve energy and greenhouse gas savings, microcogeneration systems need to be correctly sized, managed and operated. To this aim, University of Sannio, in cooperation with the Institute for Energy Economy and Application Technology (IfE) of Technical University of Munich (Germany), carried out experimental tests aimed at assessing the performance of an MCHP system in a residential building. The microcogenerator is based on a natural gas fuelled internal combustion engine; it produces 5.5 kW electric and 14.8 kW thermal power, and it is integrated with a natural gas condensing boiler. The tests were aimed at assessing the technical feasibility of a microcogeneration plant for residential applications, and at evaluating the possible energy and emissions savings it can achieve with respect to typically adopted technologies, based on separate "production" of electric and thermal energy. Results of the tests allowed to evaluate the daily and annual energy performance of the combined generation system installed at a reference building, and to evaluate the potential of energy consumption and emissions reductions with respect to a benchmark scenario.

2. Method

2.1 Building Definition

The MCHP unit is assumed to be installed at a multifamily house (MFH) consisting of 10 apartments, located in Naples, a city in the South of Italy with 1034 degree days.

Table 1. Building data

Floor area [m^2]	1216
Heated volume [m^3]	3176
Mean headroom [m]	2.61
Number of storeys [-]	4
Surface to Volume ratio [-]	0.447
Construction period	1961-1975
Number of occupants [-]	30
Space heating thermal energy requirement [kWh/m^2/year]	46.5
DHW thermal energy requirement [kWh/day]	42.9

In Table 1, characteristic data and energy requirement of the investigated building are reported, while in Table 2 heat transfer properties of the opaque and transparent devices of the building envelope are shown, namely surface, overall

heat transfer coefficient *U* and solar gain *g*.

It was not possible to perform one year-long experimental tests, therefore the type days approach was used: four type days, which represented the different climatic conditions normally occurring at the installation site, were used for testing purposes. Energy and emission assessments were then extended on an annual basis, considering the number of yearly occurrences of each type day.

Table 2. Properties of the building envelope

	Opaque devices			Windows		
	Roof	External walls	Cellar	North	South	East/West
Surface [m^2]	304	637	304	69	76	14
U [W/m^{2}K]	2.30	1.20	0.297	2.83	2.83	2.83
g [-]	-	-	-	0.76	0.76	0.76

The following type days were defined:

• 1: winter (January and February);

• 2: intermediate with space heating requirements (November 15 – December 31; March);

• 3: intermediate without space heating requirements (April, May and September 16 – November 14);

• 4: summer (June 1 – September 15).

Type days were defined considering the period of allowed operation of the space heating system, specified by Italian legislation (November 15th to March 31st), as well as hourly temperature values. No differences were defined between weekends and weekdays.
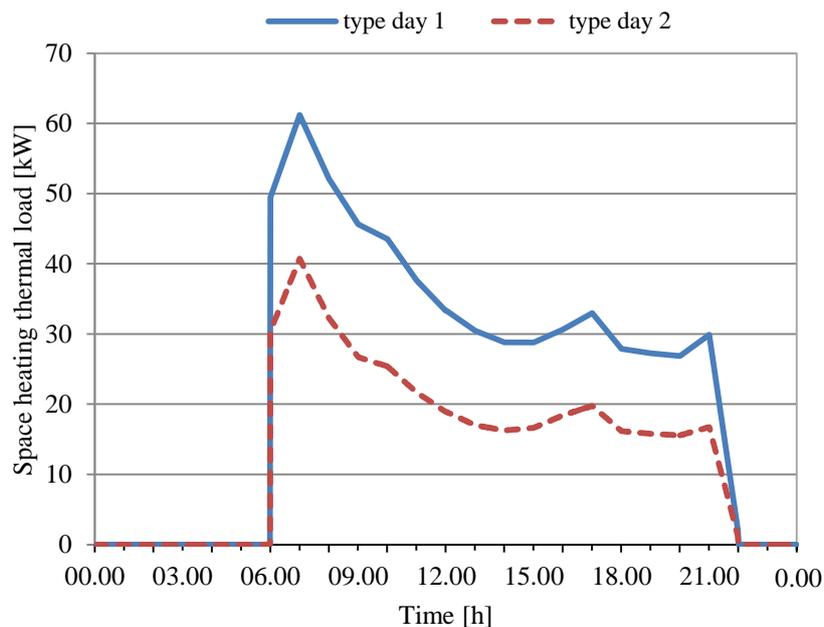
Figure 1. Space heating thermal load profiles

