Chapter 36
The Micro-cogeneration and Emission Control and Related Utilization Field

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Abstract Micro-cogeneration is a developed technology aiming to produce electricity and heat close to the final users, with the potential, if designed and operated correctly, to reduce both the primary energy consumption as well as the associated greenhouse gas emissions when compared to traditional energy supply systems based on separate energy production. The distributed nature of this generation technology has the additional advantages of (i) reducing electrical transmission and distribution losses, (ii) alleviating the peak demands on the central power plants, and (iii) diversifying the electrical energy production, thus improving the security of energy supply. Micro-cogeneration devices are used to meet both electrical requirements and heat demands (for space heating and/or hot water production) of a building; they can be also combined with small-scale thermally fed or mechanically/electrically driven cooling systems. Many micro-cogeneration units are already commercialized in different countries (such as Japan, Germany, United Kingdom, etc.) and in recent years several researches have been carried out in order to advance the design, operation, and analysis of this technology. Currently the use of commercial micro-cogeneration units in applications such as hospitals, leisure facilities, hotels, or institutional buildings is well established. The residential cogeneration industry is in a rapid state of development; the market remains not fully mature, but interest in the technology from manufacturers, energy utilities, and government agencies remains strong.

Keywords Cogeneration · Micro-cogeneration · Trigeneration · Micro-trigeneration · Distributed polygeneration · Internal combustion engine · Stirling engine · Fuel cell · Microturbine · Photovoltaic thermal · Energy · Energy saving · Environment · Sustainable development · Sustainability · Electric heat pumps ·

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Absorption heat pumps · Adsorption heat pump · Electric vehicles · Renewable sources · Load sharing

Nomenclature

Latin Letters

ABHP	ABsorption heat pump
ADHP	ADsorption heat pump
AFC	Alkaline fuel cell
CHP	Combined heat and power
COP	Coefficient of performance
D	Depth (mm)
DCS	Desiccant cooling system
DHW	Domestic hot water
DMFC	Direct methanol fuel cell
DW	Desiccant wheel
E	Energy (kWh, MWh)
EHP	Electric heat pump
EV	Electric vehicle
F_{mchp}	Fraction of thermal energy supplied by the MCHP
FC	Fuel cells
GHG	Greenhouse gases
GSHP	Ground source heat pump
H	Height (mm)
HVAC	Heating, ventilation, and air conditioning
ICE	Internal combustion engines
L	Length (mm)
LPG	Liquefied petroleum gas
LHV	Lower heating value (kJ/kg)
MCFC	Molten carbonate fuel cell
MCHP	Micro-combined heat and power
MCCHP	Micro-combined cooling heat and power
MT	Microturbines
NZEB	Nearly zero energy building
P	Power (kW)
PAFC	Phosphoric acid fuel cell
PEMFC	Proton exchange membrane fuel cell
PER	Primary energy ratio (%)
PES	Primary energy saving (%)
PV	Photovoltaic
PVT	Photovoltaic thermal
SC	Solar collectors
SE	Stirling engines
SOFC	Solid oxide fuel cell
SPB	Simple payback period (years)

TES	Thermal energy storage
THP	Thermally activated heat pump
TPV	Thermal photovoltaic

Greek Letters

Efficiency

CO_2	Avoided carbon dioxide equivalent emissions (%)

Subscripts

B	Boiler
cool	Cooling
el	Electric
GRID	Central electric grid
MCHP	Micro-Combined Heat and Power
mean	Average
th	Thermal

Chemical Compounds

CO	Carbon monoxide
CO_2	Carbon dioxide
H_2O	Water
Li-Br	Lithium bromide
Li–Cl	Lithium chloride
NH_3	Ammonia
NO_x	Nitrogen oxides
SO_x	Sulphur oxides

1 Introduction: Operation, Benefits, and Drawbacks of MCHP Systems

The electricity demand of buildings is usually satisfied by large central power plants using combustion-based energy conversion; a waste by-product of this conventional electricity power generation is heat. "Cogeneration" (CHP, Combined Heat and Power) is a proven technology (more than 100 years old) which is able to recover and use the otherwise wasted heat. It is usually defined as the simultaneous generation in one process of thermal energy and electrical and/or mechanical energy from a single primary energy stream based on the exploitation of fossil fuel or renewable energy such as oil, coal, natural or liquefied gas, biomass, solar, etc. [1]. It allows to perform power and heat transfer using an integrated system that achieves a larger overall utilization efficiency if compared to the separate energy production, thanks to the recovery and use of waste heat in addition to electricity.

In the past, mostly because of economy-of-scale reasons, cogeneration was limited to large-sized power plants operating in central locations. These stations are usually characterized by significant electric losses due to the transmission and distribution to the final user through high voltage lines and transformers; in addition, large cogeneration systems often utilize the waste heat by piping hot water into the buildings of the surrounding community and this process implies significant heat losses due to transportation of hot water over long distances, along with relevant investment costs for the pipes. For these reasons, in recent years, a great deal of attention has been focused on the transition from centralized to decentralized systems with an increasing diffusion of the so-called "micro-cogeneration" (MCHP, micro-combined heat and power) aiming to produce electricity and heat near the final user. According to the Directive 2004/8/EC [2], this process is usually defined as the local combined production of electrical and thermal energy from a single fuel source with an electric output lower than 50 kW. Some authors use the term "small-scale cogeneration" for the combined heat and power generation systems with electrical power less than 100 kW [3, 4], while the term "micro-cogeneration" is sometimes used to denote cogeneration units with an electric capacity smaller than 15 kW [3, 4].

Micro-cogeneration is a developed technology that is emerging as the fast growing technique to reduce the primary energy consumption in small/medium-scale applications [3–7] thanks to the fact that, if designed and managed properly, the efficiency of energy conversion in cogeneration systems increases to over 80 % when compared to an average of 30–40 % in conventional fossil fuel fired electricity generation systems. Figure 1 [5] illustrates how the chemical energy from the fuel is converted into useful thermal and electrical energy in a conventional generation system and a micro-cogeneration system.

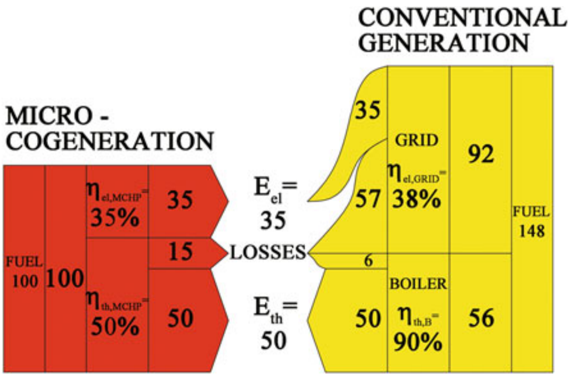

Fig. 1 Micro-cogeneration versus conventional separate generation (modified from [5])

In Fig. 1 $\eta_{el,MCHP}$ is the electric efficiency (ratio between electric output and fuel power input) of the micro-cogeneration unit, $\eta_{th,MCHP}$ is the thermal efficiency (ratio between thermal output and fuel power input) of the MCHP device, $\eta_{el,GRID}$ is the electric efficiency of the electrical power plant (production of electricity only), $\eta_{th,B}$ is the thermal efficiency of the boiler (production of heat only), E_{el} is the electricity demand, and E_{th} is the heat demand (for space heating and domestic hot water production). Figure 1 highlights how micro-cogeneration technology is potentially able to satisfy the electric and thermal needs of end users with a lower primary energy consumption when compared to the conventional methods of generating heat (in boilers) and electricity (in centralized power plants) separately, as recognized also by the European Community [2]. Several studies demonstrated the effectiveness of MCHP systems in reducing the primary energy consumption with respect to the conventional separate production of heat and electricity with a percentage difference varying from 5 to 30 %, depending on the technology and the application of the cogeneration units [8, 9]; these savings increase up to 40 % when renewable energy technologies are involved in hybrid microgeneration systems. The increase in energy efficiency from such MCHP systems brings a corresponding reduction of global equivalent CO_2 emissions in a first approximation similar to the amount of energy saving [10, 11] (assisting in meeting Kyoto targets [12]) and can result in lower operating costs (mainly depending on both the price of electricity/fuel and the economic support mechanisms) [13].

The distributed generation nature of this technology also has the potential to reduce losses due to electrical transmission and distribution inefficiencies as well as alleviate utility peak demand problems; these systems are even more attractive for remote communities where a lack of central generation stations and costly connection to the grid is neither an affordable nor a preferable option. MCHP systems have the additional advantage of diversifying electrical energy production (they are feasible to use different fuels), thus potentially improving the security of energy supply in the event of problems occurring with the main electricity grid. They could also provide new commercial opportunities for manufacturers, as well as partnerships between manufacturers, energy suppliers, financiers, and others. Moreover a widespread exploitation of micro-cogeneration units could defer huge investments in new large generation plants, substations or infrastructures. Finally it could develop competitive electricity markets and increase the customer participation to the market, providing solutions to exploit the price elasticity of electricity.

Micro-cogeneration applications have to satisfy, fully or partly, both the electrical and thermal demands. If the electric power export to the central electric grid is allowed, residential cogeneration units can operate in response to variations in heat demand. It is called "heat demand following operation." In this case, the MCHP device is sized to meet the heat needs, while electricity is either used on-site or exported to the grid. However, in a residential cogeneration unit without electric power export, the unit is designed to satisfy the electricity demand of the customer and heat is used to contribute to water and space heating; its thermal output varies in response to its electric power output that follows the electric power demand. In this case ("electricity demand following operation"), a supplementary peak boiler may be required to meet the total heat demand. Depending on the magnitude of the electrical and thermal loads, whether they match or not, and the operating strategy, the MCHP system may have to be run at part-load conditions, the surplus energy (electricity or heat) may have to be stored or sold, and deficiencies may have to be made up by purchasing electricity or heat from other sources such as the central electric grid or a boiler; the surplus heat can be stored in a thermal storage device such as a water tank or in phase change materials, while surplus electricity can be stored in electrical storage devices such as batteries or capacitors [5].

