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Review

Distributed microtrigeneration systems

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ABSTRACT

In recent years, great attention, both in research and application fields, has been focused on the transition from centralized to decentralized (or Distributed Generation, DG) energy "production" systems. This process is currently being carried out partially. The benefits and drawbacks that DG will provide to the end-user and to the community have also been analyzed in both technical and scientific literature. All over the world researchers are strongly involved in the so-called *"hydrogen economy"* scenario that expects a geographically widespread system of production, storage, transportation and use of hydrogen.

Furthermore, the actual industrial trend towards the miniaturization of the energy conversion equipment, due mainly to reducing manufacturing costs, results in the availability of a wide variety of small scale power, refrigeration and heat pump systems in the market. Very soon, small, micro and nano mechanical and thermal devices will be used in actual applications.

In many sectors, small scale energy conversion plants (Polygeneration, Trigeneration, Combined Cooling Heating and Power) allow for the satisfaction of different energy requirements (electricity, cooling and heating) with a great potential for primary energy saving and greenhouse gas emission reduction. The "core" of these technologies is a prime mover based on different technologies (Stirling, Reciprocating Internal Combustion, Fuel Cell, Gas Turbine, …), specially designed to operate in stationary conditions for a long time. This operation is accompanied by high efficiency output and very low pollutant emissions with regards to the reference separate "production" by large thermal power stations.

At the moment, the most common technology, the gas-fired Reciprocating Internal Combustion (RIC) engine, has very good features e.g. in terms of installation space, thermal efficiency, low noise and vibration and maintenance. These engines can drive electric generators and/or electric heat pumps, absorption heat pumps and so on in different ways (mechanically, electrically and thermally), thereby allowing a wide range of operating conditions to match thermal (heating and cooling) and electric end-user requirements.

The aim of this paper is to study the Energy, Economic and Environmental implications (3-E analysis) of using these complex small scale trigeneration energy conversion systems, starting with the results of an intensive theoretical and experimental research activity. In particular these systems, in comparison with conventional system, based on separate energy production, can guarantee a primary energy saving up to 28% and a reduction of equivalent CO_2 emissions up to 36% when the trigeneration system is based on a small scale cogeneration system (Micro Combined Heat and Power, MCHP) coupled to a Heat Pump (HP). Satisfactory results can be achieved considering a cogeneration system which interacts with an Electric Heat Pump (EHP). On the contrary, small scale trigeneration systems based on Thermally activated Heat Pump (THP) show low efficiency, with respect to conventional systems. This is due to the low COP of small scale cooling devices which is the reason why these systems require further improvements to be able to compete with traditional one.

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1. Introduction

Cogeneration, or Combined Heat and Power (CHP), represents the combined production of electric (and/or mechanical) and thermal energy (heating), from a single primary energy source, [1]. It is a well established technology, which has important benefits and has been noted by the European Community as one of the first elements which saves primary energy, reduces greenhouse gas emissions with respect to the reference separate "production" by large thermal power stations and avoids network losses, [2]. Furthermore, in many sectors such as hotels, hospitals, commercial buildings, Combined Cooling, Heating and Power (CCHP) systems allow for a simultaneous satisfaction of different energy requirements (electricity, cooling and heating), [3]. The "core" of these energy conversion systems is a Prime Mover, PM, based on different technologies, characterized by high efficiency and very low pollutant emissions. At the moment, gas-fired RIC engines represent the most mature technology available on the market; it achieves small installation space, high mechanical efficiency, low maintenance and long life service, [4,5]. These engines can operate, by means of mechanical, electrical or thermal energy outputs, electric generators and/or electric heat pumps, absorption heat pumps, desiccant wheels and so on, allowing a wide range of operating conditions to match thermal (space heating and cooling, domestic hot water) and electric end-user requirements, [6].

Different definitions of small-size cogeneration (microcogeneration, MCHP), with respect to maximum electric power output, are available in technical and scientific literature. European Directive on the promotion of cogeneration sets this value at 50 kW_{el}, [2]; Ugursal et al. analyze residential CHP systems considering applications that are suitable for single-family and multi-family households (generally covered by systems of <10 kW_{el} and <25 kW_{th}); De Paepe et al. study residential applications of MCHP systems (<5 kW_{el}) for detached single-family household, [7]. Simader et al., referring to MCHP systems, consider electric power output, which is lower than 15 kW_{el}, suitable to satisfy energy requirements of single buildings (residential, small commercial, …) as it does not feed thermal energy to a district or neighbourhood (district heating systems), [4]. Microcogeneration in [8] is defined as the simultaneous generation of heat and power in an individual building based on small energy conversion units below 15 kW_{el}. The authors report that these systems differ from larger ones with respect to electricity distribution, ownership models and on consumer behaviour. Dentice et al. refer to residential and light commercial application to characterize MCHP and Domestic CHP (DCHP) system considering the maximum power output of 15 kW_{el}, [9]. In [10] the electric power output of cogeneration systems that could be included in MCHP systems is lower than 10 kW, even though the authors report that there is no standard size to define microcogeneration.

As regard to the content, this study will be focused on microtrigeneration, MCCHP, systems delivering electric power output lower than 15 kW, which represents a valid and interesting application especially suitable for residential and tertiary sector.

MCCHP can represent the base of the shift, that is already partially being carried out, from centralized to decentralized energy "production" systems. In fact there is an increasing interest on this transition, proven by a significant number of R&D projects worldwide on trigeneration systems based on thermally activated equipments, [11].

Starting from the results of an intensive theoretical and experimental research activity, the Energy, Economic and Environmental implications (3-E analysis), due to the use of these complex small scale trigeneration energy conversion systems, have been reported.

1.1. Decentralized Trigeneration

Fig. 1 shows the traditional energy flow which, starting from required primary source, is converted, usually in a large plant, and then transmitted to the end-user to satisfy energy demands. In many cases, the energy flow is converted in a decentralized energy conversion plant, very close to the end-user, and then distributed to the final appliances.

In the flow path, as in each energy conversion system, losses occur and consequently the desired energy flow is always different from the supplied one. Nevertheless, the above scheme is quite general and could be used to analyze the miniaturization process (*"size"* effect) of the energy conversion devices, that has been in progress in the recent past years:

-the continuous line highlights the transition from the centralized to decentralized system that is usually approached as Distributed Generation;
-the dotted line highlights the development of Micro Chemical and Thermal Systems (Micro-CATS) and of Micro Electro Mechanical Systems (MEMS) [12].

In both cases, the miniaturization process leads to a reduction of the duct losses due to distribution and/or transmission of working fluids and energy cycling losses.

DG includes the application of small scale generators, located on the utility system, at the site of a utility customer, or an isolated site

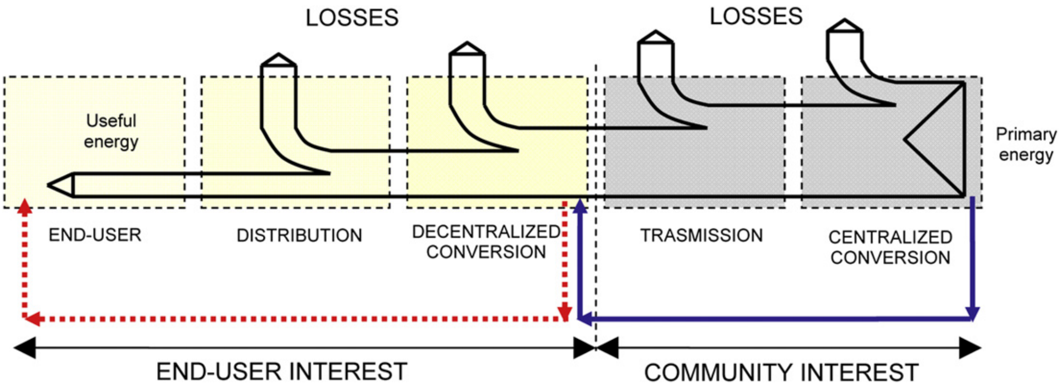

Fig. 1. Sankey diagram of energy conversion processes.

not connected to the grid, to provide electrical power needed by electrical consumers. The bulk of electric power used in the world is delivered by centralized power plants, most of them utilizing large, fossil fuel combustion or nuclear power plant to produce steam to drive steam turbine generators. DG can provide lower operating costs in many cases by avoiding or reducing transmission and distribution costs.

In order to ascertain that the miniaturization process will provide energy and environmental benefits, special attention must be paid to finding the optimal tradeoff between the advantages, due to the reduction of duct and cycling losses, and the disadvantages due to the negative influence of the size on the system performance [13,14].

In [15] the exergetic efficiency for electricity generation of the main energy conversion systems in use today, has been evaluated as a function of the electric power of the plant (*"size"*) in the range 0.01–1000 MW. All the systems, based on renewable energies (photovoltaic, solar thermal, wind and hydroelectric) and non-renewable ones (reciprocating internal combustion engines, steam and gas turbines, combined cycles, nuclear power plants and fuel cells, …) exhibit an exergetic performance index decreasing with the *"size"*.

In [16], the comparison between the centralized power system, based on plants of an average age of over 20 years, and the distributed one is analyzed.

Small, modern generators can be more efficient and less costly to operate than large and old generators. These circumstances have led some people to conclude that there is no longer an economy of scale in power generation. But a large modern power generation unit has higher electric efficiency and lower operating cost per kWh delivered than a small modern DG unit based on the same technology.

Since the *"size"* effect does not always lead to energy savings and pollutant emissions reduction, there is the need to support the diffusion of on-site small complex energy conversion devices, Decentralized Trigeneration (DT), which are able to supply, with high performance, two or more energy requirements (electric, cooling and heating) of the end-user rather than the simple single-output equipments.

In many cases, mainly in the tertiary sector (hotels, offices, shopping centres, commercial buildings, hospitals, airports, sports centres, …) a widespread use of DT systems has produced energy, economic and environmental benefits.

To define the combined "production" of electric (and/or mechanical) and thermal energy (heating and cooling) starting from a single energy source, many definitions have been used, such as, Total Energy, Trigeneration, Polygeneration and CCHP systems. In many cases polygeneration systems produce not only electric and thermal energy but also hydrogen and various chemical compounds [17].

Our analysis will be focused on a subsystem including only energy flows (electric, heating and cooling) representative of a trigeneration system.

CCHP is an upgrade of cogeneration unit where thermal or electric energy is further utilized to provide space or process cooling capacity. In this way, the energy efficiency increases and the economic payback decreases due to the large amount of operating hours per annum.