Thermal load profile for space heating requirements (type days 1 and 2) were defined by means of dynamic simulations of the building through TRNBuild interface (TRNSYS 17, 2010); they are shown in Figure 1. The typical early morning peak, when a very high thermal power is required to increase the indoor air temperature to the set-point value of 20 °C, was obtained. The load then reduces during the day, with a minimum value at about 14.00 h, when solar gain is maximum.
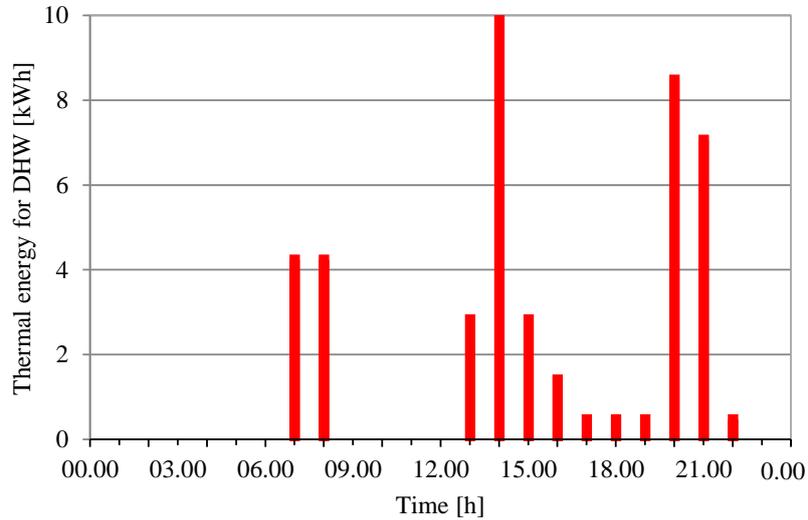
Figure 2. Thermal energy requirements for DHW (same profile for type days 2 and 3)

Thermal energy demand for DHW, shown in Figure 2 (the same profile for type days 2 and 3, the profile for the other type days is not shown for major clarity), has been defined considering a requirement of 40 l/(day·occupant).

2.2 Performance assessment

For the MCHP system, the following energy performance parameters were used:

$$\eta_{el} = \frac{E_{el,CHP}}{E_{p,CHP}} \qquad (1)$$

$$\eta_{th} = \frac{E_{th,CHP}}{E_{p,CHP}} \qquad (2)$$

$$PER = \frac{E_{el,CHP} + E_{th,CHP}}{E_{p,CHP}} \qquad (3)$$

where $E_{el,CHP}$, $E_{th,CHP}$ and $E_{p,CHP}$ are electric energy output, thermal energy output and primary energy input of the MCHP system and η_{el}, η_{th} and *PER* (Primary Energy Ratio) are electric, thermal and overall efficiency, respectively.

Energy and emissions performance of the proposed system (MCHP and integration boiler, Proposed System, PS) were compared, considering equal final energy provided to the user, with a reference scenario (Traditional System, TS), based on separate "production" of electric and thermal energy, which is conventionally adopted for energy demands supply. The TS, in each type day, has to ensure the same space heating and DHW demands provided to the building by the PS and it has to draw from the electric grid the same amount of electricity generated by the MCHP.

The assumed TS consisted of:

• a condensing natural gas fuelled boiler, supplying thermal energy for space heating and DHW, with a nominal efficiency $\eta_{th,ref} = 102\%$, based on LHV (Lower Heating Value);

• national Italian electric grid, with an average efficiency $\eta_{el,ref} = 42\%$, including transmission and distribution losses (Angrisani et al., 2014).

More details about the hydraulic schemes of both PS and TS are given in Section 2.3.

The energy comparison between PS and TS was performed by means of the *FESR* parameter (Fuel Energy Saving Ratio), defined as (Angrisani et al., 2014):

$$FESR = \frac{E_p^{TS} - E_p^{PS}}{E_p^{TS}} \qquad (4)$$

where E_p^{TS} and E_p^{PS} are the primary energy input of TS and PS, respectively.

For the emissions comparison the equivalent CO_2 avoided emissions was used:

$$\Delta CO_{2,eq} = \left(m_{CO_2,eq}^{TS} - m_{CO_2,eq}^{PS}\right) \Big/ m_{CO_2,eq}^{TS} \tag{5}$$

where the emissions of PS ($m_{CO_2,eq}^{PS}$) and TS ($m_{CO_2,eq}^{TS}$) were evaluated considering (Angrisani et al., 2014):

- equivalent carbon dioxide specific emission factors of Italian electric grid (ratio of equivalent CO_2 emissions to electric energy output) equal to 573 $g_{CO2,eq}$/kWh$_{el}$;
- equivalent carbon dioxide emission factor of natural gas (ratio of equivalent CO_2 emissions to primary energy input) equal to 207 $g_{CO2,eq}$/kWh$_p$.

A further analysis was based on the Directive on the promotion of cogeneration (Directive 2004/8/EC), which defines the *PES* (Primary Energy Saving) index, as:

$$PES = 1 - \frac{E_{p,CHP}}{\dfrac{E_{el,CHP}^*}{\eta_{el,ref}} + \dfrac{E_{th,CHP}}{\eta_{th,ref}}} \tag{6}$$

$E_{el,CHP}^*$ is the cogenerated electricity, and it coincides with the overall production from the MCHP ($E_{el,CHP}$) if the

PER is higher than a limiting value (75% for internal combustion engine based cogenerators). The symbols $\eta_{el,ref}$ and $\eta_{th,ref}$ are the harmonised efficiency reference values for separate production of electricity and heat, respectively. European Commission provides a method to evaluate harmonised values for $\eta_{el,ref}$ and $\eta_{th,ref}$ (Commission Decision of 21 December 2006, Commission implementing decision of 19 December 2011). In particular, $\eta_{el,ref}$ depends on factors such as: installation year of the cogeneration unit, climatic conditions (average ambient temperature), fuel used and a correction factor '*p*', which depends on the share of electricity used on-site and on the voltage level, and which takes into account the avoided grid losses due to decentralized production. On the other hand, $\eta_{th,ref}$ depends on the fuel and the way the available thermal energy is exploited (direct use of exhaust gases or "production" of steam/hot water).