In order to obtain the potential energy, environmental and economic benefits, micro-cogeneration units must be appropriately designed and managed in response to magnitude/trends of residential energy demands. First of all, the effective utilization of the cogeneration device's thermal output for space heating as well as for domestic hot water production is crucial to obtain high levels of overall energy efficiency, along with the associated environmental benefits. From this point of view, it should be underlined that the ability to store thermal energy is recognized as one of the core issues in optimizing a system's operation, and in enabling the integration of renewable energy resources. When designing a MCHP system it should be also taken into account that the efficiency of a cogeneration unit is strongly related to the type of prime mover, its size, and the temperature at which the recovered heat can be utilized. In addition, taking into account that the economic feasibility of a micro-cogeneration scheme is strongly related to the operating time [3], the utilization level of the unit has to be typically more than 3000–4000 running hours per year [5] and, as they are usually capital intensive technologies, financial support mechanisms appear to be necessary in order to encourage their adoption.

Today, leading governments from the countries of Europe, Japan, and United States have taken roles in promoting and advancing this technology [14]. Within the EU Member States, a broad variety of financial support mechanisms are in place or in preparation that are designed to improve the economics of cogeneration installations. European countries designed different incentives to support cogeneration: they are divided into tax advantages, feed in tariffs, certificates, grants, or other kinds of additional measures [13, 15]. The support mechanisms for micro-cogeneration devices usually require the achievement of minimum energy performance, for example in terms of primary energy saving with respect to a benchmark case. This is the reason why standard procedures are available or in a discussion stage in many countries around the world [16] for testing ex-ante the energy performance of a device, representative of a unit type, allowing to classify the energy performance of the MCHP with experimental tests performed in a test facility, possibly certified by an independent third party. Presently, simulation and optimization tools are also emerging as a useful option in order to better understand and control the operation of MCHP systems [17].

Micro-cogeneration has significant market potential especially for enterprises, hotels, hospitals, university campuses, medium family houses, etc. The Micro-Map project [18] reported that in Europe between 5 and 12.5 million homes could have

MCHP systems installed by 2020 and this would result in CO_2 emissions reductions between 3 and 7.8 million tons per year.

With respect to the potential utilization of micro-cogeneration technology, it is very important to underline that in the last years in many countries there has been an increasing demand for space cooling energy during the warm season generally satisfied by electrically driven units. This trend contributed to electrical load peaking and subsequent network congestion and failure events in different power systems worldwide. This has strengthened the awareness of governments, manufacturers, and communities about energy issues, pushing forward the search for efficiently combining micro-cogeneration units with various technologies currently available for local cooling generation. A combination of MCHP systems with various thermally fed or mechanically/electrically-driven cooling systems is possible and allows to set up a so-called micro-trigeneration system (MCCHP, micro-combined cooling heat and power) [3–7] that represents the on-site production of a threefold energy vector requested by the user from a unique source of fuel with significant potential benefits from energy, environmental, and economic points of view. MCCHP is an upgrade of micro-cogeneration unit where thermal or electric energy is further utilized to provide space or process cooling capacity: in this way, the overall energy efficiency increases and the economic payback can decrease thanks to the larger amount of operating hours per year [3]. In order to advance the design, operation, and analysis of micro-cogeneration and micro-trigeneration systems, two consecutive research projects have been sponsored and completed by the International Energy Agency [19, 20].

Together with a lot of potential benefits, some drawbacks still limit the large diffusion of micro-cogeneration systems [3, 17, 19–21]:

- the design of systems poses a significant technical challenge due to the non-coincidence of thermal and electrical loads, necessitating the need for electrical/thermal storage or connection in parallel to the electrical grid;
- capital costs considerably high (this can determine quite long payback periods);
- lack of financial supporting actions to ensure a suitable payback period (possibility to obtain funds as well as to sell the electric surplus to the grid at good price);
- insufficient political support mechanisms and administrative hurdles such as electric network grid connection;
- impact on the electric network due to the ongoing and future diffusion of distributed generation technologies;
- components that are in R&D phase or in a preselling phase;
- lack of trial data to fill the gap of optimization between the systems and the user load profile as well as to define several operating strategies and their impact on system optimum performances.

In addition, it should be highlighted that air quality standards can be quite stringent in urban areas, and the environmental impact of MCHP systems can bring environmental concerns regarding local emissions (such as NO_x, CO, SO_x, particulate matter, unburned hydrocarbons, and so on). Indeed, in urban contexts the dispersion in the atmosphere of pollutants from small-scale generators sited among buildings may be more difficult than, for instance, for large-scale power plants with high stacks. A further critical point is represented by the already high background emission level, mostly due to road traffic pollution. As a consequence, even if the diffusion of distributed cogeneration within urban areas reduces the global environmental impact in terms of equivalent carbon dioxide emissions, the presence of plants spread over the territory could increase the local pollution, and thus could worsen the local air quality [22]. The most relevant hazardous pollutants emitted by natural gas-fired systems are CO and NO_x (often subject to binding environmental constraints). NO_x formation is the one giving most concerns from a regulatory point of view, being its toxic effects turning up for concentrations 10–20 times lower than for CO [23]. At the moment few works are available in literature concerning the evaluation of the local impact associated to cogeneration systems and more detailed studies have to be performed in order to better clarify this point.

2 Prime Mover Technologies and Market Survey

Today there are several prime mover technologies which are capable of providing cogeneration devices. The conversion process can be based on combustion and subsequent conversion of heat into mechanical energy, which then drives a generator to produce electricity. Alternatively, it can be based on direct electrochemical conversion from chemical energy to electrical energy. Other processes include photovoltaic conversion of solar radiation.

There are five main technologies being developed for micro-cogeneration units including

(a) Reciprocating internal combustion engines (ICE)-based MCHP systems.
(b) Reciprocating external combustion Stirling Engines (SE)-based MCHP systems.
(c) Fuel Cells (FC)-based MCHP systems.
(d) Gas and steam microturbines (MT)-based MCHP systems.
(e) Photovoltaic thermal (PVT) MCHP systems.

At the moment micro-cogenerators based on reciprocating internal combustion and Stirling engines are already available on the market for the single-family and multi-family residential building market and small-scale commercial applications; in Europe, more than 20,000 units of internal combustion engine-based MCHPs have been sold and about 3,000 units of Stirling engine-based MCHPs have been also installed [16]. A large R&D activity which aims at producing, in the medium period, small commercially available units based on fuel cells, gas, and steam microturbines, is already in progress [3].

While selecting micro-cogeneration systems, one should consider some important technical parameters that assist in defining the type and operating scheme of different alternative cogeneration systems:

- electric and thermal load patterns of the end users;
- heat-to-power ratio of both the end users and the MCHP unit;
- available fuels;
- system reliability;
- permission of power export to the central electric grid;
- temperature levels of both the end users and the MCHP unit;
- local environmental regulations.

In the following sections, the different technologies suitable for micro-cogeneration are described and compared in terms of capacity range, fuel, electric efficiency, thermal efficiency, overall efficiency (sum of electric and thermal efficiencies), noise level, dimensions, weight, life service, pollutant emissions, capital and maintenance costs. The next sections will be focused on micro-cogeneration systems delivering electric power output lower than 15 kW, which represents a valid and interesting application especially suitable for residential and tertiary sector.

2.1 Reciprocating Internal Combustion Engines (ICE)

The reciprocating internal combustion engines are coupled with an electricity generator and heat exchangers to recover the heat of the exhaust gases, engine coolant, and lubrication oil. Internal combustion engines are the most well-established technology for small and medium MCHP applications. They are a robust and proven technology with long life service (up to 80,000 h [3]), a capital cost between 2,000 and 6,000 €/kW$_{el}$ depending on the size [3] and a typical maintenance cost from 0.010 to 0.015 €/kWh$_{el}$ [5]. ICE-based MCHP systems occupy small installation space and they also have satisfactory electric (25–32 %) and thermal (53–66 %) efficiencies under nominal conditions. In addition to fast start-up capability and good operating reliability, they are characterized by high efficiency at partial load operation and they can be fired on a broad variety of fuels with excellent availability, allowing for a range of different applications, especially emergency or standby power supplies.

Although they are a mature technology, reciprocating internal combustion engines have obvious drawbacks which need to be faced and improved: (i) relatively high vibrations require shock absorption and shielding measures to reduce acoustic noise (<60 dB(A) at 1 m of distance [3]); (ii) a large number of moving parts and frequent maintenance intervals increase maintenance costs; (iii) high emissions, particularly nitrogen oxides (NO_x emissions are less than 100 ppm with a stable shaft power output in an engine speed range between 1200–3000 rpm [3]).

The NO_x and CO emissions of a residential building-integrated micro-cogeneration system based on a 6.0 kW$_{el}$ reciprocating internal combustion engine fuelled with natural gas were evaluated and compared with those of a conventional system by Angrisani et al. [24]. The analysis was based on the experimental data collected by Lombardi et al. [25] and showed that

- in comparison to the electric load control strategy, the thermal load control strategy is characterized by lower CO emissions, but it is less favorable in terms of NO_x levels;
- the MCHP system allows for reducing the NO_x emissions in comparison to the conventional system, while the CO emissions of the latter are substantially negligible with respect to those of the micro-cogeneration application;
- whatever the MCHP control logic is, the influence of climatic conditions is quite relevant in terms of both NO_x and CO emissions.

Pehnt [26] highlighted that the NO_x emission of ICEs strongly varies, depending on the emission reduction concept used, manufacturer, operation mode, age of system, and maintenance interval; the NO_x emissions can also vary by one order of magnitude depending on whether the catalyst has been newly exchanged or not.

Major manufacturers around the world continuously develop new engines with lower emissions; at the same time, emissions control options, such as selective catalytic reduction, have been utilized.

Presently, a number of internal combustion engine-based micro-cogeneration units are commercially available. Table 1 describes the main ICE-based MCHP systems on the market (with electric output lower than 15 kW_{el}) in terms of input power, electric output, thermal output, electric efficiency (ratio of electric power to fuel input power), thermal efficiency (ratio of thermal power to fuel input power), overall efficiency (sum of electric and thermal efficiencies), fuel, weight, dimensions, number of cylinders, displacement, and noise (at 1 m of distance) based on manufacturer nominal data. The efficiency values are calculated based on the lower heating value (LHV) of the fuels.