The main benefits of gas fuelled CCHP with respect to the reference separate energy "production" system, based on a centralized Power Plant (PP), a Boiler (B) and an Electric Heat Pump (EHP), are:

- energy independence of the user;
- primary energy saving;
- low pollutant emissions;
- reduction of fuel costs;
- a widespread use of Gas Cooling Technologies, GCT, to shift from electricity to gas due to the high energy demands during warm seasons, in turn caused by the large diffusion of electrically-driven HVAC systems, especially in residential applications;
- increased safety of supply due to redundancy, in case of grid-connected systems.

On the other hand, however, the introduction of MCHP systems within urban areas, where the problem of air quality standards is very prominent, requires that the effects of local emissions, which depend, above all, on the fuel and technology used, must be taken into account, [18]. Hazardous air pollutants such as NO_X, CO, SO_X, particulate matter, unburned hydrocarbons and so on, lead to the expansion of the environmental analysis considering not only the global effects, for example through the evaluation of equivalent CO_2 emissions, but also the local effects. The concentration of these pollutants is also affected by the morphology of the territory and climatic conditions and could happen that MCHP systems could lead to an increase in local emissions, [19,20]. Furthermore, specific emissions of MCHP and MCCHP systems at partial load are greater than those found at the rated load. These aspects lead to the introduction of a further element of variability in the analysis of the local environmental impact, [21].

Typical CCHP operating modes are:

- *"separate"*: the system provides heating during cold season, cooling during hot period and power all year round (seasonal operating cycles). This strategy is usually adopted in residential and tertiary sector;
- *"simultaneous"*: the CCHP, in addition to supplying electric energy, simultaneously satisfies cooling and heating requirements to meet industrial or residential loads.

CCHP system, CHP/THP, which is usually adopted consists of four basic components, Fig. 2:

- a prime mover, PM;
- an electricity generator, G;
- a thermal recovery system (exhaust gas and engine cooling liquid);
- a cooling energy "production" system which is usually adopted as a Thermally activated Heat Pump, THP, fuelled by thermal energy instead of mechanical energy. This energy system, interacting only with external thermal reservoirs, operates as a heat transformer.

Further technologies allow for the satisfaction of cooling demands using CHP mechanical energy outputs:

- mechanically-driven system, CHP/HP: which is a Heat Pump (HP) activated by mechanical energy supplied by PM;
- electrically-driven system, CHP/EHP which is a conventional EHP driven by G.

It is common knowledge that a CCHP, or a CHP, usually interacts with the external electricity grid to optimize the system operating modes with respect to technical, energy and economic restraints.

1.2. Micro-cogenerators

At the moment micro-cogenerators, based on reciprocating internal combustion and Stirling engines, are already available in the market and a large R&D activity which aims at producing, in the medium and long period, small commercially available units based on fuel cells, gas and steam turbines, is already in progress, [4–23].

1.2.1. Reciprocating internal combustion engine based systems

A lot of the current micro-cogenerators, based on RIC engines, fuelled by natural gas, have been designed starting with small Gas engine driven Heat Pumps, GHP, which were developed since 1979, in Japan, USA and in Europe [24,25]. An MCHP could be derived by a GHP if the compressor is substituted by an electric generator. A lot of effort has been put into both developing new small displacement engines for stationary use and allowing engine heat recovery, with a particular attention on the design of the exhaust gas heat exchanger, which is also the engine muffler. Some specifications were required:

- high efficiency: an appropriate combustion chamber was designed to achieve a rapid combustion and a reduction of frictional losses;
- good durability: a forced oil circulation was employed for all engine surfaces together with the development of oil specially produced for gas engines. Furthermore, an appropriate choice of materials and valve seat angle, and also an improvement of material quality, shape and surface treatment were made to optimize the engine maintenance.

The manufacturer data of different MCHP systems based on RIC engine are shown in Table 1:

- these systems occupy small installation space;
- they have satisfactory electric (24–34%) and thermal (50–65%) efficiencies even though the size is very small, while cogeneration systems with a rated power exceeding 1 MW have electric efficiencies in the range 37–47%, [26];
- they have acceptable noise (<60 dB(A) at 1 m) and vibrations, comparable with those of large-size cogenerators;

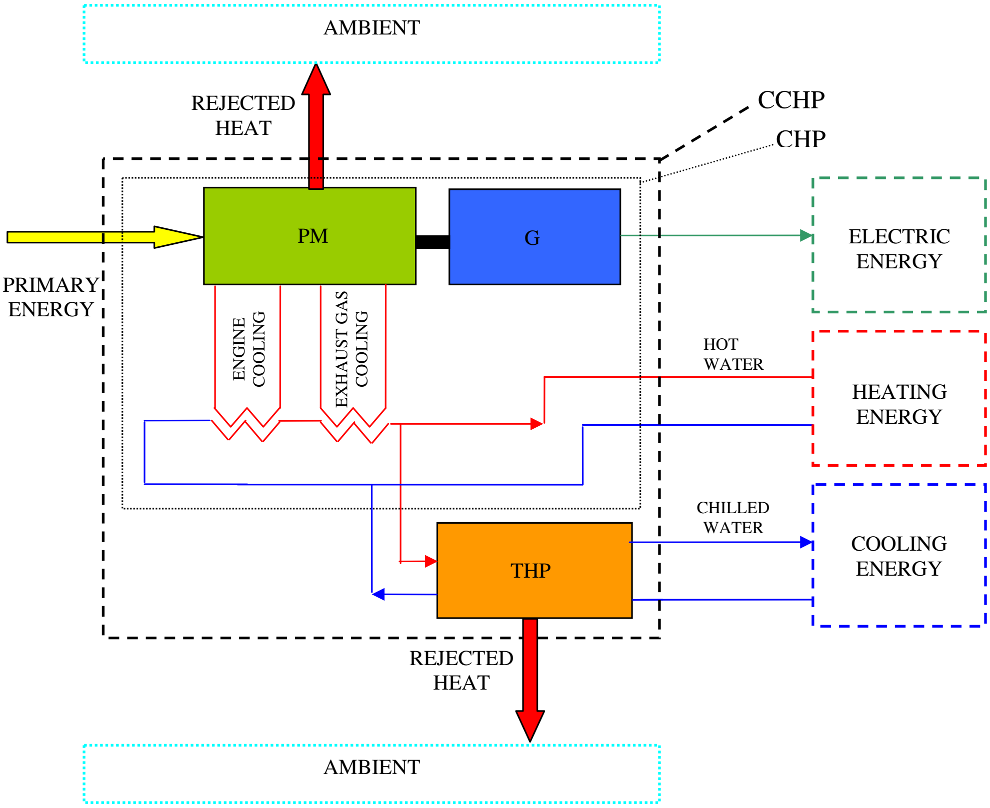

Fig. 2. A CCHP system.

Table 1
RIC based micro-cogenerator manufacturer data.

		Honda Ecowill	Aisin Seiki GECC 46 A2	Ecopower e4.7	Senertec Dachs HKA G 5,0	Yanmar CP5VB	Senertec Dachs HKA H 5,3	Senertec Dachs HKA G 5,5	Aisin Seiki GECC 60 A2	Tedom micro T7 AP	Yanmar CP10VB1	Cogengreen Ecogen-12AG	ECpower XRGI 13 NGAS
Power [kW]	Input power	4.4	18.0	18.9	19.6	17.2	17.6	20.5	20.8	27.0	31.4	31.4	46.4
	Electric power	1.0	4.6	4.7	5.0	5.0	5.3	5.5	6.0	7.0	9.9	11.7	13.0
	Thermal power	2.8	11.7	12.5	12.3	9.6	10.3	12.5	11.7	18.0	16.8	26.5	29.0
Efficiencies [%]	Electric efficiency	22.5	25.5	24.8	25.5	29.0	30.0	26.8	28.8	25.9	31.5	28.5	28.5
	Thermal efficiency	63.0	58.5	66.0	62.7	55.8	58.5	59.8	56.2	66.7	53.5	64.6	62.5
	Overall efficiency	85.5	84.0	90.9	88.2	84.8	88.5	86.6	85.0	92.6	85.0	93.1	90.5
Fuel		Natural gas, LPG	Natural gas, LPG	Natural gas, Propane	Natural gas	Natural gas, LPG	Biodiesel	Natural gas, LPG	Natural gas, LPG	Natural gas, LPG	Natural gas, LPG	Natural gas, LPG	Natural gas
Weight [kg]		83	465	390	530	410	530	530	465	645	790	750	750
Dimensions [mm]	L	580	1100	760	720	1100	720	720	1100	1350	1470	1450	1250
	H	880	1500	1080	1000	1500	1000	1000	1500	1250	1790	1200	1110
	D	380	660	1370	1070	500	1060	1060	660	760	800	750	750
Engine	No. Cyl.	1	3	1	1	3	1	1	3	3	3	4	4
	Displ. [cm^3]	163	952	270	579	699	579	579	952	962	1642	1600	2237
Generator		Inverter three phases	Inverter synchronous single phase	Inverter synchronous three phase	Asynchronous three phase	Single phase	Asynchronous three phase	Asynchronous three phase	Inverter synchronous single phase	Inverter three phase	Inverter three phase	Asynchronous three phase	Asynchronous three phase
Noise [dBA]		44	54	56	56	51	58	56	54	58	54	53	49

- they have low maintenance cost (only change of spark plugs and oil once a year, corresponding to about 4000 h) and long life service (up to 80,000 h, corresponding to about 10 years).

Finally due to lean burn, NO_X emissions are less than 100 ppm with a stable shaft power output in an engine speed range between 1200–3000 rpm.

A number of RIC engine based cogeneration systems, suitable for the residential sector, are currently available in the market and their specific cost range between 2000 and 3000 €/kW$_{el}$ (see Fig. 3) when electric power is higher than 5 kW and strongly depends on the country where the product is sold on the basis of economic support measures that may be present, [9].

A Japanese manufacturer [27] *has* developed a small scale cogenerator [28]. This is a 1 kW electrical and 2.80 kW thermal output cogeneration unit, designed for single-family applications with an overall energy efficiency of 85%. In the period 2003–2009, about 86,000 units were sold in Japan with the introduction of a new model in the North American market in 2006, capable of supplying 1.2 kW of electric power [29].

An MCHP, [30–35], also produced in Japan, was introduced on the market in February 2002; it is based on a 3-cylinder-952 cm^3 RIC engine, supplies an electric output of 6 kW and 11.7 kW of thermal power, with a total efficiency, at full load, equal to 85%.