With respect to the MCHP unit considered, the evaluation of *PES* was carried out considering that:

• the prime mover is a reciprocating internal combustion engine;

• thermal energy recovered by the MCHP is used to produce hot water;

• the fuel is natural gas;

• the installation year is 2014;

• the average ambient temperature is 16.04 °C (0.104%-point reduction of $\eta_{el,ref}$ with respect to a reference temperature of 15 ℃);

• the electricity is produced at low voltage (<400 V, $p = 0.860$ for electricity consumed on-site, $p = 0.925$ for exported electricity).

With the above listed information, the Commission Decision provides $\eta_{th,ref} = 90\%$ and a base value of $\eta_{el,ref} = 52.5\%$.

When the electric rated power of CHP unit is less than 50 kW, the *PES* has to be higher than zero in order to achieve the "high efficiency cogeneration" qualification. High efficiency cogeneration units can access several benefits, such as: distribution priority, subsidies on gas price, net metering (for CHP units with electric power lower than 200 kW), revenues related to white certificates (energy efficiency credits) mechanism, investment subsidies (guarantee or revolving funds, public grants) up to 40% of the investment cost for plants with electric power up to 200 kW. These incentives can promote the economic feasibility of MCHP systems with respect to traditional technologies.

2.3 The Test Facility

The test facility allows to simulate thermal energy demands for space heating and DHW of a residential building (MFH) and to evaluate energy flows of energy conversion devices in actual operating conditions.
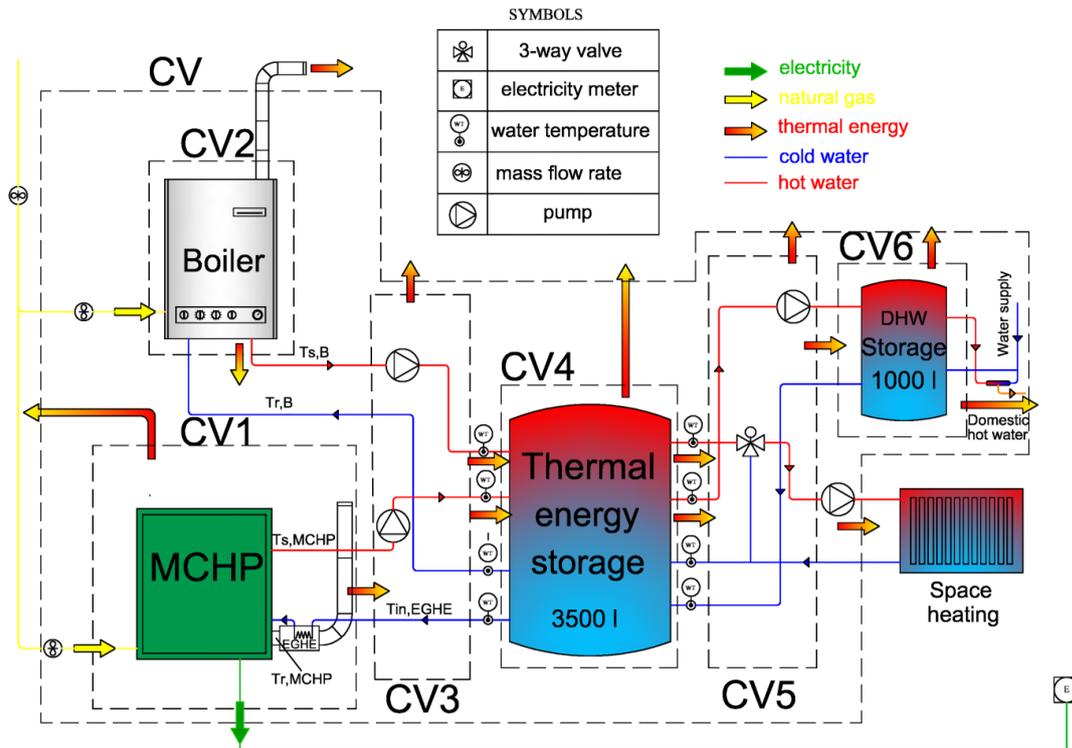
Figure 3. The test facility

Figure 3 shows the layout of the test facility and the different control volumes (CV) defined for the energy balances.

The following main components are present (Arndt, Mauch, Mühlbacher, Tzscheutschler, & Geiger, 2008):

- a MCHP (CV1);
- a condensing boiler for thermal integration (CV2), fuelled by natural gas and with a nominal thermal efficiency of 102%, based on LHV;
- a 3500 l thermal energy storage (CV4);
- a 1000 l DHW storage (CV6);
- a simulator of thermal energy demands for space heating of the building;
- a simulator of thermal energy demands for DHW;
- auxiliaries (pumps, 3-way valves, etc.);
- sensors for water temperature, water and natural gas mass flow rates.