2.2 Reciprocating External Combustion Stirling Engines (SE)

Unlike reciprocating internal combustion engines, a Stirling engine is an external combustion device. This means that the cycle medium, generally helium or hydrogen (but also oxygen, nitrogen, carbon dioxide), is not exchanged during each cycle, while the energy driving the cycle is applied externally. Stirling engines can operate on almost any fuel (gasoline, alcohol, natural gas or butane) and renewable energy sources (solar or biomass), with external combustion process that facilitates its control and results in low emissions (they can be 10 times lower than those of reciprocating internal combustion engines with a catalytic converter, making the emissions generated from SEs to be comparable with those from modern gas burner technology [5]). Pehnt [26] noticed that whereas the emissions of air pollutants for Stirling engines are extremely low, ICEs emit more significant amounts of NO_x, CO, and hydrocarbons.

Compared to the ICE-based systems, Stirling engines have fewer moving parts and lower vibrations, longer life service, lower noise level, longer maintenance free

Table 1 Manufacturer data of main ICE-based micro-cogenerators

	SENERTEC Dachs G 5.5 [80]	YANMAR CP5WN-SN [105]	YANMAR CP10WN-SN [105]	TEDOM micro T7 AP [106]	COGENGREEN ecoGEN-12AG [107]	EC POWER XRGI 9 [108]	HONDA Ecowill [109]	AISIN SEIKI GECC 46 A2 [110]	AISIN SEIKI GECC 60 A2 [110]	VAILLANT Ecopower e4.7 [111]	SENERTEC Dachs G 5.0 [80]
Input power (kW)	20.5	17.8	31.5	25.9	43.0	31.0	3.8	18.0	20.8	18.9	19.6
Electric power (kW)	5.5	5.0	9.9	7.0	12.0	9.0	1.0	4.6	6.0	4.7	5.0
Thermal power (kW)	12.5	10.0	16.8	17.2	28.0	20.0	2.5	11.7	11.7	12.5	12.3
Electric efficiency (%)	26.8	28.1	31.4	27.0	27.9	29.0	26.3	25.6	28.8	24.9	25.5
Thermal efficiency (%)	61.0	56.2	53.3	66.4	65.1	64.5	65.8	65.0	56.3	66.1	62.8
Overall efficiency (%)	87.8	84.3	84.8	93.4	93.0	93.5	92.1	90.6	85.1	91.0	88.3
Fuel	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas, LPG	Natural gas, propane, butane	Natural gas, LPG	Natural gas, LPG	Natural gas, LPG	Natural gas, propane	Natural gas
Weight (kg)	530	400	756	645	700	440	71	465	465	390	530
Length (mm)	720	1100	1470	1315	1340	920	580	1100	1100	760	720
Height (mm)	1000	1500	1790	1480	1218	960	750	1500	1500	1080	1000
Depth (mm)	1060	500	800	700	780	640	298	660	660	1370	1070
No. of cylinders	1	3	3	3	4	4	1	3	3	1	1
Displacement (cm^3)	579	699	1642	962	1600	2237	163	952	952	270	579
Noise (dB(A))	56	53	56	58	55	49	43	54	54	56	56

operating periods. The overall efficiency is generally higher than 85 %, and it may even go beyond 95 %, with good performance at partial load. The capital costs depends on the size, ranging from 2,700 to 5,500 €/kW$_{el}$ [3]; an estimated maintenance cost for the unit is around 0.013 €/kWh$_{el}$ [5].

Despite many advantages, the Stirling engine has not found the expected applications due to low electric efficiency (ranging from 12 to 25 %), difficult power control due to the presence of different heat exchangers (heater, cooler, regenerator and auxiliary heat exchangers), high pressure level of working gas, low durability of parts, and long start-up time.

Different small-scale Stirling-based cogenerators are commercially available or under development. Table 2 describes the main SE-based MCHP systems available

Table 2 Manufacturer data of main SE-based micro-cogenerators

	WHISPERGEN [112]	BAX ecoGEN [113]	Qnergy QCHP7500 [114]	SUNMACHINE [115]	SOLO 161 [116]
Input power (kW)	8.3	7.4	38.0	12.0	38.8
Electric power (kW)	1.0	1.0	7.5	3.0	9.5
Thermal power (kW)	7.0	6.0	30.0	7.8	26.0
Electric efficiency (%)	12.0	13.5	19.7	25.0	24.5
Thermal efficiency (%)	84.3	81.1	78.9	65.0	67.0
Overall efficiency (%)	96.4	94.6	98.7	90.0	91.5
Fuel	Natural gas	Natural gas, biogas	Wood pellets, biomass, liquid fuels, natural gas, propane	Wood pellets	Natural gas, LPG, biogas, biomass
Weight (kg)	137	110	200	410	460
Length (mm)	480	450	630	1160	1280
Height (mm)	840	950	770	1590	980
Depth (mm)	560	426	1380	760	700
No. of cylinders	4	–	–	1	2
Displacement (cm^3)	–	–	–	520	160
Working gas	Nitrogen	–	–	Nitrogen	Helium, hydrogen
Maximum pressure (bar)	–	–	–	36	150
Noise (dB(A))	–	45	65	–	–

on the market (with electric output lower than 15 kW) in terms of input power, electric output, thermal output, electric efficiency, thermal efficiency, overall efficiency, fuel, weight, dimensions, number of cylinders, displacement, working gas, maximum working pressure, and noise (at 1 m of distance) based on manufacturer nominal data.

2.3 Fuel Cells (FC)

Fuel cell cogeneration-based systems have, perhaps, the greatest potential in micro-cogeneration applications thanks to their ability to produce electricity at high efficiency with a significant reduction of greenhouse gas emissions. In a fuel cell, the chemical energy within the fuel is directly converted to electricity (with by-products of heat and water) without any mechanical drive or generator. Currently, most of the fuel cells are either based on the low-temperature (80 °C) proton exchange membrane fuel cell (PEMFC) technology, or on the high-temperature (800–1000 °C) solid oxide fuel cell (SOFC) technology. They normally run on hydrogen, but can also be run on natural gas, methanol, or other fuels by external or internal reforming. SOFC performs better than PEMFC technology, but start-up and cooling phases take longer, which immediately affects time and costs required for installation, maintenance, repair, and durability of fuel cells [3]. Additional types of fuel cells are available: alkaline fuel cells (AFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), and lately direct methanol fuel cells (DMFC).

Fuel cells have several benefits, such as (i) high electric efficiency (30–60 %) and overall efficiency (80–90 %), (ii) a good match with the residential thermal to power ratio, (iii) reliability, (iv) quiet operation, (v) potential for low maintenance, (vi) excellent part-load management, (vii) almost zero emissions (due to the lack of a combustion process, FCs have extremely low emissions of NO_x and CO; their CO_2 emissions are also generally lower than those of other technologies due to their higher efficiency [5]). Pehnt [26] highlighted that the local emission factors for fuel cells are orders of magnitude lower if compared to the internal combustion engines.

Nevertheless, the high costs (varying from 6,700 €/kW_{el} for PEMFC to 60,000 €/kW_{el} for SOFC [3]) and relatively short lifetime of fuel cell systems are their main limitations. Typically, the total cost is represented by the stack subsystem (25–40 %), the fuel processor (25–30 %), the electronics (10–20 %), the thermal management subsystem (10–20 %), and ancillary (5–15 %) [3]. Fuel cell maintenance costs vary with the type of fuel cell, size, and maturity of the equipment. Major overhaul of fuel cell systems involves shift catalyzer, reformer catalyzer, and stack replacement: for example, the cost to replace the stack of a 10 kW_{el} PEMFC is estimated to be 0.0188 €/kWh_{el} [5]. Ongoing research to solve technological problems and to develop less expensive materials and mass production processes are expected to result in advances in technology that will reduce the cost of fuel cells.

Fuel cells have experienced irregular sales levels in the 2000s; however, in the years after 2010, FCs have begun selling at markedly increased rates and, as of

Table 3 Manufacturer data of main FC-based micro-cogenerators

	KYOCERA (SOFC) [117]	PANASONIC ENE FARM (PEMFC) [118]	HEXIS Galileo 1000 N (SOFC) [119]	BlueGEN (SOFC) [120]	VAILLANT FCU 4600 (PEMFC) [111]	VIESSMAN Vitovalor 300-P (PEMFC) [121]
Electric power (kW)	0.70	0.75	1.00	1.50	4.60	0.75
Thermal power (kW)	0.65	1.08	1.80	0.54	7.00	1.00
Electric efficiency (%)	42.0	35.2	30.0	60.0	35.0	37.0
Thermal efficiency (%)	39.2	50.6	62.0	25.0	50.0	53.0
Overall efficiency (%)	81.2	85.8	92.0	85.0	85.0	90.0
Fuel	Natural gas	Natural gas	Natural gas, biogas	Natural gas, propane, butane, ethanol, biodiesel	Natural gas	Natural gas
Weight (kg)	94	95	170	–	–	125
Length (mm)	600	400	620	600	–	516
Height (mm)	935	1850	1640	1010	–	1667
Depth (mm)	335	400	580	660	–	480

2012, became the leading technology in terms of volume of units sold among the range of microgeneration prime movers (this was achieved through high numbers of newly installed systems in Japan) [14].

Table 3 describes the main FC-based micro-cogeneration units on the market (with electric output lower than 15 kW) in terms of electric output, thermal output, electric efficiency, overall efficiency, fuel, weight, and dimensions based on manufacturer nominal data.

2.4 *Gas and Steam Microturbines (MT)*

Microturbines extend combustion turbine technology to smaller scales. They are primarily fuelled with natural gas, but they can also operate with diesel, landfill gas, ethanol, gasoline, propane, hydrogen, and other bio-based liquid and gaseous fuels.