A German manufacturer, [34–40], which until now has installed over 25,000 units in Europe, produces a cogeneration unit of 5.5 kW electric and 12.5 kW thermal power. This unit is based on a one-cylinder four-stroke Sachs engine which has a displacement of 579 cm^3 and can be fuelled by natural gas, LPG, fuel oil or biodiesel. The total efficiency at full load was lower than 90%. With an optional exhaust gas heat exchanger, the thermal output could be raised to 13.3 kW with a total efficiency equal to 92%.

A German company proposes an MCHP, [39–43], based on Briggs & Stratton 5HP engine, fuelled by natural gas or propane, of 4.7 kW electrical and 12.5 kW thermal outputs for an overall energy efficiency of up to 92%. The cogenerator can modulate the electric power between 2.0 kW (6.0 kW of thermal power) and 4.7 kW (12.5 kW of thermal power).

A further Japanese based company produces MCHP systems (5 and 10 kW$_{el}$). These units can use different fuels including natural gas, propane, biogas. Since 1998, about 3500 units (1500 for 10 kW$_{el}$ model) were sold in Japan [44].

A Czech Republic company is commercializing a micro-cogenerator which delivers 7 kW of electric power and 18 kW of thermal power with an overall efficiency of about 93% [45].

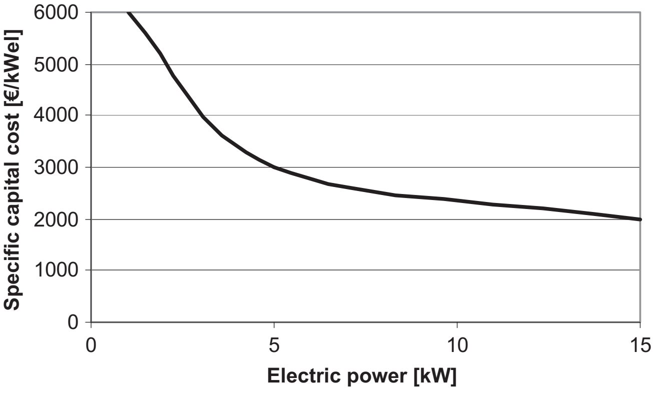

Fig. 3. Specific capital cost as a function of electric power.

The success in marketing RIC based small CHP is due not only to technical reasons but also to non-technical reasons. Among these the direct involvement of gas utilities is of primary importance. They should offer complete maintenance service operation, to make customers feel confident in purchasing MCHP, and summer discounted rates, to provide the end-user with significant operation savings.

1.2.2. Stirling engine based systems

The Stirling engine was invented in 1816 by Robert Stirling in Scotland, but at the beginning of last century, due to the rapid development of internal combustion engines, these engines were partially abandoned [46]. This technology is based on an external combustion engine allowing the use of different primary energy sources including fossil fuels (oil or natural gas) and renewable energy sources (solar or biomass). In this engine, the working gas (helium, hydrogen, oxygen, nitrogen, carbon dioxide, …) operates on a closed regenerative thermodynamic cycle, with cyclic compression and expansion of the working gas at different temperature levels.

The technology is not fully developed yet, and it is not widely used. However, there is an increasing interest in the use of small scale cogeneration systems based on Stirling engines because of their prospect for high global efficiency, good performance at partial load, fuel flexibility, low emission level, low vibration and noise level. Despite many advantages, the Stirling engine, with respect to RIC engine, has not found the expected applications due to low electric efficiency, difficult power control system because of presence of different heat exchangers (heater, cooler, regenerator and auxiliary heat exchangers), high pressure level of working gas, high specific investment cost and the fact that the engine needs few minutes to warm up.

Different small scale Stirling-based cogenerators are available in the market or under development. The manufacturer data of these systems are shown in Table 2 and their specific cost is reported in Fig. 4. It is important to remark that the operating life, up to 80,000 h, of these systems is comparable with RIC engine based MCHP systems.

A New Zealand company has been offering an MCHP unit based on an Alpha-type 4-cylinder Stirling engine since 1995 [47]. The unit supplies an electric power of 1 kW and a thermal power of 12 kW. This MCHP is also currently being distributed in the UK by power and gas companies. The unit can be fuelled by diesel oil, kerosene, natural gas, petrol.

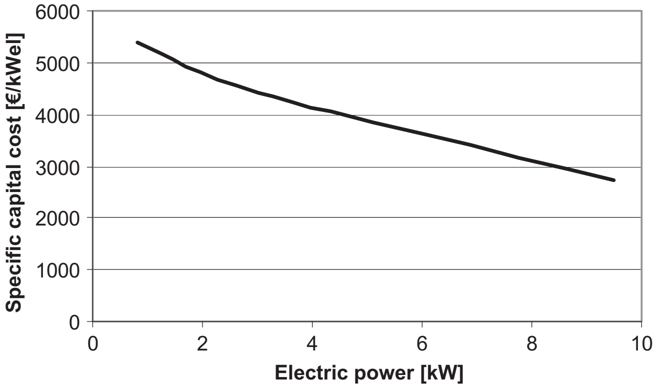

Fig. 4. Specific capital cost as a function of electric power.

Another MCHP model [48] has become commercially available in the Netherlands since 2010 and will also be introduced in France, the UK and Germany, where field tests are underway [49].

A German company started selling MCHP unit in 2004 and until the beginning of 2007, when the company went into insolvency, about 150 units had been sold. The units were designed for natural gas and LPG, but a few units were modified to work with biogas, sewage gas, wood pellets and solar source [50]. This MCHP is based on a 2-cylinder, 160 cm^3, Alpha-type Stirling engine. Helium is used as working gas for the MCHP, while the solar based system uses hydrogen. The working gas pressure varies between 35 and 150 bar, providing a corresponding variable output of 2–9 kW electric and 8–26 kW thermal power.

Another German manufacturer produced a cogeneration unit of 3 kW electric and 10.5 kW thermal power based on Stirling engine powered by biogas, wood pellet and solar source [51]. The Company, however, had to start insolvency proceedings due to technical problems.

Starting from the cooperation with Danish Technical University, a Danish company has developed an MCHP unit which is not yet available in the market. The cogenerator, based on a beta-type Stirling engine, delivers, at nominal condition, 8.1 kW of electric power and 24.9 kW of thermal power [52]. The unit uses helium as working gas and was developed for utilization of biogas.

Table 2
Stirling-based micro-cogenerator data.

		Whispegen	BAXI Ecogen	HRE-boiler	Sunmachine	SM5A	Solo 161
Power [kW]	Input power	8.3	7.4	8.0	15.0	38.4	36.0
	Electric power	1.0	1.0	1.0	3.0	8.1	9.0
	Thermal power	7.0	6.0	6.4	10.5	24.9	26.0
Efficiencies [%]	Electric efficiency	12	13.5	12.5	20.0	21.1	25.0
	Thermal efficiency	84.3	81.1	80.0	70.0	64.8	72.2
	Overall efficiency	96.3	94.6	92.5	90.0	85.9	97.2
Fuel		Natural gas	Natural gas, biogas	Natural gas, LPG	Wood pellet	Biogas	Natural gas, LPG, biogas, biomass
Weight [kg]		137	110		410	900	460
Dimensions [mm]	L	480	450		1160	650	1280
	H	840	950		1590	1505	980
	D	560	426		760	990	700
Engine	No. Cyl.	4			1	1	2
	Displ. [cm^3]				520	550	160
Working gas		Nitrogen			Nitrogen	Helium	Helium, hydrogen
Maximum pressure [bar]					36	80	150
Engine type		Alpha	Linear Free Piston	Linear Free Piston	Alpha	Beta	Alpha
Generator		Single phase				Asynchronous	Three phase
Noise [dBA]			45				

Finally in 2005, a Dutch company entered into cooperation with boiler manufacturers to develop a natural gas-fired MCHP unit that supplies 1 kW of electric power and 6.4 kW of thermal power [53].

Further MCHP units, based on Stirling engine, are still under development and will be available in the market within the next few years [4,5,54].

1.2.3. *Fuel cell-based systems*

Fuel cell cogeneration based systems have, perhaps, the greatest potential in residential and small scale commercial applications because of their ability to produce electricity at relatively high efficiency with a significant reduction of greenhouse gas emissions [55]. Many types of fuel cells are available: Alkaline Fuel Cells, AFC, Proton Exchange Membranes Fuel Cells, PEMFC, Phosphoric Acid Fuel Cells, PAFC, Molten Carbonate Fuel Cells, MCFC, Solid Oxide Fuel Cells, SOFC, and lately Direct Methanol Fuel Cells, DMFC. However, PEMFC and SOFC are the preferred technologies for MCHP, [55]. In fact, for small scale cogeneration application, PEMFC and SOFC based systems guarantee the advantage of high overall efficiency, reduced environmental impact, and a good match with the residential thermal to power ratio, [56]. Fuel cells are expected to achieve high electrical (30–60%) and overall efficiency (70–90%), even with small units, [57,58]. The range of efficiency achieved depends on the method used to produce the fuel. In fact, energy losses may have occurred outside the system in producing a suitable fuel. PEM fuel cell running at temperatures of up to 90 °C, has less problems with the material used (plastic such as Nafion) than SOFCs, in which the process temperature amounts to about 800 °C. SOFC performs better than PEMFC technology (electrical efficiency of 40%, at cell level), but start-up and cooling phases take longer, which immediately affects time and costs required for installation, maintenance and repair and durability of fuel cells.

The advantages of fuel cell cogeneration systems include low noise level, potential for low maintenance, excellent part load management and low emissions. At the moment, the high cost (varying from 6700 €/kW$_{\mathrm{el}}$ for PEMFC, [58], to 60,000 €/kW$_{\mathrm{el}}$ for SOFC) 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%), [58].

Current research is focused on solving technological problems, developing less expensive materials. Furthermore, mass production processes, from synergies and economies of scale arising from automotive applications, are expected to upgrade the technology that will reduce the cost of fuel cells.

According to [59], widespread commercialization of stationary fuel cell technology can be attained when fuel cells reach 300 to 550 €/kW$_{\mathrm{el}}$. In the meantime, many countries offer assistance that offset some of the purchase and installation costs, such as grants, low-interest loans and tax deductions.

Different fuel cell-based cogenerators are available in the market or under development [60]. The manufacturer data of some of these systems are shown in Table 3.