CV3 contains the pipes between the energy conversion devices (MCHP and boiler) and the main thermal storage (CV4), while CV5 contains the pipes between CV4 and energy demands (space heating and DHW storage). The overall control volume (CV) contains the whole test facility.

The space heating simulator consists of several vessels with different capacities, which simulate thermal loads as well as thermal inertia and losses of radiators and distribution pipes within the building. In particular, energy related to thermal loads and losses is simulated by means of heat exchangers interacting with a cooling circuit. Thermal energy demands for DHW are simulated by means of taps, drawing water from the related 1000 l storage.

The MCHP is heat-led, i.e. the unit follows thermal energy demands of the buildings, while cogenerated electricity can be consumed on-site or exported to the grid.

When water temperature inside the main storage falls below the set-point value, the MCHP starts providing thermal energy to CV4; when water temperature in the storage is higher than the set-point, the MCHP stops. When water temperature entering the MCHP ($T_{r,MCHP}$) is higher than 65 °C, the MCHP also stops, as this quite high value of return

temperature points out a very low thermal demand from the user.

When water temperature required by the heating circuit is higher than water in the storage and the MCHP is already operating, the integration boiler activates providing thermal energy shortage.

Table 3. Nominal characteristics of the MCHP

Engine	Internal combustion engine
Fuel	Natural gas
P_{el} [kW]	5.5
P_{th} [kW]	14.8
P_p [kW]	20.5
η_{el} [-]	0.27
η_{th} [-]	0.72
PER [-]	0.99

In Table 3, the nominal characteristics of the tested MCHP are reported. The unit is equipped with an optional heat exchanger (Exhaust Gas Heat Exchanger, EGHE in Figure 3), externally installed, which allows a further thermal energy recovery from the condensation of water in exhaust gases, which have a temperature of about 150 ℃ at the exit of the MCHP; by means of the EGHE, with a water temperature from the storage at 35 ℃, exhaust gases can be cooled down to about 55 ℃, condensing about half the water contained in the gases, similarly to a condensing boiler.

The recovered latent heat from water condensation, which adds to thermal recovery from engine and from electric generator cooling, allows obtaining very high values of thermal efficiency and PER.

The TS, consisting of a condensing natural gas fuelled boiler and the national Italian electric grid, has a layout similar to that of Fig. 3, the differences are related to the absence of the control volumes CV1, CV3 and CV4. The boiler in TS is directly connected, by means of CV5, to the DHW storage and to the space heating circuit.

3. Results

In Figure 4, the supply and return water temperature from the MCHP ($T_{s,MCHP}$ and $T_{r,MCHP}$, respectively), supply water temperature from the boiler ($T_{s,B}$), as well as the temperature of water entering the EGHE ($T_{in,EGHE}$) are shown for type day 1. Starting from about 13:30, even if thermal power provided by the MCHP is lower than user's requirement, an intermittent operation of the cogenerator is established. This is due to the hydraulic layout of the test facility (parallel connection of MCHP and boiler to the main storage). Furthermore, the integration boiler provides a thermal power of at least 25 kW, which is almost enough to cover user's demands during the periods with low energy requirements; this causes an increase of $T_{r,MCHP}$ and the consequent intermittent operation of the MCHP. This anomalous circumstance does not determine a significant reduction of daily energy performance of the microcogenerator, as the operation stoppages are quite brief (about 70 minutes per day).
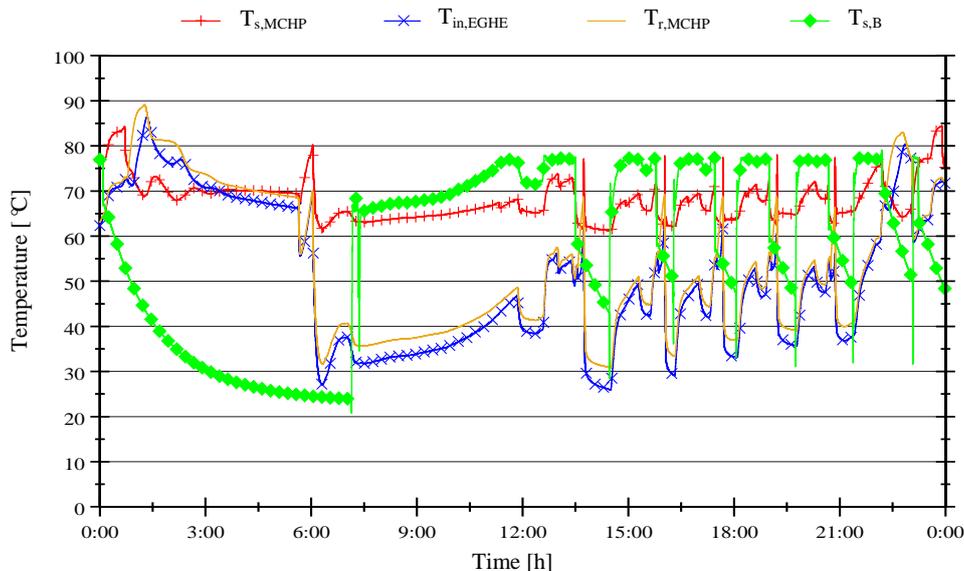
Figure 4. Temperatures for type day 1
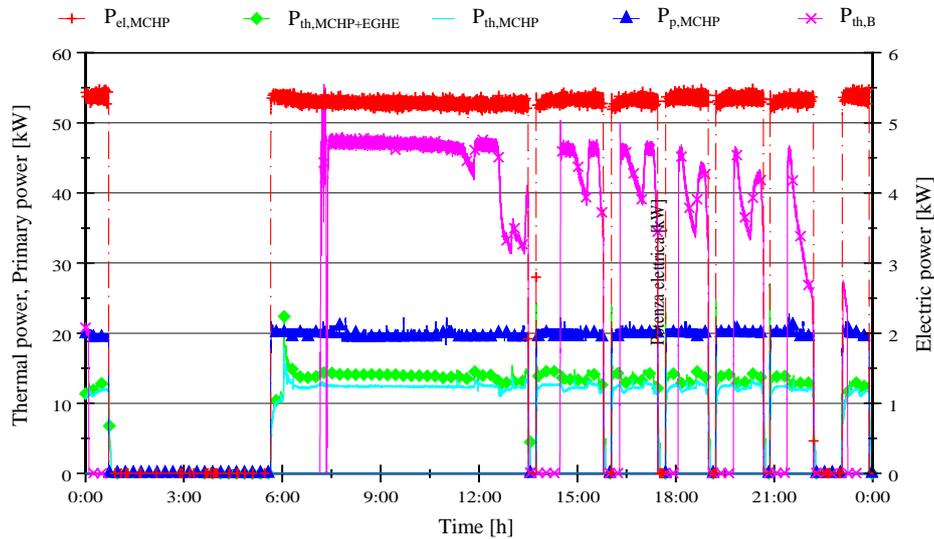
Figure 5. Thermal, electric and primary powers for type day 1