In comparison to internal combustion engine, they offer a number of advantages like more compact size, lower weight, shorter delivery time, smaller number of moving parts, lower vibration and noise, and minimum maintenance requirements (maintenance costs are in the 0.006–0.01 €/kWh$_{el}$ range [5]). Additionally, microturbines have a significant advantage over reciprocating internal combustion engines in terms of environmental impact: current expectations for NO_x emissions from microturbines are already below those of ICEs. However, in the low power ranges, microturbines have a lower overall efficiency (up to 80 %) when compared to reciprocating internal combustion engines. Mancarella and Chicco [10, 11] investigated the local emissions of two different MTs available on the market (with 30 and 60 kW_{el} as nominal electric output, respectively) fuelled with natural gas. Their analyses highlighted how the full-load emission characterization can be unsuitable to estimate the environmental impact due to actual operating conditions; critical situations have emerged in the specific case for what concerns high NO_x emissions at low load (for the 30 kW_{el} MT) and high CO emissions mainly at medium–low loading condition. Canova et al. [27] characterized both a 60 kW_{el} microturbine and a 180 kW_{el} internal combustion engine fed with natural gas in terms of air pollutants (in particular, NO_x, CO, and non-methane organic compounds). The results from the case study showed that in general the microturbine always performs better than the internal combustion engine in terms of NO_x (but when it is operated at partial load the CO levels increase dramatically), while the CO emissions from the ICE are only negligibly affected by the engine load.

Limitations of MTs are mainly due to high capital costs and relatively short life. Other issues include relatively low electrical efficiency and its sensitivity to changes in ambient conditions. This technology has only recently been commercialized and is offered by a small number of suppliers.

Table 4 describes the main MT-based micro-cogeneration units available on the market (with electric output lower than 15 kW) in terms of electric output, thermal output, electric efficiency, overall efficiency, fuel, weight, dimensions, and noise level based on manufacturer nominal data.

Table 4 Manufacturer data of main MT-based micro-cogenerators

	FLOWGROUP (steam MT) [122]	OTAG (steam MT) [123]	MTT (steam MT) [124]
Electric power (kW)	1.0	2.0	3.0
Thermal power (kW)	10.0	18.0	14.4
Electric efficiency (%)	10.0	10.4	15.0
Thermal efficiency (%)	80.0	83.6	72.0
Overall efficiency (%)	90.0	94.0	87.0
Fuel	–	Natural gas, LPG	Natural gas
Weight (kg)	–	195	225
Length (mm)	–	62	610
Height (mm)	–	126	970
Depth (mm)	–	83	1120
Noise (dB(A))		54	<58

2.5 Photovoltaic Thermal (PVT) Generators

The solar energy conversion into electricity and heat with a single device is obtained with the so-called PVT collectors.

A PVT collector is a module in which the photovoltaic (PV) system is not only producing electricity, but also serves as a thermal absorber. PV cells utilize a fraction of the incident solar radiation to produce electricity and the remaining is mainly rejected as waste heat in the cells and substrate raising the temperature of PV. The PVT technology recovers part of this heat and uses it for practical applications [28]. In this way both heat and power are produced simultaneously. The dual functions of the PVT result in a higher overall solar conversion rate (up to around 60–70 %) than that of solely PV or solar thermal collector, and thus enable a more effective use of solar energy. Different types of PVT collector are being used presently such as PVT/air, PVT/water, and PVT concentrated collector [29]. Currently commercial PVT applications are still limited due to product reliability and cost. Hence significant research is required in the field of PVT mainly in thermal absorber design and fabrication, material and coating selection, energy conversion and its effectiveness, cost minimization, performance testing, control and the reliability of the system [29].

In addition to the above-mentioned typology of PVT devices, an innovative system able to convert the radiant energy of combustion into electrical energy by using photovoltaic cells is under investigation. This technology (also known as Thermal Photovoltaic (TPV)) mainly consists of a heat source, an emitter, a filter, and a photovoltaic cells array [30, 31]. The thermal production of the TPV is realized by recovering the heat from the cooling of the PV cells and the exhaust combustion products.

The main advantages of TPV systems can be found in the (i) high fuel utilization factor (close to the unity thanks to the recovery of the most of the thermal losses), (ii) low noise levels (due to the absence of moving parts), (iii) easy maintenance (similar to a common domestic boiler), and (iv) great fuel flexibility. According to the values reported in literature associated to realized prototypes, the electric efficiency of TPV systems is low (from 0.6 up to 11.0 % [30, 31]), but the potential overall efficiency is always higher than 90 % [30, 31]. Presently the capital cost of thermophotovoltaic generators is high (around 6,000 €/m^2 [30, 31]) and it does not appear much favorable for the development of this technology.

3 Operating Schemes and Main Results of MCHP Applications

A large variety of microgeneration technology choices and applications is currently available depending on the building's electric and thermal load profiles taking into account that

- engines can drive electric generators and/or electric heat pumps, absorption/adsorption heat pumps, gas heat pumps and so on in different ways (electrically, thermally or mechanically), thereby allowing to match the heating, cooling and electric end-user requirements in a wide range of operating conditions;
- the development of absorption and adsorption chillers with low cooling capacity offers new possibilities to apply these technologies in combination with MCHP systems in applications with significant cooling needs [6, 32];
- thanks to its energy and environmental benefits, the use of desiccant technology coupled with MCHP units is also spreading to tertiary and residential buildings;
- cross-linking approaches as load sharing and virtual power plants seem very promising, as well as concepts such as smart energy networks and microgrids, because the behavior of individual users or households demonstrates highly stochastic profiles (making it difficult to optimize microgeneration systems); in particular, the concept of smart grid is expected to be the driver for micro-generation penetration [33] and several countries have launched programs and pilot projects to reach this target in the future [34];
- MCHP units can balance intermittent renewable sources, accelerate the utilization of renewable energy technologies as well as achieve tighter integration between energy vectors at the point of end use;
- thermal storages utilization and their implementation into energy supplies are usually crucial, while also considering the charging of electric vehicles or using batteries within buildings.

Given the rapidly increasing numbers of micro-cogeneration installations around the world, there is a pressing need for knowledge so that informed choices can be made on where and when the installation of micro-cogeneration systems is appropriate. This section provides a short overview of the main operating schemes of MCHP systems as well as their extension to MCCHP applications, highlighting the most relevant results available in current scientific literature.

3.1 MCHP Systems Coupled with Thermally Activated Heat Pumps (THPs)

Thermally activated heat pumps (THPs) are the systems that use thermal energy to satisfy cooling demands. The possibility of an efficient use of thermal waste energy leads to an upgrading of the cogeneration performance, thereby increasing the yearly operating hours including the cooling season.

Main THPs include absorption heat pumps (ABHPs) and adsorption heat pumps (ADHPs). These cooling systems can be run by steam, hot water, or hot exhaust gas derived from MCHP units. However, waste heat from various prime movers falls into different temperature ranges; at the same time, THPshave their own suitable working temperature. For these reasons there are some constraints on each MCHP technology in order to activate different types of THP systems. For small-scale applications, THPs are typically operated with a temperature level of the hot source in the range of 60–90 °C.

Absorption heat pumps represent the most common thermally activated technology applied in existing MCCHP systems [6, 17]. Typical absorption chiller installations, with a cooling capacity ranging from 10 to 15 kW producing chilled water at a temperature level between 15 and 18 °C, are operated using a hot source with a temperature in the range 75–90 °C and are characterized by a COP (coefficient of performance) equal to approximately 0.65–0.80. Lithium bromide/water and water/ammonia are the working pairs that are typically used in these systems operating in single or double effect [35, 36].

The main data of some small-scale absorption chillers, available on the market or under preselling phase, operating with different working pairs, are reported in Table 5.

Adsorption systems are a novel technology that incorporates low-grade heat sources; however, this technology has the problems of low COP (0.3–0.6), low cooling power per volume, and significant weight [37–39]. ADHPs with silica gel/water or zeolite/water as working pairs are typically used for MCCHP systems. Few systems with cooling power lower than 50 kW are available on the Chinese and American markets, and they are characterized by high investment costs (around 600 €/kW$_{cool}$ of cooling power installed). In terms of small machines, three new German companies are proposing novel products: SOLARNEXT [40], SorTech [41], and INVENSOR [42].

Table 5 Manufacturer data of small-scale absorption chillers

	Rotartica solar 045 V [125]	SonnenKlima [126]	SOLARNEXT chillii PSC12 [40]	EAW Wegracal SE15 [127]	YAZAKI WFC-SC5 [128]
Working pair	Li-Br/H_2O	Li-Br/H_2O	H_2O/NH_3	Li-Br/H_2O	Li-Br/H_2O
Cooling capacity (kW)	4.5	10	12	15	17.6
Thermal input (kW)	7.2	12.8	18.5	21	25.1
COP	0.62	0.78	0.65	0.71	0.70
Electric input (kW)	1.11	0.12	0.30	0.30	0.05
Inlet hot water temperature (°C)	90	75	75	90	88
Outlet chilled water (°C)	7	15	15	17	7
Length (mm)	1202	1130	800	1750	594
Height (mm)	1202	1960	600	760	1736
Depth (mm)	803	795	2200	1750	744
Weight (kg)	290	550	350	700	420

The main advantages of ADHPs with respect to ABHPs are

- they can be powered by thermal energy at a temperature as low as 50 °C; therefore they are especially suitable for coupling with solar collectors and ICE-based cogenerators;
- adsorption is a robust technology with no risk of crystallization, which can occur in an ABHP operating with H_2O/Li-Br as working pair;
- the materials (zeolite, silica gel, etc.) are environmental friendly, while ammonia is toxic;
- high potential of cost reduction in production series due to the small amount of individual parts.

The main disadvantages of ADHPs with respect to ABHPs are

- slightly lower COP than those associated to the absorption technology (typical COP value of ADHP is about 0.6, while double effect ABHP can achieve a COP as high as 1.2);
- commercially available machines are more expensive and only some suppliers are on the market.

Advantages of ABHPs/ADHPS over conventional electrically-driven heat pumps can be summarized as follows:

- negligible electricity consumption;
- waste heat recovery applications;
- few moving parts (less noise, vibration and maintenance);
- no harmful emissions;
- use of environmentally friendly working fluids (low global warming potential, and ozone depletion potential).