1.3. *3-E analysis*

According to a typical 3-E simplified approach, the performances of the Alternative System, AS ≡ CCHP, are usually compared to those of the Conventional energy System, (CS ≡ electric grid, gas boiler, EHP), based on separate "production". Both the alternative and conventional systems have to satisfy the electric and thermal requirements of the users (space heating and cooling, domestic hot water). For European countries a very common CS is based on electric grid, gas-fired boiler (domestic hot water and space heating) and EHP (space cooling). The energy efficiency of both AS and CS is evaluated by means of the Primary Energy Ratio (PER) performance factor, defined as the ratio of the useful energy output ($E_{\mathrm{el}} + E_{\mathrm{th}}$) supplied to the end-user to the primary energy consumption (E_p):

$$\mathrm{PER} = \frac{E_{\mathrm{el}} + E_{\mathrm{th}}}{E_p} \tag{1}$$

According to scientific literature [61,62], and European directive, [1,63], in order to compare the ability of energy conversion systems to satisfy the same user, it is important to evaluate the Primary Energy Savings, PES, which is defined as:

$$\mathrm{PES} = \frac{E_{p,\mathrm{CS}} - E_{p,\mathrm{AS}}}{E_{p,\mathrm{CS}}} \tag{2}$$

Furthermore, environmental impact is a key factor in the selection of proper energy system. A simplified approach is based on the evaluation of carbon dioxide equivalent emissions of the analyzed energy systems. The comparison is then based on the avoided CO_2 equivalent emissions, ΔCO_2, defined as:

$$\Delta\mathrm{CO}_2 = \frac{\mathrm{CO}_{2,\mathrm{CS}} - \mathrm{CO}_{2,\mathrm{AS}}}{\mathrm{CO}_{2,\mathrm{CS}}} \tag{3}$$

PER, PES and ΔCO_2 are strongly influenced by energy performance parameters (η, COP, …) and fuel used by both alternative and conventional systems. For instance, the power plant efficiency and emission

Table 3
Fuel cell-based microcogenerator data.

Model		Kyocera-Toyota SOFC	Panasonic ENE-FARM	Ballard and Ebara PEMFC	Sulzer Hexis Galileo 1000 N SOFC	Ceramic Fuel Cells SOFC	Nuvera[a] Avanti PEMFC	Vaillant FCU 4600 PEMFC	Acumentrics RP-SOFC 5000	Arcotronics PENTA H2
Electrical Power [kW]		0.70	0.75	1.0	1.0	1.0	4.6	4.6	5.0	5.0
Thermal Power [kW]		0.60	1.0	1.7	2.0	1.0	7.6	7.0	3.0	3.0
Electric Efficiency [%]		45.0	40.0	34.0	30.0	40.0	30.0	35.0	50.0	45.0
Overall Efficiency [%]		85.0	90.0	92.0	92.0	80.0	80.0	80.0	80.0	
Fuel		Natural gas	Natural gas	Natural gas	Natural gas, biogas	Natural gas, propane, butane, ethanol, biodiesel	Natural gas	Natural gas	Natural gas, methane, propane, ethanol, methanol, hydrogen	Hydrogen
Weight [kg]		80	225		170		400			200
Dimensions [mm]	L	560	1065		550		1200			
	H	900	1883		1600		1400			
	D	300	480		550		560			

[a] Performance based on HHV

factor can be characterized with respect to a specific country mix (e.g. Italy: $\eta_{PP} = 46.1\%$, $CO_{2,PP} = 0.531$ kgCO$_2$/kWh$_{el}$), to the Best Available Technology, BAT (combined cycle: $\eta_{PP} = 58\%$, $CO_{2,PP} = 0.400$ kgCO$_2$/kWh$_{el}$) or through different other approaches [64].

The method described by Equation (3) uses the standard emission factors approach, which takes into account all the GHG emissions due to energy consumption, either directly due to fuel combustion or indirectly via fuel combustion associated with electricity and heat/cold usage. The standard emission factors are based solely on the carbon content of each fuel, like in the context of the Kyoto protocol. Furthermore, the CO_2 emissions from the sustainable use of biomass/biofuels, as well as emissions of certified green electricity, are considered to be zero.

Further analysis could be performed on environmental impact introducing a method based on life cycle analysis (LCA) of greenhouse gas emissions from thermal and power generation systems of both AS and CS, [65].

The LCA approach takes into consideration the overall life cycle of the energy carrier. This approach includes not only the emissions of the final combustion, but also all emissions of the supply chain. It also includes emissions from exploitation, transport and processing (e.g. refinery) steps. Hence emissions that take place outside the location where the fuel is used are also included. In this approach, the GHG emissions from the use of biomass/biofuels, as well as emissions of certified green electricity, are higher than zero.

The standard approach, although it does not reflects the total environmental impact related to the use of an energy carrier, has several advantages with respect to the LCA approach, [66]. In particular, it is compatible with the monitoring of progress towards EU's 20-20-20 target and, above all, all emission factors needed are easily available. In fact, the standard emission factors depend on the carbon content of the fuels and therefore do not vary significantly from case to case. In the case of LCA approach, obtaining information on the emissions upstream in the production process may be challenging and considerable differences may occur even for the same type of fuel. This is especially the case of biomass and biofuels. Therefore, in this paper, the standard emission factors approach is used.

Finally, to complete the analysis, the evaluation of proper economic performance indices is necessary. In fact, aiming at a large diffusion of MCCHP technology, characterized by energy and environmental benefits, a reasonable short payback period should be obtained. However, the external factors that affect the market access vary with country, and there is a large number of parameters (initial and operating costs, tax rates, economic contributions, …) involving both government and private operators (gas utilities, manufacturers, …). For example, the possibility of obtaining funds or that of conveniently selling the electric surplus to the grid could strongly contribute to the market access of new equipments. A performance index typically used in economic analysis is the Simple Pay-Back period (SPB), that evaluates the number of years required to recover the typical higher investment cost of the AS with respect to the CS.

A more comprehensive method allows to evaluate the Discounted Pay-Back period (DPB), which also considers the actualization factor, that discounts back to the present time future cash flows or economic savings.

However, for a simplified estimation, in this work the Simple Pay-Back period has been used.

2. MCCHP systems

2.1. MCHP/HP

The energy system shown in Fig. 5 consists of an engine, PM, operating an electricity generator, G, and/or the compressor of a vapour compression heat pump, HP, and a heat recovery system. By varying r_m value in the range 0–1, different conditions to split engine shaft work are taken into account. The global system, MCCHP≡MCHP/HP, satisfies heating, cooling and electric requirements starting from the primary energy, E_p, corresponding to the chemical energy of the fuel consumed in the prime mover. Obviously, all energy flows depend on the efficiency parameters (η, COP) of each MCCHP component.

It operates in different modes:

a) MCHP mode: the system operates as MCHP plant delivering electric and thermal energy to the user without HP operation, $r_m = 0$;
b) HP mode: the shaft power delivered by MCHP is totally used to activate the HP and the user thermal load can be satisfied by both HP (condenser-heating, evaporator-cooling) and MCHP thermal recovery systems. So in this case, the system can be considered a Gas engine driven Heat Pump, $r_m = 1$. It basically consists of a reversible vapour compression heat pump with an open compressor driven by an internal combustion gas engine

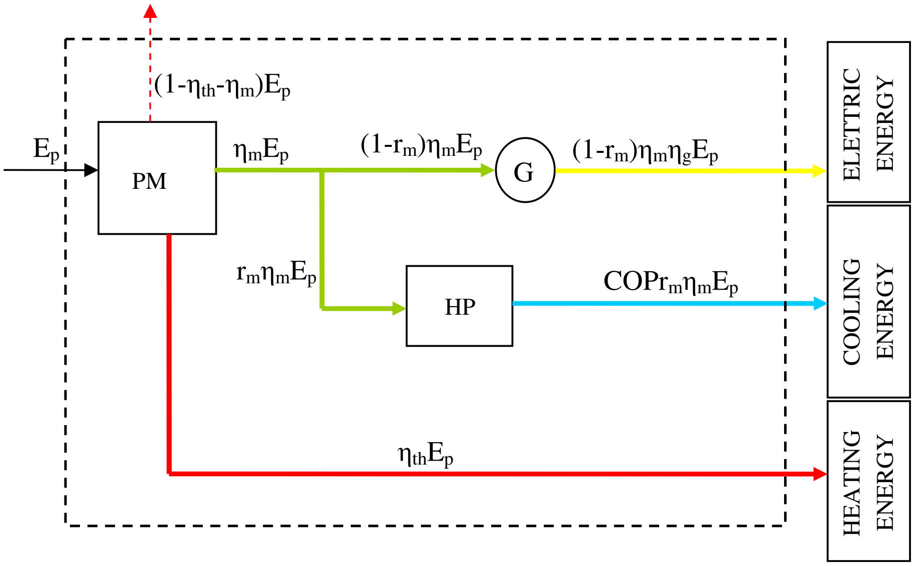

Fig. 5. MCHP/HP trigeneration system.

instead of an electric engine. The recovered waste heat of the engine, $\eta_{th}E_p$, can directly improve HP heating capacity. Otherwise the heat recovered can indirectly raise the lower pressure of the vapour compression cycle, thereby enhancing its output heating capacity [24,67–71];

c) MCHP/HP mode: the mechanical power delivered by MCHP is used to activate HP (cooling or heating) and to drive generator to supply electricity, $0 < r_m < 1$. Obviously in this configuration, the energy conversion system operates as a CCHP device, as reported in Fig. 5, in which the trigeneration system operating in cooling mode is represented.

The last operation mode could be considered as an evolution of GHP. Japanese manufacturers have developed and commercialized GHPs, in the range of cooling capacity 56–71 kW, with power generator that delivers electricity to satisfy both auxiliary devices (fan, circulation pump, ...) and/or external electric requirements [72]. For example GHP with a cooling capacity of 56 kW and a heating capacity equal to 63 kW, can generate 2–4 kW of power for external use, not including self-consumption of the outdoor unit [73].

During the hot season an MCHP/HP system supplying 56 kW of cooling power, 22 kW of thermal output for domestic hot water and 1.35 kW of electric power has a PER = 1.80 and also saves primary energy of about 28% and has a $\Delta CO_2 = 36\%$ in comparison to the conventional system (power plant: $\eta_{PP} = 46\%$, $CO_2 = 0.53$ kgCO$_2$/kWh$_{el}$; boiler: $\eta_b = 85\%$, $CO_2 = 0.20$ kgCO$_2$/kWh$_{Ep}$; $COP_{EHP} = 3.76$).