Thermal power supplied by the MCHP (with and without the contribution from the EGHE) and by the boiler, as well as electric power output and primary power input to the MCHP are shown, for type day 1 (winter) in Figure 5. The boiler provides a very high thermal power in the early morning, when there is high thermal energy demand for space heating and DHW. The MCHP provides net electric power output constantly equal to about 5.3 kW, as it is a non-modulating unit; the self-consumption of MCHP auxiliaries is about 200 W.

The EGHE provides a thermal power of about 2 kW, and this contribution rises when $T_{in,EGHE}$ reduces (Figure 4), as the condensation effect is enhanced.

As regards primary power input to the MCHP and to the boiler, the temperature and pressure of natural gas are measured, in order to correlate its actual LHV to the standard value. An average value of 10.0 kWh/Nm^3 has been assumed for the LHV.
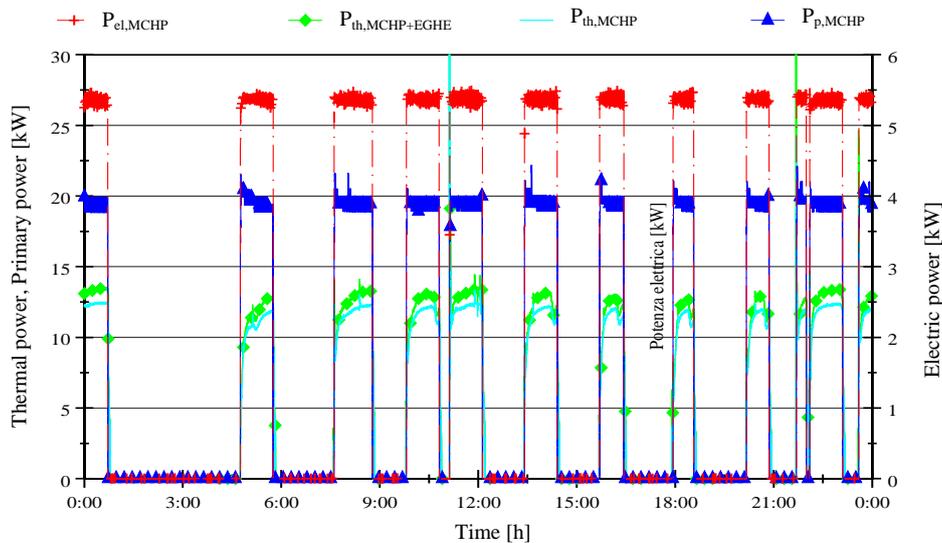
Figure 6. Thermal, electric and primary powers for type day 4

A similar analysis has been also performed for the other type days. In Figure 6 the main electric and thermal power for