The typical energy flows of a micro-trigeneration system including a THP are reported in Fig. 2. The thermal energy recovered from the MCHP device can be

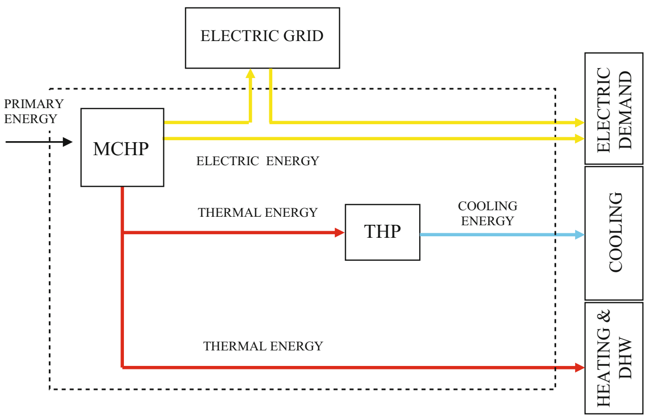

Fig. 2 MCCHP system including a THP (modified from [3])

provided to the absorption or adsorption system and/or directly used for domestic hot water production and space heating.

In [43] a MCCHP system, based on a 5.5 kW_{el} internal combustion engine MCHP unit and a 4.5 kW_{cool} absorption chiller, has been installed to satisfy the energy requirements of a research center located in Vitoria-Gasteiz (north of Spain). The performance has been estimated in terms of primary energy ratio (PER) defined as the ratio between the useful energy output supplied to the end user and the primary energy consumption. In cooling mode, the trigeneration system achieved a value of PER equal to 46 % due to the low performance of the ABHP and an incomplete use of the thermal energy available from the MCHP system, while during the winter the system operating under cogeneration mode attained a PER of 82 %. In [44] different MCCHP systems have been evaluated: among these, a MCHP/ABHP has been also analyzed, with the absorption chiller characterized by a cooling capacity of 6 kW and a COP equal to 0.67 (with a generating temperature of 70 °C, heat rejection inlet temperature of 31 °C and chilled water of 7 °C). An energy analysis of a trigeneration system based on a four strokes engine powered by LPG is reported in [45]. The engine has been directly coupled to the electric generator (0–12 kW_{el}, $\eta_{el,MCHP}$ = 0–21.4 %), and two heat exchangers have been used to recover the engine thermal power from both exhaust gases and cooling system (14.1–28.1 kW_{th}, $\eta_{th,MCHP}$ = 50.0–83.1 %). A PER value ranging between 83.1 % (at minimum load) and 71.4 % (at maximum load) has been obtained. The hot water supplied by the MCHP device (with a temperature level in the range 60.1–91.6 °C) was used to drive an adsorption system supplying a cooling power ranging from 5.1 kW (COP = 0.3) to 9.7 kW (COP = 0.34). Mittelmanet al. [46] investigated the performance and cost of a solar cooling with concentrating photovoltaic/thermal system using a single effect absorption cooling unit. The results showed that under a wide range of economic conditions, the proposed trigeneration system can be comparable to and sometimes even significantly better than the conventional alternative. Moya et al. [47] experimentally determined the efficiency and viability of an advanced trigeneration system consisting of a 28 kW_{el} micro-gas turbine in which the thermal recovery has been used to produce both cooling, with a 17 kW_{cool} air cooled absorption chiller, and hot water for heating purposes and DHW (Domestic Hot Water) for a large residential building or a medium-sized hotel. The results showed the highest energy saving for the large residential building with a simple payback period (SPB) equal to approximately 5.2 years. A computer simulation program has been developed by Pilatowsky et al. [48] to determine the optimum operating conditions of a trigeneration system composed of a 1 kW_{el} PEMFC coupled with a refrigeration-absorption cycle operating with monomethylamine-water solutions. The results showed the feasibility of using PEMFC for cooling, increasing the total efficiency of the fuel cell system. An experimental study related to a small-scale cogeneration plant, consisting of a 28 kW_{el} microturbine, a heat recovery steam generator and a 13.3 kW_{cool} ammonia/water absorption chiller, was presented in [49]; the plant has been proved to be technically feasible for power generation and refrigeration.

A 6.6 kW_{el} micro-cogenerator based on a natural gas-fuelled reciprocating internal combustion engine coupled with a 10 kW_{cool} absorption system was experimentally investigated by Angrisani et al. [50] in order to assess the feasibility of the micro-trigeneration system in the residential sector.

Simulation of an open cycle operation of an adsorption chiller in MCCHP systems has revealed large values of COP [51]. Zhang et al. [52] successfully employed adsorption cooling system driven by waste heat for both air conditioning and continuous cold production with two identical sorption reactors. Vasta et al. [53] designed, built, and integrated mobile adsorption chiller prototype, driven by heat of an engine coolant, in a truck cabin; continuous cooling at 9 °C was obtained, even under non-favorable operating conditions. An innovative MCCHP system with lithium chloride (Li-Cl)/water desiccant cooling system driven by engine exhaust gases and coolant heat has been also developed [54].

3.2 MCHP Systems Coupled with Electric Heat Pumps (EHPs)

The Directive 2009/28/EC [55] recognizes aero-thermal, geothermal, and hydrothermal energy as renewable energy sources, thus considering electric heat pumps (EHPs) as a useful tool to achieve European targets concerning energy efficiency. The utilization of the electric heat pump technology has been proved to be an efficient and economical alternative to the traditional boilers [56]. However, the deployment of EHPs at an increasing rate would result in electric household demand characteristics from those seen until today and it could also pose a threat to the stability of the electrical grid; from this point of view, MCHP technology is considered as one of the most interesting electric demand-limiting strategies in order to reduce the huge investment needed to reinforce the electric infrastructure. In addition, the combination of MCHP units with electric heat pumps can help in

- running the cogeneration device for longer time at higher average loads, thus achieving better energy and environmental performance and shorter investment payback periods;
- profitably exploiting the excess electrical production from renewable sources when selling the surplus electricity to the grid is not inconvenient.

Figure 3 indicates a possible micro-trigeneration scheme consisting of a bivalent electric heat pump coupled with a micro-cogenerator. The electric power delivered by the MCHP can be used to activate the EHP and/or cover the electric demand associated to the domestic appliances of the building; otherwise it can be sold to the central electric grid (that is also used as a backup system for the electric peak demands). The bivalent EHP is used to satisfy the space cooling load of the building during the cooling season as well as to cover the space heating demand during the heating period. The thermal output of the MCHP is used to fulfill the space heating (during the heating season) and the DHW requirements (during the whole year).

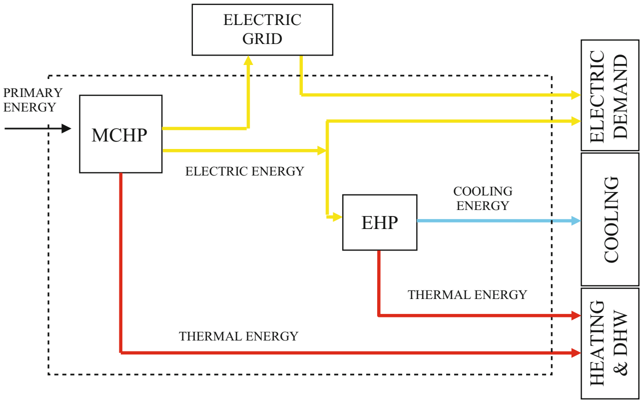

Fig. 3 MCCHP system including an EHP (modified from [3])

Several studies relating to different countries have highlighted how the incorporation of electric heat pumps in micro-cogeneration schemes represents an efficient and environmental friendly alternative to the traditional systems and could enhance the benefits of both technologies. Smith and Few [57, 58] analyzed the steady-state operation of a domestic scale prototype micro-cogeneration plant incorporating an electric heat pump in terms of operational costs, first law and second law of thermodynamics. The experimental data clearly demonstrated the advantages of the investigated system with respect to a conventional plant from both energy and economic point of views. The results of the prototype testing were further used by the authors in the development of a simulation model [59] and a good agreement with experimental results was found. Malinowska and Malinowski [60] compared a small-scale combined heat and power plant incorporating an electric heat pump with a conventional system by carrying out a theoretical parametric analysis in terms of exergetic efficiency. Their work highlighted that the exergetic efficiency of the cogeneration plant can be two times higher than that of the corresponding conventional system. The experimental performance of a prototype plant consisting of a micro-cogeneration unit coupled with an electric heat pump installed in Vigo (North-West of Spain) was analyzed from an energy point of view by Porteiro et al. [61, 62]; the experimental results highlighted that the best performance can be achieved during the winter. Possidente et al. [63] analyzed the energy, economic, and environmental performance, on a yearly and seasonal basis, of a natural gas-fuelled micro-cogenerator combined with an electric heat pump, starting from the results of an intense experimental activity developed in a test facility under a wide range of conditions [64]. Cooper et al. [65] analyzed the relative energy and environmental performances of six micro-trigeneration systems composed of an electric air source heat pump and a solid oxide fuel cell micro-cogeneration unit by using a simulation approach. They found that the way in which the electric heat pumps are controlled has the potential to reduce their impacts by more than a third, while the largest savings achieved by the micro-cogeneration unit occur when it is

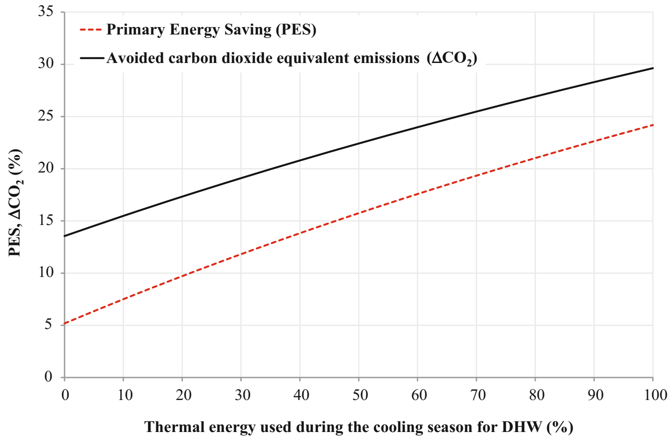

Fig. 4 PES and ηCO_2 versus thermal energy used for DHW in cooling mode for the scheme MCHP/EHP (modified from [3])

running continuously at full output. The on-site performance during the cooling season of a micro-trigeneration plant composed of a MCHP unit coupled with an electric chiller was experimentally evaluated by Ciampi et al. [66]: their analysis highlighted how the micro-trigeneration system is potentially able to save primary energy up to around 20 %, reduce the operating costs up to around 39 %, and decrease the carbon dioxide equivalent emissions up to around 23 % when compared to a conventional system based on separate energy production. The review of the scientific literature highlighted that the effective utilization of the cogeneration device's thermal energy is crucial to obtain high levels of overall energy efficiency, along with the associated environmental benefits. This is particularly important in small-scale applications and especially during the cooling season. As an example, Fig. 4 [3] shows the annual primary energy savings (PES) and avoided carbon dioxide equivalent emissions (ηCO_2) associated to the combination of MCHP and EHP as a function of the percentage of thermal output of the micro-cogeneration system used during the cooling period for DHW production (assuming that the system operates at full-load for 2500 h per year in heating mode and 1500 h per year in cooling mode). The proposed scheme, compared to the separate production, provides a primary energy saving ranging from 6 to 24 % and a reduction of the equivalent CO_2 emissions between 14 and 30 %.