Another system consisting of a reciprocating internal combustion engine (four-stroke, gas fuelled, 359 cm^3), operating an electric generator (rated power 4800 VA), a heat recovery system, a heat accumulator and batteries has been developed. Simultaneously, the engine also operates a heat pump compressor. In trigeneration mode, the system, supplying 9.1 kW of cooling power, 19.6 kW of thermal output and 1.5 kW of electric power, performs its best with PER equal to 1.67 [74]. An annual simulation has been carried out on the prototype plant considering a typical 150 m^2 dwelling located in Spain. The PER for this varies in the range 0.58(July)–0.91(January) with a mean value equal to 0.77. Efficiency is high in winter when no recovered heat is rejected and when the heat pump contribution is high [75].

2.2. MCHP/EHP

The system, MCCHP≡MCHP/EHP, consists of an electric heat pump, EHP, operated by the electric generator, G, of the micro-cogenerator, Fig. 6. The MCHP electric power can be split between the EHP and/or the other electric appliances or exported to the grid. By means of r_e parameter (0–1) different operating modes could be considered [76–78].

It operates in different ways:

a) MCHP mode: the system operates as a cogenerator delivering all electricity and heating energy to the user without EHP operation, $r_e = 0$;

b) EHP mode: performs similarly to HP mode of MCHP/HP system. The electric power delivered by MCHP is totally used to activate the EHP and the thermal load can be satisfied by both EHP (condenser-heating, evaporator-cooling) and MCHP thermal recovery systems, $r_e = 1$. Also in this case, the system operates as a GHP;

c) MCHP/EHP mode: the power delivered by MCHP is used to activate EHP (cooling or heating) and to supply electricity, $0 < r_e < 1$. This configuration allows for a satisfaction of electric, cooling and heating energy requirements (CCHP). Obviously this approach has a lower energy efficiency with respect to MCHP/HP in which there is a direct coupling of the prime mover and the compressor of the heat pump. The main reasons why an MCHP/EHP is used are the following:
   - the possibility of driving EHP by electric grid whenever an engine failure occurs or a more convenient energy cost is achievable. From an energy and economic point of view, the availability of a system with high levels of operation modes helps to arrive at the optimum match between the equipment and the end-user load profile;
   - the opportunity to use mass production units in order to reduce the first cost of the MCHP/EHP. In particular the refrigeration section could be a low priced and easy-to-use water-to-air heat pump.

[79] reports the Energy, Economic and Environmental analysis, on yearly and seasonal basis, of a natural gas fuelled micro-cogenerator combined with an electric heat pump, starting with

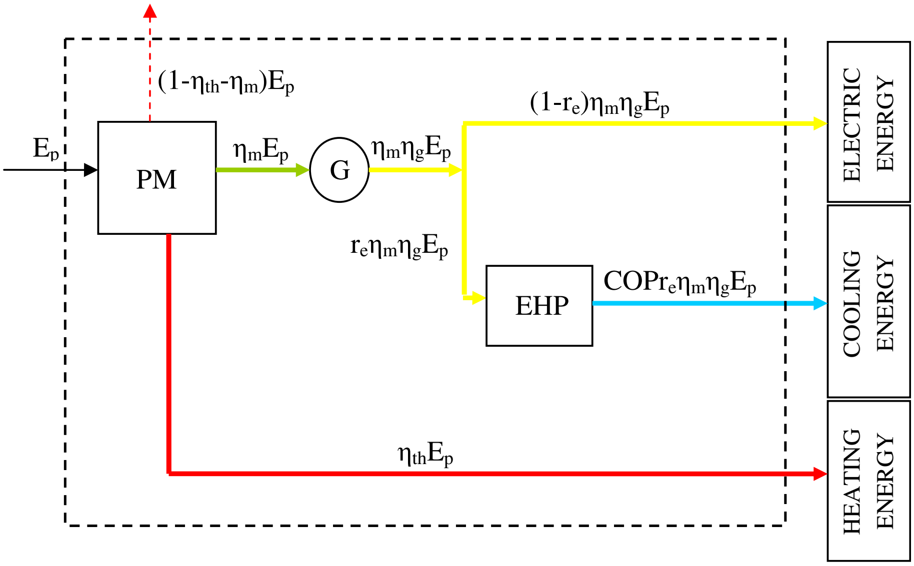

Fig. 6. MCHP/EHP trigeneration system.

the results of an intense experimental activity developed in a test facility under a wide range of conditions [80]. In the following analysis, a new model of the MCHP, different from the device considered in [79] has been taken into account. The MCHP electric and thermal power outputs are 6 kW and 11.7 kW at nominal operating conditions, (rated electric efficiency is 28.8% and rated thermal efficiency is 56.2%, based on LHV). The EHP requires more than 2 kW of electric power with a COP equal to 2.5 and 2.8 for heating and cooling operating modes respectively.

In heating mode, at full electric power (2.3 kW to EHP and 3.5 kW to electric appliances), the thermal contribution, with a MCHP primary power input of 21 kW, is split between the MCHP (11.7 kW) and the EHP (5.8 kW). In cooling mode, at full electric load, the EHP delivers 5.8 kW for space cooling and the MCHP provides 11.7 kW for Domestic Hot Water, DHW, and 3.5 kW for electric requirements.

For example if this system operates at full load for 1500 h per year in heating mode and 1000 h per year in cooling mode, under the best conditions, the maximum PER of the MCCHP system will be about 100% because both in cooling and heating mode this system works with a global efficiency higher than 100%, as can be deducted by the above reported data. In order to evaluate the performance of the MCHP/EHP system on yearly basis, a sensitivity analysis as a function of heating and cooling operating hours per annum, in terms of PES and ΔCO_2 has been considered. The analysis performed considering that the trigeneration system operates at full load, shows satisfactory results both in terms of primary energy savings (PES = 23–25.5%), Fig. 7, and equivalent CO_2 emission reduction ($\Delta CO_2 = 29.2–30\%$), Fig. 8.

Ability of the user to spend as much thermal energy generated by the system as possible, becomes one of the crucial aspects of the cogeneration. This is particularly important in small scale applications and especially in cooling mode. The use of thermal energy to produce DHW in cooling mode was considered, ranging from the best condition of total recovery of heat (100%), to the worst operational condition of total dissipation of heat recovered by the MCHP in cooling mode (0%), on yearly basis. Fig. 9 shows the primary energy savings and the avoided greenhouse gas emissions as a function of hot thermal energy used in cooling mode considering that the system operates at full load for 2500 h per year in heating mode and 1500 h per year in cooling mode. The alternative technology, compared to the separate production, provides 6–24% primary energy savings and reductions of equivalent CO_2 emission between 15 and 30%.

The SPB is also evaluated for a general estimation. The estimated capital cost of the MCHP/EHP is about € 2200 for generating a kW of electric power output, considering a financial support of 30%. This is quite high when compared to cogeneration market standards.

With respect to the Italian market, electric energy price of € 0.17/kWh and a natural gas price of €0.70/Sm^3 have been assumed. A reduction of the natural gas price for cogenerative use, which is inversely proportional to MCHP electric efficiency has been considered. This ranges between 0 to € 0.22/Sm^3 when electric efficiency is about 42%. The maintenance cost for MCHP of € 0.025/kWh_{el} has also been considered.

The SPB at full load, as a function of hot thermal energy usage in cooling mode, is shown in Fig. 10. The results of the SPB analysis seem to be very favourable for the MCHP/EHP. With a discount in the price of the natural gas, it is possible to obtain the SPB, in the best case, within about 5 years. The importance of the capital cost is highlighted by the fact that, without a contribution of 30% financial support on this cost, the SPB becomes higher than 6 years, [81]. It is therefore evident that the relatively high capital cost is the main obstacle for the implementation of the small-size cogeneration and trigeneration systems as compared to the large-size plants.

Another parameter that affects the economic analysis is the operating time (hours per year). In fact, under the same hypothesis considered in the previous analysis, if the MCHP works at full load for 1500 h in heating mode and 1000 h in cooling mode, the SPB is higher than 7 years.

In [82] different MCCHP systems for residential or small business applications in terms of energy, economic and environmental analysis have been evaluated by means of simulation software. A 210 m^2 single-family house located in Ontario and equipped with a commercially available 6 kW_{el} and 11.7 kW_{th} MCHP system, where space heating and DHW are satisfied by MCHP and space cooling is provided by an electric chiller, was simulated.

In Ontario electric energy production for the base load is achieved through nuclear and hydro power plants, while marginal demand is satisfied through coal fired, natural gas power plants and small scale hydro. The average efficiency based on fuel mix is 33.2%. This value includes transmission and distribution losses assumed equal to 6%.

In the simulation carried out electricity delivered by MCHP system is partially sold back to the grid. Since this electricity is not likely to replace the base electricity production, the authors assumed there would be a reduction in the marginal production. Two scenarios were then considered. One was where only electricity produced by coal fired plants was replaced ($\eta_{PP} = 31.4\%$,

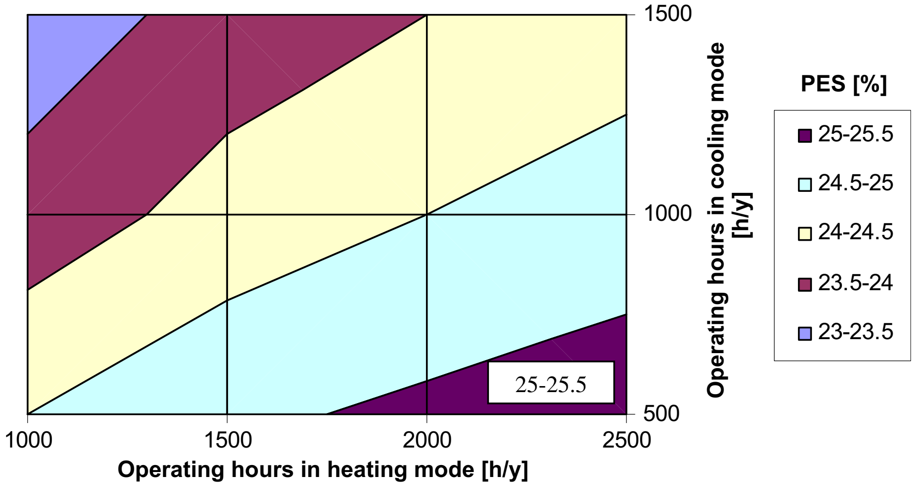

Fig. 7. PES at full load as a function of heating and cooling mode operating hours per year.