type day 4 (summer) are shown. During summer, the MCHP can provide the whole thermal energy required, as user's demand is related to DHW only, and the boiler never activates.
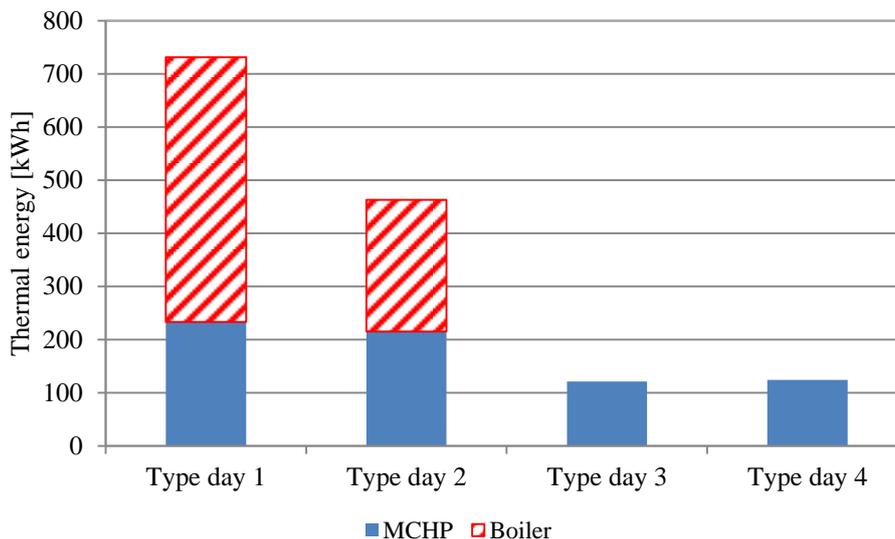
Figure 7. MCHP and boiler contribution to thermal energy demands for each type day

In Figure 7 the contribution of the MCHP and of the boiler to thermal energy requirements of the user for each type day is shown. The MCHP provides about 31.9% and 46.4% of the required thermal energy during type day 1 and 2, respectively, and about 48.2% on an annual basis. Therefore, the MCHP is not the main contributor to the thermal energy demand, especially during winter, as its size was chosen to maximize the number of operating hours during activation period of the space heating plant (November 15th to March 31st, type days 1 and 2). In fact, nominal thermal power of the microcogenerator (14.8 kW) is lower than the minimum thermal power required for space heating purposes during type day 2 (Figure 1).

Table 4. Daily energy balance for the MCHP in each type day

	Type day 1	Type day 2	Type day 3	Type day 4
E_p [kWh]	336	300	185	190
E_{el} [kWh]	90.7	81.0	50.0	51.3
E_{th} [kWh]	233	215	121	124
t_{MCHP} [h]	16.9	15.2	9.40	9.66
η_{el} [-]	0.270	0.270	0.270	0.270
η_{th} [-]	0.693	0.717	0.654	0.653
PER [-]	0.963	0.987	0.924	0.923

In Table 4, the main energy flows related to the MCHP (CV1) on a daily basis are reported. Electric efficiency is equal to the nominal value, as the related transient losses are negligible, while thermal efficiency, and accordingly the PER, are lower than the nominal values. In particular, the lower values of η_{th} and PER are obtained during type days 3 and 4, due to the thermal losses related to cycling operation of the MCHP (higher number of start and stop, Figure 6, with respect to winter type day, Figure 5). The reduction of thermal energy requirements in type days 3 and 4 determines an abatement of MCHP operating hours (t_{MCHP}, Table 4) and the disappearance of the boiler energy contribution (Figure 7).

The MCHP achieves efficiencies values very similar to the nominal ones (Table 3) during type days 1 and 2, when the space heating thermal load allows the cogenerator to work at stationary full thermal load conditions for several continuative hours. The best performance are achieved in type day 2 (intermediate with space heating requirements), as the contribution of the boiler is lower than in type day 1 (Figure 7), therefore a reduction of the intermittent operation of the MCHP is obtained.

On an annual basis, the *PER* of the MCHP is equal to 95.5%, with more than 4300 overall operating hours per year, which is a very favourable value for residential small scale cogeneration.

Table 5. Annual energy balance for each control volume

	CV1	CV2	CV3	CV4	CV5	CV6	CV
E_p [MWh]	85.9	47.8	-	-	-	-	133.7
$E_{th,in}$ [MWh]	-	-	107.1	101.6	95.5	31.7	-
$E_{th,out}$ [MWh]	58.4	48.7	101.6	95.5	87.6	16.8	73.4
$E_{th,loss}$ [MWh]	4.3	-	5.50	6.10	7.90	14.9	38.6
E_{el} [MWh]	23.2	-	-	-	-	-	23.2

In Table 5 the annual energy balance for the control volumes defined in Figure 1 are reported. E_p represents primary energy input, $E_{th,in}$ is thermal energy input, $E_{th,out}$ is thermal energy output, $E_{th,loss}$ is thermal energy lost and E_{el} is electric energy output. The boiler (CV2), thanks to the condensation of exhaust gases, provides a thermal energy output higher than primary energy input, as the latter is based on LHV, not HHV (Higher Heating Value). Therefore, no thermal losses have been assumed for CV2, even if they are higher than zero but impossible to be evaluated within the test facility used for the tests.