3.3 MCHP Systems Coupled with Desiccant Wheel (DW)

During last years, air conditioning demand has widely spread, mainly in commercial and residential sectors of industrialized countries, where people spend the major part of the day in confined environments. This demand is usually met by electrically-driven units that dehumidify air by cooling below its dew point temperature. These systems are very energy consuming, have a significant environmental impact and can determine high electric peak loads and blackouts, when powered by the electric grid. A suitable alternative is represented by dehumidification systems based on desiccant materials, the so-called desiccant cooling systems (DCS), where the main energy input is low temperature heat.

In the most common configuration, the core of a desiccant cooling system is the desiccant wheel (DW) that adsorbs water vapor from the air on the process side. On the other side, desiccants need to be regenerated by supplying heat to the regeneration air, to remove the adsorbed water vapor. The DW rotates between process and regeneration section to obtain continuous operation. When process air is dehumidified, its temperature increases, as the adsorption process occurs at nearly constant enthalpy of humid air. While the latent load is met by the DW, the sensible load is typically handled by a water cooling coil served by a chiller (hybrid DCS), and/or by means of direct or indirect evaporative cooling, or by direct expansion evaporators.

DCSs with DWs have been used since the 1930s, mainly for industrial applications where significant economic benefits are achieved from an accurate humidity control. Nowadays, they are starting to be used in commercial and residential sectors too, thanks to relevant advantages, such as reduction of reliance on grid electricity; energy, and greenhouse gas emissions savings; reduction of energy costs; better indoor air quality and thermal comfort; a higher energy performance of the chiller in hybrid DCS, because it has to handle only sensible loads, therefore a higher chilled water temperature is required; reduction of the refrigerant charge thanks to the lower size of the chiller in DCS.

Thermal energy input for regeneration in DCS can be provided by renewable energy technologies or thermal wastes. Therefore, hybrid DCS can be perfectly matched with MCHP systems, whose application in residential and commercial sectors is typically limited by the low thermal energy demand during summer period. Figure 5 indicates a micro-trigeneration system consisting of a DCS with DW coupled with a MCHP [3]. The electric power delivered by the MCHP can be used to activate the auxiliaries and/or to cover the electric demand associated to the appliances of the building; otherwise it can be exported to the external electric grid, that is also used as backup and integration system for the electric peak demands. The space cooling load of the building is met by the hybrid DCS, the thermal output of the MCHP is used to regenerate the DW and to meet DHW requirements.

Some investigations were carried out to evaluate the performance of DCS interacting with CHP systems. In [67], a test facility with a hybrid HVAC (Heating, Ventilation and Air Conditioning) system, placed in the South of Italy, was investigated. A MCHP supplied electricity to an electric heat pump and other devices. Waste heat recovered from the MCHP was used in summer to regenerate the DW. Surplus thermal energy was used to produce DHW. During winter, thermal energy from the cogenerator was used for heating purposes. Results indicated an electricity saving higher than 30 % in comparison to state-of-the-art conventional technology. In [68], a hybrid HVAC system coupled with a MCHP was analyzed.

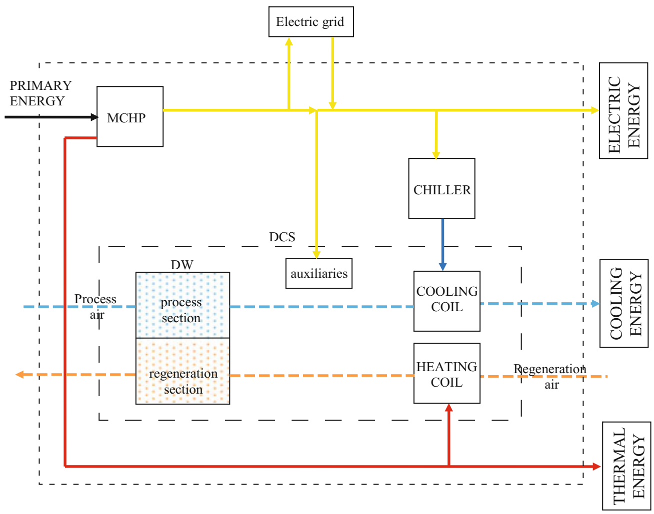

Fig. 5 MCHP/DCS-DW trigeneration system [3]

The test facility, placed in Hamburg, Germany, consisted of a MCHP, a desiccant assisted ventilation system and borehole heat exchangers, for sensible cooling by means of a radiant floor system. Thermal energy recovered from the MCHP, at a temperature between 55 and 65 °C, was used to heat the regeneration air, while electricity from the cogenerator powered the electric devices of the office. This system was compared with other systems, such as a hybrid HVAC system without MCHP and a conventional HVAC system. It was found that considerable primary energy savings can be achieved (70 %). Furthermore, running costs can be reduced drastically.

In [69], the performance of a DCS, where thermal energy for regeneration was provided by heat recovery from a gas-fired reciprocating internal combustion engine, was evaluated. Energy efficiency of the desiccant cooling system were evaluated and compared with those of a conventional system. In particular, the DCS operated with an electrical COP of about 5.3 that is more efficient than typical conventional systems. In [70], a natural gas-fired cogeneration system was employed in a leisure complex. Waste heat from the cogenerator was used to regenerate a desiccant wheel that performs dehumidification for the indoor swimming pools. To satisfy the thermal and electric load profiles, the installation of two gas-fired reciprocating cogenerators was considered, with electric power output of 185 and 95 kW. A payback period of about 4 years was predicted for the system. In [71], several HVAC configurations for product drying based on DW were investigated, in order to find the appropriate integration of refrigerating machines, adsorption wheels and cogenerators. It was shown that primary energy savings can reach 70–80 % compared to the reference technology. In [72], a hybrid air conditioning system, incorporating an engine-driven chiller and a DCS, was experimentally tested.

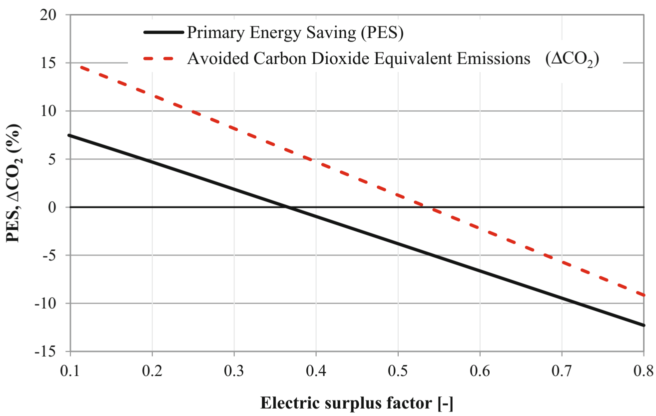

Fig. 6 PES and ΔCO_2 versus electric surplus factor for the MCHP/DCS-DW system [73]

Economic benefits of the hybrid air conditioning system over the conventional electric chiller were calculated for a reference building; the results revealed that, under current electricity/gas price ratio, about 30–40 % savings on operation costs can be achieved. The review of the scientific literature highlighted that the on-site utilization of the cogenerated electricity is crucial to obtain high levels of overall energy efficiency, along with the associated environmental benefits. As an example, Fig. 6 [73] shows the annual PES and ΔCO_2 associated to the combination of MCHP and DCS with DW as a function of the electric surplus factor, that is the ratio between the share of electricity from the MCHP exported to the grid and the overall electric output. The proposed system, compared to a conventional HVAC system based on separate production, provides a maximum primary energy saving and equivalent CO_2 emissions reduction of about 8 and 15 %, when the electric surplus factor is minimum (0.1, i.e., 90 % of cogenerated electricity is used on-site, for both auxiliaries and building appliances requirements).

4 Integration of MCHP Systems with Renewable Sources

About 40 % of final energy demand in the EU is related to residential and commercial sectors [74], most of this demand derives from winter and summer air conditioning of buildings.