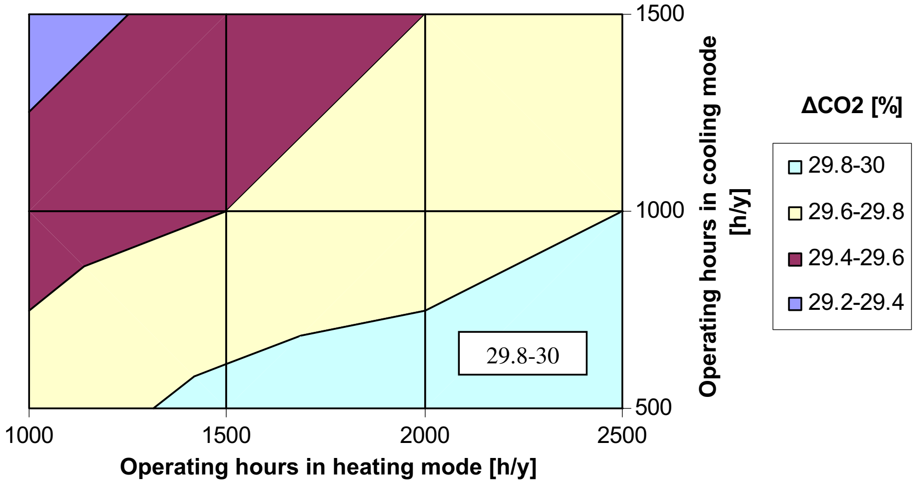

Fig. 8. ΔCO_2 at full load as a function of heating and cooling mode operating hours per year.

including losses) and the second considered the fuel mix in 2008 in Ontario ($\eta_{PP} = 61.5\%$, including losses). The reference value for the second scenario is very high because a large part of marginal electricity production is based on small hydro. Environmental analysis with the same assumptions has been carried out. The environmental impact depends on the actual fuel mix, if the electricity produced is sold back to the grid. Thus two scenarios should be considered: coal fired plant is replaced ($CO_2 = 0.941$ kg/kWh$_{el}$) or the electricity replaces a fuel mix. In the second case since hydro electricity makes up a large portion of the marginal electricity production, it is considered to have a negligible environmental impact. The equivalent CO_2 emission is estimated to be about 0.175 kg/kWh$_{Ep}$ for natural gas. PES and ΔCO_2 for two different scenario are reported in Table 4. The PES in the second comparison is not positive and ΔCO_2 is low because a large part of the marginal electricity production is based on a renewable source.

2.3. MCHP/THP

Thermally activated Heat Pump, THP, includes all the equipments that use thermal energy to satisfy cooling energy demands. The possibility of an efficient use of thermal waste energy leads to an upgrade of cogeneration performance thereby increasing the yearly operating hours including the hot season. Furthermore, it is a well known fact that it is very simple to export the electricity surplus to the grid, while the storage of a cogenerator thermal output requires large hot water storage tanks.

Major Heat Transformers include Absorption Heat Pump, ABHP, and Adsorption Heat Pump, ADHP [6,83]. These cooling systems can be run by steam, hot water or hot exhaust gas derived from PMs. However, waste heat from various prime movers falls into different temperature ranges. At the same time, cooling systems have their own suitable working temperature. For this reason there are some constraints for each MCHP technology in order to activate different types of THP systems. For small scale application, the range of the temperature available from thermal energy source is in the interval of 60–90 °C thereby reducing the technologies that could be used in coupling the cogeneration system. The main advantages of absorption and adsorption refrigerators with respect to the usually adopted electrically operated systems, based on inverse vapour compression cycle, are:

- use of environmentally friendly working fluids (low Global Warming Potential, GWP, and Ozone Depletion Potential, ODP);
- low noise;
- little maintenance required due to few moving parts (operating cost saving);
- long operating lifetime.

With respect to the market availability of small scale absorption and adsorption heat pumps, the equipments at the moment are in R&D phase and only few and expensive models are in a pre-selling phase. A strong effort towards the diffusion of THP systems will be due to the development of solar cooling plants in which the heat is supplied by efficient solar collectors [84,85].

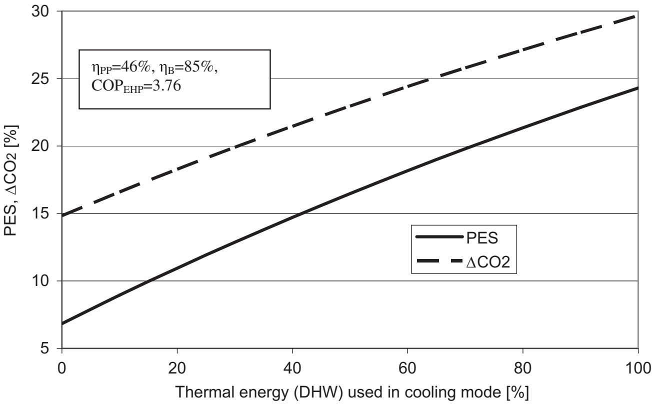

Fig. 9. PES and ΔCO_2 vs. thermal energy (DHW) used in cooling mode.

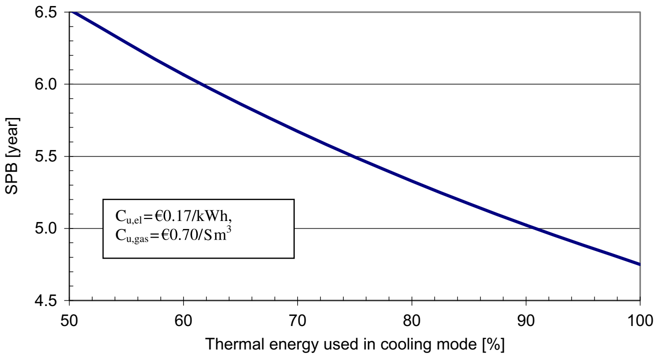

Fig. 10. SPB vs. thermal energy (DHW) used in cooling mode.

Table 4
PES and ΔCO_2 for two different scenarios.

	Scenario 1	Scenario 2
PES [%]	28.9	−9.87
ΔCO_2 [%]	123	7.61

The energy flows of the MCCHP≡MCHP/THP system, shown in Fig. 2, are reported in Fig. 11. The thermal power can be split between the absorption or adsorption system and the direct use (domestic hot water, space heating). By means of r_t parameter (0–1), different operating modes could be considered.

A small amount of generated electricity could be used for self-consumption (fan, pump, …).

It operates in different modes:

a) MCHP mode: the system is a cogenerator supplying electric and thermal energy to users without THP operation, $r_t = 0$;
b) THP mode: the thermal power is totally used to activate heat transformer, $r_t = 1$;
c) MCHP/THP mode: the thermal power is used both to activate THP and to satisfy energy demand of users, $0 < r_t < 1$, (CCHP).

2.3.1. MCHP/ABHP

Absorption heat pump is the most common thermally activated technology widely applied in existing CCHP systems (hotels, hospitals, commercial buildings, …), [86]. In the basic cycle, a volatile liquid refrigerant evaporates in the evaporator vessel at a low pressure, thus producing cooling at a low temperature. Then, it is absorbed by a separate adjacent absorber. The diluted sorbent solution is pumped to the high temperature and pressure generator on desorber side of the system, where the solution can be reconcentrated by heat input. Usually, during the absorption process, the condensation and mixing heat is rejected to the ambient heat sink. The most common working pairs are NH_3/Water and Water/LiBr, operating in single or double-effect systems using steam, liquid hot water (indirectly fired) or combustion of fossil fuels (directly fired) as heat source [87].

The main data of some small scale absorption chillers available in the market or under pre-selling phase, operating with different working pair [6,83,88–90] are reported in Table 5.

In [91] an MCCHP system, based on an internal combustion engine and an absorption chiller, has been installed to satisfy energy requirements of a research center located in Vitoria-Gasteiz, north of Spain. In cooling mode, the trigeneration system reaches a PER of 46% due to the low performance of ABHP and an incomplete use of the thermal energy available from MCHP. In heating mode the system works in cogeneration mode attaining a PER of 82%.

A very particular small scale trigeneration system has been considered in [92]. It is based on an oversized air cooled, two-cylinder, reciprocating internal combustion engine (9.5 kW shaft power), operating an electric generator (rated power 10 kVA), and a heat recovery system. It also includes a very small absorption refrigerator driven by MCHP exhaust gases. The absorption fridge, which is widely commercialized, is usually powered by electricity (DC or AC) and by liquefied petroleum gas, supplying maximum cooling capacity of 8.1 W (maximum COP equal to 0.039). In trigeneration configuration, the best refrigerator performances are: cooling capacity 7.4 W and COP = 0.031. Experimental results in MCHP/ABHP operating mode show a useful power output (electric ≈ 6 kW, thermal and cooling ≤ 10 W) varying between 5.54 kW and 17.8 kW at full load with a PER in the range 64–67%.

In [93] there is a trigeneration system similar to the previous one which is based on a single-cylinder, four strike, water cooled, 3.7 kW_{el} diesel engine. The system includes a Water/Ammonia pair based absorption fridge, powered by thermal energy available from MCHP exhaust gases. The heat input to ABHP from MCHP is 174 W while the cooling power is 40.5 W (COP = 0.232). Experimental results in MCHP/ABHP operating mode at full load show a useful power output (electric = 3.7 kW, thermal = 5.8 kW and cooling = 40 W) with a PER of 86.2%.

As reported in 2.2 in [82] different MCCHP systems have been evaluated: among these an MCHP/ABHP has been analyzed too. The ABHP has a cooling capacity of 6 kW with a COP of 0.67 at the generating temperature of 70 °C, heat rejection inlet temperature of 31 °C and chilled water of 7 °C. On the basis of the reference value considered in 2.2 to characterize reference systems two scenarios have been analyzed.

PES and ΔCO_2 for two different scenario are reported in Table 6. As mentioned before the PES in the second comparison is not

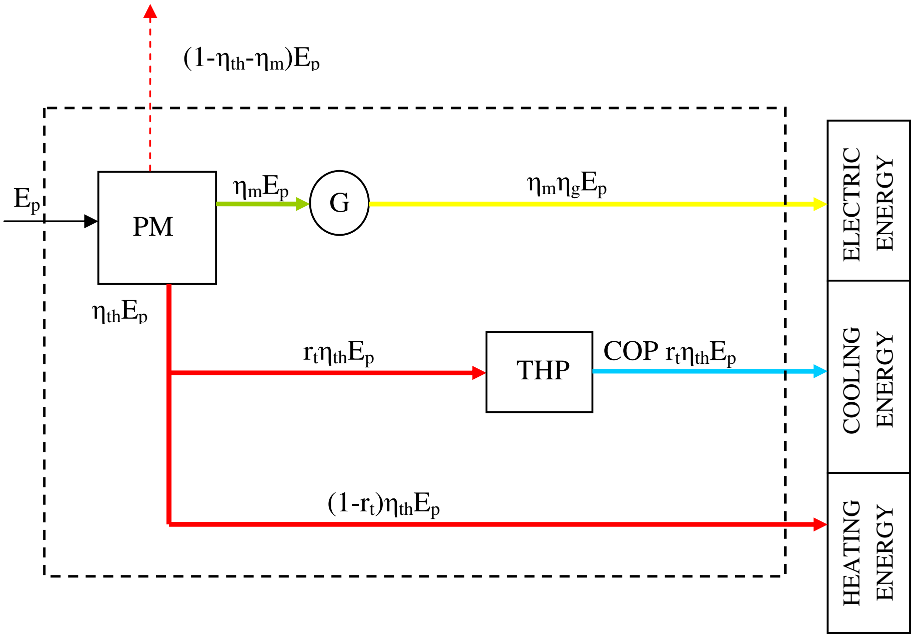

Fig. 11. MCHP/THP trigeneration system.