Regarding CV6, $E_{th,loss}$ takes into account thermal energy losses of both the DHW storage and of the recirculation circuit, which is a closed loop, connected to the DHW tank, where the fluid is continuously pumped, so that even the users most distant from the tank itself can instantly have hot water available at any time. As regards the overall control volume (CV), $E_{th,out}$ is the sum of thermal energy for DHW ($E_{th,out}$ from CV6) and for space heating ($E_{th}^{SH} = 56.6$ MWh).
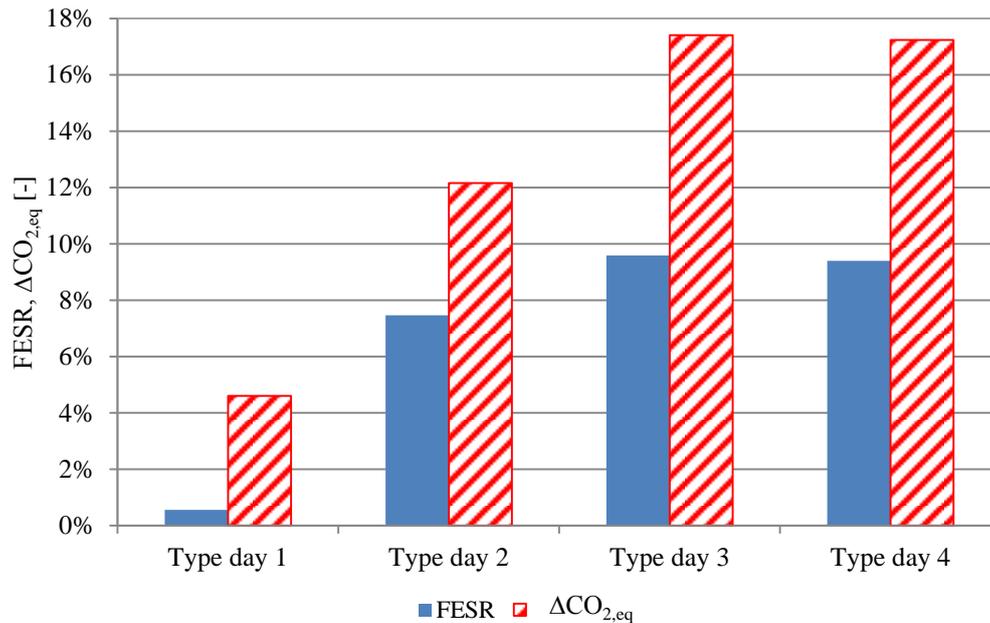
Figure 8. *FESR* and $\Delta CO_{2,eq}$ for each type day.

To apply Eq. 4, the primary energy input of PS (E_p^{PS}) and TS (E_p^{TS}) have to be evaluated with the following equations:

$$E_p^{PS} = E_p^{CV1} + E_p^{CV2} \tag{7}$$

$$E_p^{TS} = \frac{E_{el}^{CV1}}{\eta_{el,ref}} + \frac{E_{th,in}^{CV6} + E_{th}^{SH}}{\eta_{th,ref}} \tag{8}$$

Figure 8 shows the *FESR* and $\Delta CO_{2,eq}$ parameters for the four type days. Both parameters are positive for any type day, and they vary from a minimum for type day 1 (0.6% and 4.6%, respectively) to a maximum for type days 3 and 4 (about 9% and 17%, respectively). The low values of the energy and emissions parameters during the winter type day are due to the very high contribution of the condensing boiler in the PS to the thermal demands of the user, while during type days 3 and 4 the boiler is always switched off, and the MCHP achieves the highest energy saving. On an annual basis, the *FESR* is about 5.8%, while the $\Delta CO_{2,eq}$ is about 11.4%.

These results justify the support given to cogeneration by European Union, according to which a wide diffusion of cogeneration could significantly contribute to the greenhouse gas emissions reduction towards 2020.

As regards the application of the European Directive (Directive 2004/8/EC), the *PER* of the MCHP on annual basis is about 95.8%, which is higher than the limit value for internal combustion engine based systems (75%); therefore $E_{el,CHP}^* = E_{el,CHP}$ in equation 6.

Figure 9 shows the *PES* as a function of the ratio between electricity consumed on-site to overall production from the MCHP. The constraint defined by the Directive (*PES* > 0) is abundantly met by the investigated MCHP, even in the worst case where no electricity from the cogenerator is consumed within the simulated building. The *PES* rises with the share of electricity consumed on-site, as the correction factor '*p*' defined by European Directive for $\eta_{el,ref}$ is lower if electric energy from the MCHP is consumed on-site, to take into account the avoided grid losses related to electricity distribution. Therefore, the investigated microcogenerator is a high efficiency cogeneration unit and it can access the several benefits defined in section 2.2.
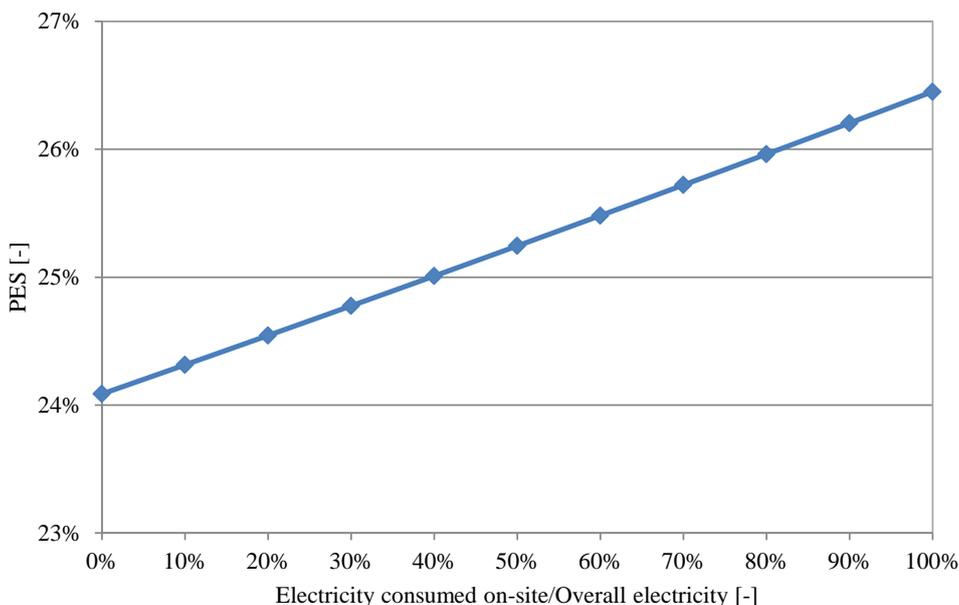
Figure 9. PES as a function of the ratio between electricity consumed on-site to overall production from the MCHP