In order to reduce the resulting primary energy demand and thanks to legislative measures and economic support mechanisms, renewable energy technologies, in particular solar systems solar collectors (SC), have been advantageously adopted. In the last few years they found a significant market diffusion. Today solar systems are used not only for space heating and DHW demands, but also for air conditioning of buildings (“solar cooling”) [75]. Solar-driven plants are usually integrated with devices fuelled by conventional fossil energy sources, boilers and/or heat pumps that can operate continuously, balancing the discontinuity and uncertainty of the renewable energy source. On the other hand, the integration of SC with high efficiency energy conversion devices, such as MCHP systems, is a solution designed and implemented only in few cases, even if the two technologies have been widely investigated and applied singularly. The coupling of SC and MCHP reduces the natural gas demands and the GHG emissions compared to the use of the micro-cogenerator alone. Nevertheless, these hybrid systems are very complex, therefore a detailed optimization tool is required to perform a correct design and control. Furthermore, they are characterized by very high installation costs and acceptable payback periods are quite difficult to be obtained. Therefore, the economic feasibility analysis is a very crucial tool in the assessment of these systems. In [74], an analysis of a combined solar-cogeneration installation to satisfy the energy demand in a set of four residential buildings was performed. Several sensitivity analyses were conducted, in terms of number and orientation of collectors, number of buildings grouped together, type of microturbines used in the cogeneration system, and their daily and annual operating period. In particular, four microturbines were considered, three of them with net electrical output lower than 100 kW. Economic and environmental analyses were also performed. The scenario that led to the highest energy, economic, and environmental savings is the integration of both technologies and the centralized installation for the four buildings together. A payback period lower than 8 years was obtained, but it was also concluded that maintaining the existing subsidies for these technologies and lowering the costs of the equipment are essential factors to ensure the feasibility of this type of installations. In [76], the comparison of several solar thermal, cogeneration, and thermally driven heating/cooling systems implemented into a typical mid-rise apartment, located in Canada, was presented. TRNSYS simulation software was used to model the system and to predict the primary energy consumption, GHG emissions and annual utility costs of the various systems and compare them to the base case. The highest annual utility cost and GHG emission savings (21 and 16 %, respectively) were attained by operating a cogeneration device in priority over the SC, and using thermal energy to feed an ABHP. Comparing this system to a cogeneration only system, a primary energy saving of 12 % was predicted demonstrating the benefit of adding SC and a thermally driven heat pump to a cogeneration system. In [77], a study dealing with the hybridization of Stirling-based MCHP systems with SC was performed. Simulation results of four configurations applied in various Canadian locations were presented and compared to systems without solar input. The results showed that adding solar collectors to a residential MCHP system has a clear potential to reduce natural gas consumption (in the range 10–15 %) and GHG emissions (approximately 700–1200 kg per house per year). In [78], the performance of hybrid renewable microgeneration systems in load sharing application between a detached residential house and a small office building was investigated. Two systems were considered: a ground source heat pump (GSHP) system and a hybrid GSHP/FCsystem. Their performance was compared with that of a conventional system that used boiler and chiller to meet the thermal loads of the two buildings. Models were developed for the three systems and then simulated over one full year under Ottawa, Canada weather conditions. The results showed that the integrated hybrid GSHP/FC system achieved an overall energy saving of 24 % and, thanks to the additional electricity generated with respect to GSHP alone, can lead to more significant cost savings. Additionally, the GSHP/FC system's capability to generate both heat and power at the point of use was considered more attractive for inclusion in "smart" grid applications.

The literature review stated that hybrid MCHP/SC are more suitable for cold climates, where large amounts of thermal energy is required for space heating needs of buildings. In hot climates locations, such as Mediterranean regions, to achieve significant operation hours of both the MCHP and the SC, it is necessary to add a thermally activated cooling system that provides air conditioning service during summer, as seen in Sect. 3 and as shown in [75], where a DCS is activated by means of thermal energy from the MCHP or the SC, respectively.

Figure 7 shows the scheme of a trigeneration system based on MCHP and solar thermal collectors. In summer, thermal energy from the SC and MCHP is stored in a (Thermal Energy Storage) TES and used to activate a THP and to cover possible heating needs, for example for DHW. In winter, thermal energy is used to directly meet the thermal loads of the user. The electricity produced by the MCHP meets the electric load of the user and drives the auxiliaries of the plant. When the electricity production is low compared to the required amount, further electric power is taken from the electric grid; when the production exceeds the demand, the exceeding part is fed into the grid.

The authors simulated the summer operation of a system with MCHP, SC, and ABHP that serves an 81 m^2 open space office, with square plan and located on the ground floor of a building in Naples, Southern Italy. It has north and south external walls and east and west internal walls with thermal characteristics set according to the Italian legislation. With respect to Fig. 7, the simulated plant contains an additional electric backup system that heats up the water at the outlet of TES to ensure the minimum operating temperature of the ABHP (70 °C). No heating demand was considered. The solar field consists of evacuated tube solar collectors facing south

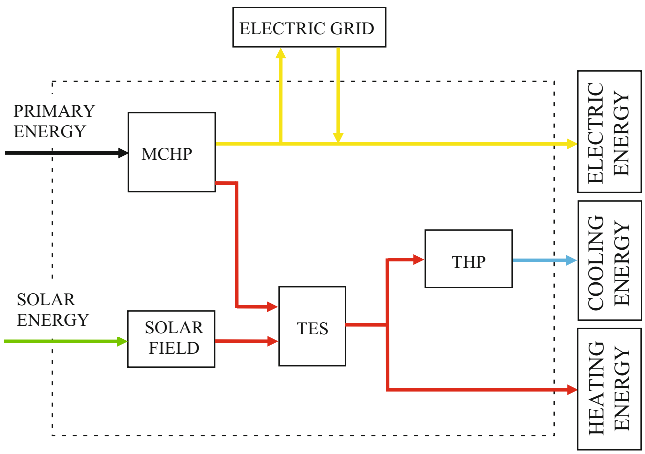

Fig. 7 MCHP/SC-based trigeneration system

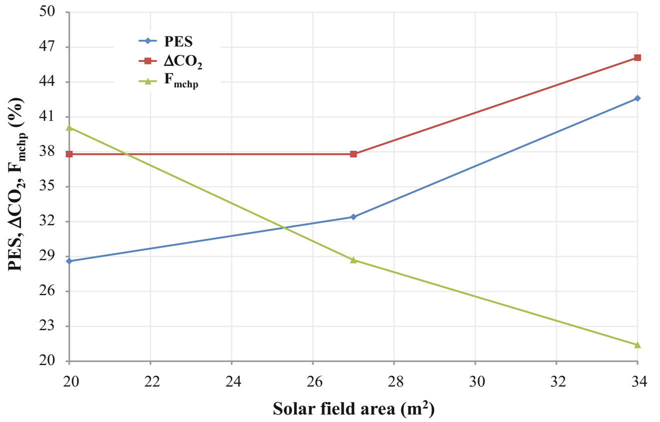

Fig. 8 Energy and environmental impact analysis of the MCHP/SC system

with tilt angle of 35°. Three collector areas were considered: 20, 27, and 34 m^2 [79]. The MCHP has a rated electric power of 5.5 kW [80]; the absorption heat pump has a rated cooling capacity of 17.6 kW [81]. The system is compared with a conventional scenario, where an EHP (COP = 3.0) and the electric grid are used to meet cooling and electric energy demands, respectively. Figure 8 shows that the increase of the solar field area determines a rise in PES (up to 42 %) and ΔCO_2 (up to 46 %). Instead the fraction of thermal energy supplied by the MCHP with respect to the total thermal energy needed to operate the plant (F_{mchp}) decreases.

5 Building-Integrated MCHP Systems: "Load Sharing Approach"

The diffusion of MCHP and MCCHP systems can significantly contribute to the reduction of primary energy consumption and equivalent CO_2 emissions attributed to the residential and commercial sectors. In recent years, different researches [3, 82, 83] highlighted the advantages of MCHP or MCCHP system in a typical residential or commercial buildings. All these studies highlighted how the energy and the environmental benefits of these systems in residential and commercial users cannot be disputed, but some obstacles could jeopardize the diffusion of these promising technologies. First, the high specific investment cost (€/kW) of MCHP systems due to size effect and immature state of some technologies leads to long investment's payback period. In addition, the installation of MCHP systems in residential or tertiary applications brings about low operating hours per year of the system, and consequently high payback periods. This aspect is more obvious in Mediterranean area due to the relatively mild climatic conditions, which negatively affect the operating hours per year. As regards the electricity network, the advantages or disadvantages related to the distributed generation depend on its penetration. With low and moderate use of distributed generators, costs can be saved while with very high penetration the network may even need to be reinforced [84].

In order to overcome these negative aspects, one interesting solution can be the load sharing approach, which consists in the introduction of a small electric and thermal microgrid allowing the share of electric, thermal, and cooling loads among a group of diversified end users (residential, commercial, institutional, etc.). In this way it is possible to increase the operating hours of the MCHP system. In moderate climatic conditions, like Italian ones, typically characterized by low thermal load and few hours of heating system operation, the MCHP can achieve satisfying economic, energy, and environmental performance. In fact, as an example, the thermal load of residential users typically occurs in the evenings and early mornings, while for commercial users it occurs during the day time hours. By coupling these two users, a single common energy conversion system can be considered to satisfy their thermal energy requirements, increasing its operating hours. In addition, the introduction of a small microgrid in load sharing approach can reduce the load flow between the microgrid and the distribution network, increasing the percentage of self-consumed electricity. In this way, the microgrid can operate closely to "island" mode and reduce the impact of the large-scale diffusion of distributed generation. Figure 9 shows a MCCHP system in load sharing approach that consists of a MCHP that interacts with a TES and a thermally activated heat pump (ABHP or ADHP). The MCCHP system meets the electric, thermal, and cooling loads of a group of diversified users (load sharing).

The application of micro-cogeneration and micro-trigeneration in residential or tertiary buildings with load sharing strategy has been addressed in some literature works. Angrisani et al. [85] investigated a MCHP unit serving two users, an office building and a residential one, connected through a district heating microgrid. Particular attention was paid to the choice of the users, in order to obtain more stable and continuous electric and thermal loads. The operation of the MCHP was