Table 5
Small scale absorption chiller characteristics.

Model	Rotartica solar 045v	SonnenKlima	Climatewell	Solarnext Chillii PSC12	EAW Wegracal SE15	Yazaki SC-5 Chillii WFC18
Working pair	Lithium bromide/Water	Lithium bromide/Water	Lithium chloride/Water	Water/Ammonia	Lithium bromide/Water	Lithium bromide/Water
Cooling capacity [kW]	4.5	10	10	12	15	17.6
Thermal input [kW]	7.2	12.8	14.7	18.5	21	25.1
COP [−]	0.62	0.78	0.68	0.65	0.71	0.70
Electric input [kW]	1.11	0.12	0.11	0.30	0.30	0.05
Inlet hot water temperature [°C]	90	75	72	85	90	88
Outlet chilled water [°C]	7.0	15	18	18	17	7.0
Dimensions L, H, D [mm]	1202 - 1202 - 803	1130 - 1960 - 795	1380 - 700 - 1850	800 - 600 - 2200	1750 - 760 - 1750	594 - 1736 - 744
Weight [kg]	290	550	740	350	700	420

positive and ΔCO_2 is low because a large part of the marginal electricity production is based on a renewable source.

Furthermore, small scale trigeneration systems based on ABHP are under analysis, but there are no experimental data suitable for a 3-E analysis [1,94].

2.3.2. MCHP/ADHP

The conventional adsorption cycle, which occurs when gas or liquid, called solute (usually water), accumulates on a surface of a solid, called adsorbent (usually silica gel), forming a film, called adsorbate, has been presented extensively in the literature [95–97]. The most important phases are:

1. adsorbent cooling with adsorption process, which results in refrigerant evaporation inside the evaporator, thus giving the desired refrigeration effect;
2. adsorbent heating with adsorption process, also called generation, in which the necessary heat can be supplied by a low-grade heat source, such as recovered engine heat and solar energy.

In comparison with liquid absorption system, ADHP has the advantage of being powered by large range of heat source temperatures (50–500 °C). In spite of strong research effort to increase physical-chemical properties of the working pairs [98] (such as zeolite-water, zeolite-ammonia, activated carbon-ammonia, …), they currently have the problem of low COP (0.3–0.5) with a thermal energy source of 60–90 °C and low cooling power per volume and weight. Only few models with a cooling power 10–100 kW are available in Chinese and American markets with high investment cost (600 €/kW of cooling power installed) and used as solar or exhaust gas powered ice makers and air conditioning, usually installed in transportation systems.

For small machines, two new companies are offering new products. They are SorTech AG from Germany with an 8 kW and 15 kW water-silica gel chiller and Invensor GmbH also from Germany with a 7 kW and a 10 kW water-zeolite chillers. Prototypes have been built and tested at the Shanghai Jiao Tong University in China and at the Dutch Energy Research Centre ECN but the status of the availability of a commercial machine is not known.

An energy analysis on a trigeneration system based on a four-stroke engine powered by LPG, is reported in [99]. The engine is directly coupled to the electric generator (0–12 kW, $\eta_{el} = 0$–21.4%), and two heat exchangers recover engine thermal energy from exhaust gas and from the cooling system (14.1–28.1 kW, $\eta_{th} = 83.1$–50.0%) thereby assuring a PER ranging between 83.1 (minimum load) and 71.4% (maximum load). The hot water produced by MCHP heat recovery (60.1–91.6 °C) is used to drive adsorption system that supplies cooling power ranging from 5.1 kW (COP = 0.3) to 9.7 kW (COP = 0.34). In Fig. 12, the experimental results of the tests performed, at full electric load, on MCHP/ADHP system are compared to the conventional system, CS (power plant: $\eta_{PP} = 30\%$, electric heat pump: $COP_{EHP} = 2.5$, boiler: $\eta_b = 85\%$). PERs of the two compared systems and the primary energy saving are a function of the r_t parameter defined in Fig. 13:

- $r_t = 0$, MCHP mode: the PES is about 23% and the trigeneration system performs a primary energy ratio of about 71%;
- $r_t = 1$, THP≡ADHP mode: the PER of the alternative system is equal to 37.5% and is lower than the conventional one. There is no energy saving due to the low COP of thermally activated heat pump;
- $0 < r_t < 1$, MCHP/ADHP mode: the system supplies cooling, heating and electrical power simultaneously performing energy saving since the rate of waste heat energy directly used to satisfy thermal load is lower than 80%. For $r_t = 0.50$, at full load, the thermal power is equal to 14.1 kW, the cooling power is equal to 4.7 kW and the PERs of alternative and conventional systems are 55% and 50% respectively (PES = 9%).

Further researchers investigated the introduction of small scale ADHP suitable for trigeneration applications focussing the analysis only on the cooling machine only [100–103].

Table 6
PES and ΔCO_2 for two different scenarios.

	Scenario 1	Scenario 2
PES [%]	35.8	−12.2
ΔCO_2 [%]	145	2.71

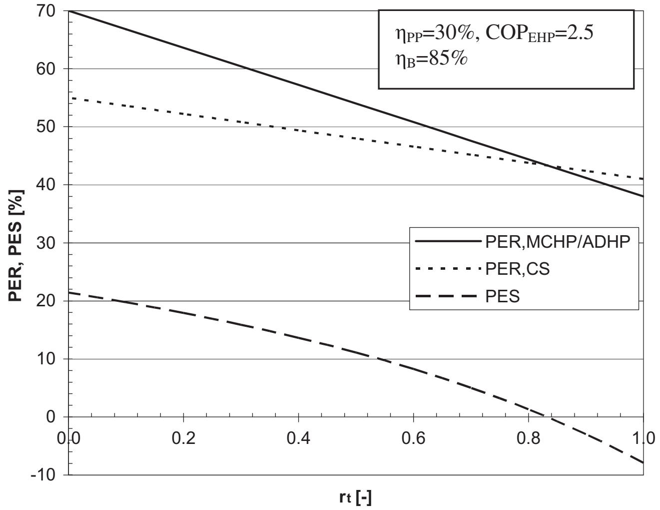

Fig. 12. PER of AS and CS and PES as a function of r_t at full electric load (12 kW).

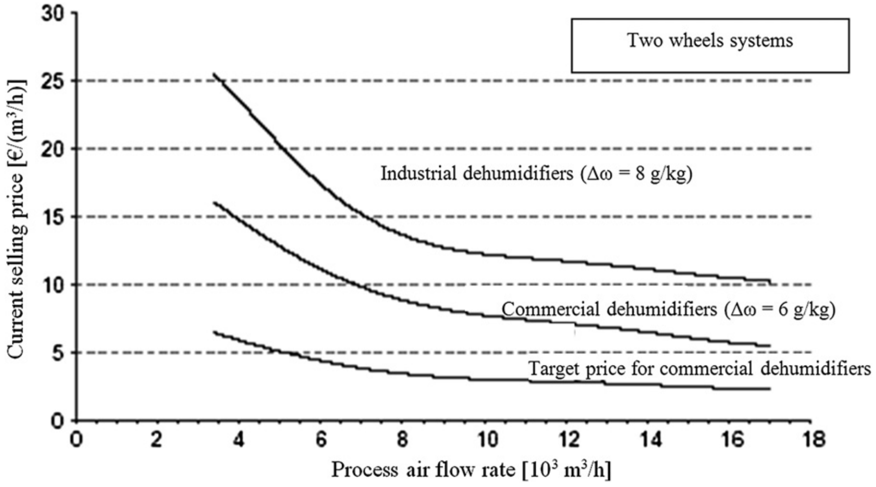

Fig. 13. Average specific cost of dehumidification systems, including both the desiccant wheel and the heat recovery wheel, as a function of the process air volumetric flow rate.

As reported in 2.2 in [82] different MCCHP systems have been evaluated: among these an MCHP/ADHP has been analyzed. The ADHP considered has 5.4 kW of cooling capacity with a COP of 0.57 at a chilled water temperature of 10 °C, generator inlet temperature of 70 °C and inlet heat rejection temperature of 31 °C. On the basis of the reference value considered in 2.2 to characterize reference systems two scenario has been analyzed.

PES and ΔCO_2 for two different scenario are reported in Table 7 and the results are similar to those ones shown in Section 2.3.1.

Different small scale trigeneration systems based on ADHP are undergoing testing, but there are no data suitable for a 3-E analysis [1].

2.3.3. Comparison between ABHP and ADHP

The main advantages of ADHPs with respect to ABHP are, [104]:

- 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, [105], and RIC based cogenerators;
- it is a robust technology with no risk of crystallization, which can occur in ABHP with H_2O/LiBr working pair;
- the materials used (zeolite, silica gel) are environmental friendly, while ammonia is toxic;
- very low intrinsic electricity consumption due to lack of a pump. Electricity is only required for the switching valves and the control unit;
- very few moving parts with low noise, maintenance effort and costs;
- high potential of cost reduction in production series due to the small amount of individual parts.

The main disadvantages are:

- slightly lower COP than for comparable absorption technology. Typical COP value of ADHP is about 0.6, while double-effect ABHP can have a COP as high as 1.2;
- commercially available machines are expensive and only some suppliers are on the market.

Table 7
PES and ΔCO_2 for two different scenarios.