4. Discussion

In this paper, a microcogenerator for residential users have been investigated at a test facility of the Institute for Energy Economy and Application Technology (IfE) of Technical University of Munich (Germany). It is based on a natural gas fuelled internal combustion engine, with 5.5 kW and 14.8 kW electric and thermal power, respectively, and it is integrated with a condensing boiler. The test facility allows to simulate thermal energy demands for space heating and domestic hot water purposes of a multifamily house consisting of ten apartments, and to evaluate the main energy flows of the energy conversion devices in actual operating conditions.

The performance assessment of the microcogeneration plant has been performed by means of experimental tests for four type days (winter, intermediate – with and without space heating demands – and summer), representing the climatic conditions of the installation site (Naples, Italy).

The energy analysis on a daily basis showed electric, thermal and overall efficiencies of the MCHP very close to the nominal values; the condensing boiler strongly contributed to user's thermal energy requirements during winter type day, due to the high demands for space heating purposes. Boiler contribution went zero when thermal energy was required for domestic hot water only.

The parallel connection of the MCHP and of the boiler to the main thermal energy storage did not allow an optimal management of the microcogenerator. In fact the boiler provided thermal power almost enough to cover user's needs during low demand hours; this caused an increase of return temperature from the storage to the MCHP and its consequent intermittent operation. Nevertheless, this circumstance did not determine a significant reduction of energy performance of the microcogenerator, but it could determine a reduction of the technical life of the device. Further tests should be performed to assess the performance of the system with alternative hydraulic schemes, as those described in Arndt et al., 2007.

Experimental data have been used to perform an energy and greenhouse gas emissions analysis, with a comparison between the microcogeneration plant (proposed system), with a reference traditional system, consisting of a natural gas fuelled condensing boiler and the national electric grid. The Fuel Energy Saving Ratio (*FESR*) and the equivalent CO_2 avoided emissions ($\Delta CO_{2,eq}$) are the parameters used for the energy and emissions analysis, respectively.

Both parameters were positive for any type day: the *FESR* varied from a minimum of 0.5% to a maximum of 9%, while the $\Delta CO_{2,eq}$ ranged from 4.6% to 17%. On an annual basis, the *FESR* was about 5.8%, while the $\Delta CO_{2,eq}$ was about 11.4%.

Finally, the calculation method defined by the European Directive on the promotion of cogeneration was applied. The reference harmonised values of thermal and electric efficiency were calculated; the results showed that the Primary Energy Saving (*PES*) was positive (above 24%), and it raised with the ratio between electricity consumed on-site to overall production from the MCHP. Therefore, the experimentally tested device is a high efficiency cogeneration system, and it can access all support mechanisms defined by European and Italian governments to promote the economic feasibility of this technology.

In conclusion, cogeneration is an energy efficiency measure with a high potential of energy consumption and emissions reductions also in residential applications (microcogeneration), provided that recovered thermal energy is completely used and never wasted.

Nomenclature

E	energy, kWh
FESR	Fuel Energy Saving Ratio, -
g	solar gain, -
LHV	Lower Heating Value, kWh/Nm^3
$m_{CO_2,eq}$	mass of equivalent CO_2, kg
p	correction factor, -
P	power, kW
PER	Primary Energy Ratio, -
PES	Primary Energy Saving, -
t	time, h
T	temperature, ℃
U	overall heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
$\Delta CO_{2,eq}$	equivalent CO_2 avoided emissions, -
η	efficiency, -
CV	Control Volume
DHW	Domestic Hot Water
EGHE	Exhaust Gas Heat Exchanger
GHG	Greenhouse Gas
MCHP	Micro Combined Heat and Power
MCCHP	Micro Combined Cooling Heating and Power

MFH	Multifamily House
PS	Proposed System
TS	Traditional System

Subscripts

B	boiler
CHP	Combined Heat and Power
EGHE	Exhaust Gas Heat Exchanger
el	electric
in	inlet
loss	losses
MCHP	Micro Combined Heat and Power
out	outlet
p	primary
r	return
ref	reference
s	supply
th	thermal

Superscripts

CV	Control Volume
PS	Proposed System
SH	Space Heating
TS	Traditional System

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