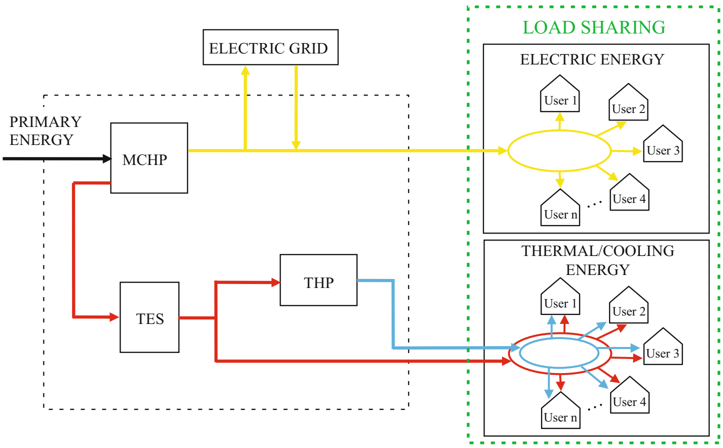

Fig. 9 MCCHP system in load sharing approach

governed by a control system, aimed to optimize a thermo-economic objective function. The paper showed how the introduction of a load sharing approach allows to increase the operational hours of the MCHP unit. Piacentino et al. [86] analyzed an algorithm oriented to optimize synthesis, design and operation of polygeneration systems including thermal energy storages and interconnected by a hot/warm fluid distribution network, serving with heat, cooling and electricity a cluster of buildings located over a small area. A mixed integer linear programming algorithm allowed to optimize the design and operation of the trigeneration system. Hirvonen et al. [87] investigated the energy performance of a MCHP system serving a cluster of several different buildings in Japan. Absorption and conventional electric chillers were used for cooling demand. Different operation modes and CHP capacities were tested for a cluster of an office building and a residential building. The reduction of primary energy consumption resulting from load sharing was between 1 and 9 % when using biogas as primary energy source of the CHP and between 1 and 6 % when using natural gas. The same research group in [88] analyzed energy-sharing possibilities among four different buildings in Japan (office buildings, hotels, hospitals, and shopping centers). The comparisons between the separate and shared cases showed that the advantages of energy-sharing cases depend on the type of combined buildings and on the CHP operational strategy. The load sharing approach was investigated also for small-scale hybrid trigeneration systems by Canelli et al. [89]. Once the advantage of load sharing approach was demonstrated, the performances of two different hybrid systems in load sharing scenario were analyzed. The first hybrid system consisted of a micro-cogenerator based on a FC and a GSHP, while the second consisted of PVT collectors and a GSHP. The hybrid micro-cogeneration systems showed good improvements both in terms of energy and environmental performance. In particular the GSHP-FC allows a PES of 12.8 % and a ΔCO_2 equal to 15.8 %. The hybrid GSHP-PVT obtained the best performance in relation to the other cases, with a PES equal to 53.1 % and a ΔCO_2 equal to 52.0 %. The authors demonstrated how the load sharing approach allows to improve the economic performance also in case of hybrid MCCHP system. The SPB resulted equal to 12.7 and 18.5 years for the GSHP-FC and GSHP-PVT, respectively. Angrisani et al. [90] analyzed the installation of MCHP system, based on a reciprocating internal combustion engine, in buildings with low energy demand in load sharing approach. The results indicated that, in well-insulated residential or tertiary buildings, the introduction of a thermal and electric microgrid between different users can help to have thermal and electric load profiles suitable for the MCHP application. Well-insulated buildings, having lower demand-side heat-to-power ratios (in the range 2.5–3 in the investigated paper) with respect to the average existing stock, perfectly match with the quite low values of the plant-side heat-to-power ratio of MCHPs based on internal combustion engines (about 2 in the investigated case). This aspect allowed to increase the percentage of self-consumed electricity reducing the bidirectional electricity flow between the local users and the external grid, with positive effects on the economic analysis and on the impacts of the large diffusion of distributed generation systems on the grid. The climatic conditions played an important role on the MCHP operational hours and hence on the thermo-economic performance of the system, therefore the energy, environmental and economic performances were investigated in two geographical locations (Naples and Turin). The primary energy saving of the system located in Turin was equal to 8.8 % with respect to 6.2 % of the system located in Naples. Also the environmental performance, evaluated in terms of equivalent CO_2 avoided emissions, is better in Turin (8.3 %) than in Naples (6.7 %). The economic analysis showed acceptable values of the payback period in the presence of economic support mechanisms. The findings of this study showed that the introduction of a MCHP system in load sharing approach leads to thermo-economics advantages even considering the lower heating needs of well-insulated buildings.

5.1 MCHP Systems Integrated with Electric Vehicles (EVs)

The diffusion of electric vehicles (EVs) could help in (i) reducing the large energy consumption of the transport sector and related greenhouse gases emissions [91], (ii) improving the local air quality in urban areas thanks to the reduced emission of local pollutants (such as NO_x, CO, SO_x, particulate matter, unburned hydrocarbons, and so on [22, 24]), (iii) alleviating the almost total dependence of the transport sector on oil (moving the energy demand from oil to electricity, and thus offering the opportunity to use innovative high conversion efficiency technologies and/or renewable energy sources), and (iv) lowering the costs per kilometer for the end users when compared to internal combustion engine vehicles [92]. The number of electric vehicles is still a small percentage of the total fleet, but it is increasing exponentially. However, a widespread adoption of electric vehicles could result in the need of upgrading the electricity distribution infrastructure in the case of utilities not being able to meet the additional requirements [93, 94]. Building new power generation capacity takes time and, thus, foresight on future power generation capacity requirements is necessary for appropriate planning. Several possible electric demand-limiting strategies have been investigated [95–98], such as (i) the time shifting of EVs battery charging (battery charging was restricted to periods of off-peak electrical demand), (ii) the transmission of electricity from an on-board battery to the central electric grid and (iii) the smart battery charging (customers and network operators can schedule EVs charging profiles in order to get technical and economic benefits). However, one of the most promising options in order to avoid or at least contain the negative effects on the electric distribution network associated to a widespread use of EVs is using micro-cogeneration systems. In addition, it should be underlined that the primary function of most MCHP systems applied in residences is to provide heat for space heating and for domestic hot water; the micro-cogeneration device generally operates under a heat-load following control strategy, with a large fraction of the electricity usually being produced at times when the electric load of the building is low, requiring substantial amounts of electricity to be exported with low revenues. EVs consume considerable amounts of electricity and they could thus be a way to drastically increase the own use of electricity produced by the micro-cogeneration devices as well as boost the profitability of the system. The possibility of charging the EV also in the case of an electric grid failure occurring is an additional potential advantage.

Several papers analyzed the possible synergy between micro-cogeneration and electric vehicle charging. Ribberink et al. [99] investigated the impact of electric vehicle charging on the economics of a 2 kW_{el} internal combustion engine-based MCHP system applied in a detached house in Ottawa (Canada) in a simulation study. In [100] the performance of a fuel cell cogenerator system combined with a plug-in hybrid EV was studied through an optimal operation planning model based on mixed integer linear programming. The effect of the introduction of overnight EV charging on the energy, environmental and economic performance of a residential building-integrated micro-cogeneration system was simulated in [101, 102]. Angrisani et al. [103] analyzed the integration between a MCHP system and the energy demands of both an electric vehicle and a typical semidetached house by means of dynamic simulations. Sibilio et al. [104] investigated the yearly operation of a building-integrated micro-trigeneration system by considering four different EV charging profiles representing scenarios in which electric vehicles would drive two different daily distances (30 and 53 km) and would be charged at different power levels (2.2, 3.6 and 6.6 kW_{el}). The simulation results demonstrate that, whatever the EV charging profile is, the micro-cogeneration technology is potentially able to alleviate the impact on the central electric grid by reducing both the values of the annual average electric power demand as well as the values of the annual electric energy consumption (Fig. 10). In addition, the analysis highlighted

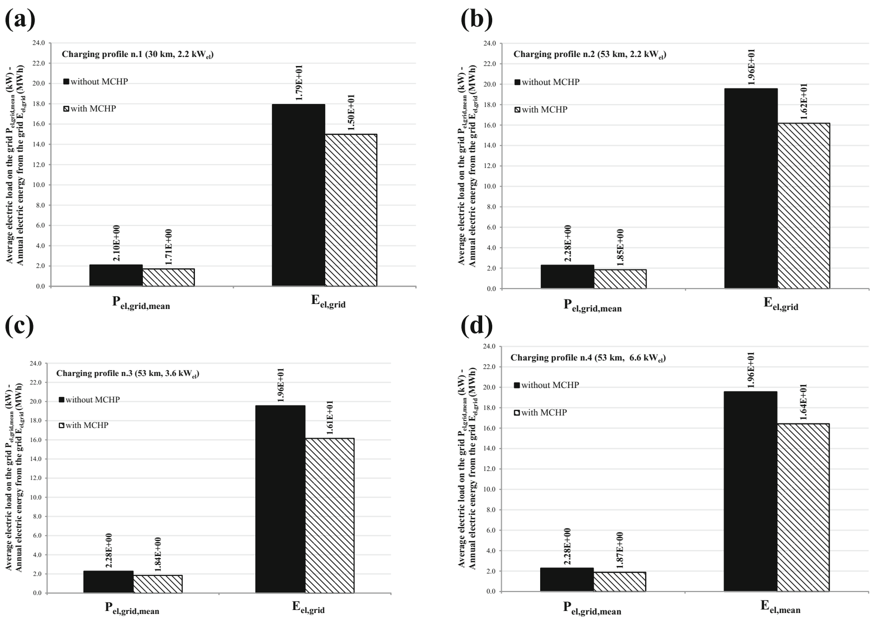

Fig. 10 Average electric power load on the central grid and annual electric energy purchased from the power line upon varying the EV charging profile (modified from [104])

that the combination of a MCHP unit with EVs allows for a reduction of the annual primary energy consumption in comparison to a conventional system based on separate energy production equal to around 6.6 %.

6 Conclusions

The transition from conventional centralized energy systems, based on separate "production", to the incoming decentralized MCHP units is currently in progress. This is due to the market availability of a wide variety of micro-cogeneration devices.

Fossil fuel-based microgeneration systems can achieve primary energy and emissions savings in the range of 5–20 %, depending on the type of system and application. These savings increase up to 40 % when renewable energy technologies are involved in hybrid microgeneration systems. The increase in energy efficiency with such MCHP systems brings a corresponding reduction of global emissions of equivalent CO_2 in a first approximation similar to the amount of energy saving, and can also contribute in reducing the local pollution. In terms of economic performance, the initial installation cost is often still considerably high. This can determine quite long payback periods, even assuming that selling the electric surplus to the grid is possible and all the support mechanisms introduced by national legislations are effectively achieved. Therefore, additional specific financing mechanisms should be promoted.

The development of small cooling units, namely absorption and adsorption chillers and their integration into MCHP systems, offers new possibilities to apply this technology in applications with relatively low heating requirements but significant cooling needs.

However, significant research has still to be performed in order to optimize their integration into the building energy supply systems (solar thermal collectors, PV systems, geothermal heat pumps, etc.), thus allowing the achievement of energy targets of Nearly Zero-Energy Buildings (NZEB). Additional investigations should be carried out in order to improve the layout and operation of MCHP/MCCHP systems, as well as to develop advanced control schemes. Storage technologies and their implementation into building energy supplies should be investigated further, taking into consideration charging of electric vehicles or using second-life batteries within buildings.

Integration of MCHP units into smart energy networks and microgrids should be also analyzed in more detail in order to support the security of supply by offering system services as demand response, as well as additional work on the impact of a significant number of microgeneration installations on the power supply system should be carried out in the near future.

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