	Scenario 1	Scenario 2
PES [%]	35.4	−14.7
ΔCO_2 [%]	149	0

2.4. MCHP/HVAC-DW

In a conventional Heating Ventilation and Air Conditioning (HVAC) system, air is usually cooled below the dew point for dehumidifying purposes, usually by a large electrically powered compression chiller, and subsequently heated up to the desired supply temperature, typically by an electric resistance or a boiler. In a desiccant-based HVAC system, moist air is dehumidified by means of a Desiccant Wheel, DW. The process air stream flows through the desiccant material (such as silica gel, activated alumina, lithium chloride salt, or molecular sieves) that retains the moisture of the air. The desiccant capacity of the material can be restored through its regeneration via a heated air stream (at a temperature typically in the range 50–120 °C, depending on the desiccant material and the desired humidity reduction). Thermal energy for this heated air stream is usually supplied by a gas-fired boiler. To guarantee continuous operation of the system, the DW slowly rotates between the process and the regeneration air flows.

Process air exiting the DW is quite warm (the adsorption process in the desiccant rotor is almost isenthalpic) and has to be cooled down to the desired supply temperature by an electrically powered compression chiller, for example. These systems are usually defined as hybrid. The latent load balancing by the DW, instead of the chiller, increases overall energy efficiency of the system by avoiding overcooling of the air and precluding oversized capacity of the cooling machine to meet dehumidification load.

The main advantages of these hybrid systems [106] in comparison with conventional ones, are:

- they can separately control sensible and latent load;
- the cooling machine only has to cool the process air without dehumidifying it, so that it can operate with a higher chilled water temperature compared to a cooling machine coupled to a conventional cooling and dehumidification system. Hence, the cooling machine, interacting with the hybrid HVAC system, has a higher COP;
- due to the higher value of COP, electric energy requirement of the cooling machine is reduced;
- as the cooling machine only has to cool the process air without dehumidifying it, a reduction of the chiller size and consequently of the refrigerant fluid mass is obtained. Therefore, a lower environmental impact is achieved both in terms of direct impact (ozone layer reduction and greenhouse effect due to refrigerant fluids) and of indirect impact

(the reduced use of electric energy determines lower equivalent CO_2 emissions of the power plants);

- the re-heating process is not required in the desiccant dehumidification;
- they can reach very low dew point temperatures of process air (lower than −6.0 °C), while dew point temperatures of conventional systems are usually not lower than about 4.0 °C. Thus, the desiccant dehumidification technology is particularly used when very dry air is needed in the operating processes of chemical, pharmaceutical and food industries, or when a very low indoor humidity ratio is needed in order to preserve or manipulate hygroscopic or humidity sensitive materials;
- a better indoor air quality can be obtained, due to sanitizing effects of desiccant materials.

The disadvantages of this technology are high investment costs. In Fig. 13, the average specific cost of dehumidification systems, comprising both the desiccant wheel and the heat recovery wheel, is shown as a function of the process air volumetric flow rate, for different applications (industrial and commercial). The target price for commercial dehumidifiers, that should be met in order to obtain a widespread use of the technology, is also shown.

The waste heat of a small cogeneration plant can be effectively used to regenerate the desiccant material, while the cogenerator electricity can operate the chiller to meet room sensible load, the auxiliaries and further electric appliances (computer, lights, ...).

The energy flows of the MCCHP≡MCHP/HVAC-DW system are reported in Fig. 14. The electric power can be split between the chiller and the direct use (lights, appliances, ...) and by means of r_e parameter (0–1) different operating modes can be considered. In the same way, the thermal power can be split between the regeneration of the desiccant wheel and the direct use (space heating, domestic hot water) by varying r_t parameter.

The system operates in different modes:

a) MCHP mode: the cogenerator supplies electricity and thermal energy to the end-user. The HVAC system does not operate, $r_t = r_e = 0$;
b) HVAC-DW mode: the electric and thermal energy delivered by MCHP are totally used to activate the hybrid HVAC system, $r_t = r_e = 1$;
c) MCHP/HVAC-DW mode: this configuration allows to satisfy electric, heating and cooling energy requirements, $0 < r_t < 1$, $0 < r_e < 1$.

Schmitz and Casas in [107] and [108] report an energy and economic analysis of an HVAC system based on a desiccant wheel and a natural gas fuelled micro-cogenerator (electric power 4.7 kW, thermal power 12.5 kW, electric efficiency 25.9%, thermal efficiency 65.0%, based on HHV). This equipment is located in an office building in Germany with an air conditioning area of 1300 m^2. An evaluation of annual primary energy consumptions of a conventional electric air conditioning system ($\eta_{PP} = 40\%$, COP = 3), a desiccant assisted system interacting with a condensing boiler and then a demonstration plant based on MCHP/HVAC-DW was carried out. With respect to the conventional system, the one based on the desiccant wheel allows a primary energy saving of about 10% (22% if it is coupled to the cogenerator).

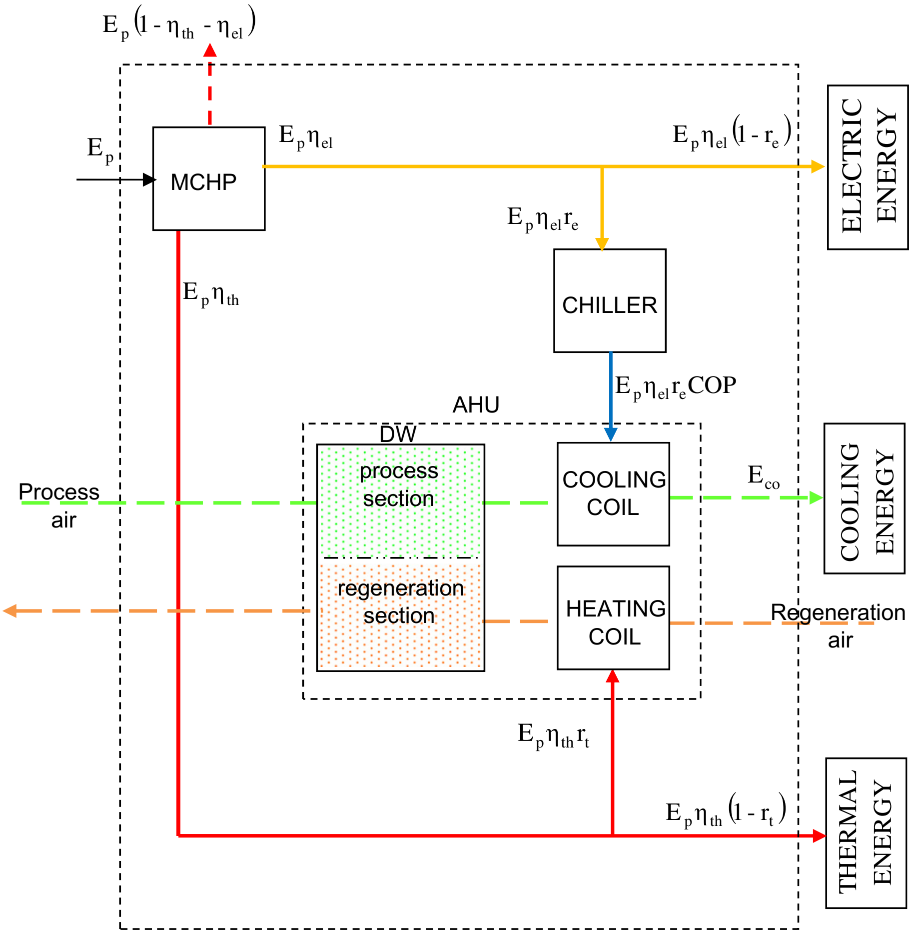

Fig. 14. MCHP/HVAC-DW trigeneration system.

Economic analysis revealed considerable advantages for the demonstration plant regarding investment costs as well as operating costs in comparison with the conventional solution.

Other examples of desiccant cooling systems that use waste heat from cogeneration systems, but with a greater size, are available in the scientific literature [109–111].

Our research group is currently involved in a theoretical and experimental analysis of a trigeneration system based on a natural gas-fired Micro-CHP and a hybrid HVAC system with a desiccant wheel. In accordance with this aim, an experimental facility has been realized and tests are in progress. A micro-cogenerator (electric power 6.0 kW, thermal power 11.7 kW) supplies electricity to an air cooled water chiller (cooling power 8.5 kW), and thermal energy to a desiccant wheel (volumetric air flow rate 800 m^3/h).

The primary energy consumption of the desiccant-based HVAC system, in different configurations, has been evaluated in order to identify the most efficient one [112–116]. For example, the hybrid system powered by the MCHP guarantees an average PES of 18% with respect to the same system powered by separate "production". Even if the electric energy "production" is based on the Best Available Technology (BAT, i.e. with natural gas combined cycle power plants, $\eta_{PP} = 0.58$), PES remains positive (8.2% on average).

Subsequently, the desiccant-based Air Handling Unit, AHU, interacting with the MCHP has been compared with a AHU based on the conventional cooling dehumidification process and powered by separate "production".

The COP of the electric chiller interacting with the conventional AHU has been numerically evaluated by means of well known simulation codes of inverse machines, as a function of outdoor air temperature and supply air humidity ratio. In Fig. 15, outdoor air thermal-hygrometric conditions that give a positive PES of the former with respect to the latter are shown to highlight the influence of outdoor air properties on the energy performances of both systems.

The electric grid efficiency, η_{PP}, is a key factor for the energy performance of the system based on separate "production". The influence of η_{PP} on PES is reported in Fig. 16. PES obviously increases as η_{PP} reduces.

The influence of the partial load operation of the MCHP on the global energy performance has been analysed too. The net electric power for computers, lights and other electric load, has been gradually increased up to 1.5 kW to allow the full load of the cogenerator (the electric power supplied by the MCHP to the chiller and to the auxiliaries is about 4.5 kW). Fig. 17 shows that PES increases with the net electric power supplied to the final user, and so it is convenient to operate the MCHP at full load for the maximum number of hours which, in fact, increases the electric efficiency of the micro-cogenerator.

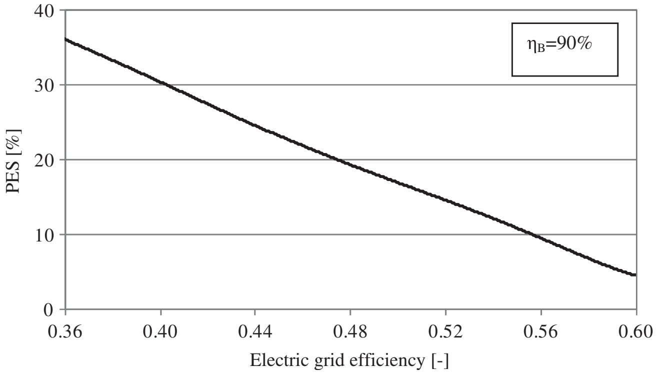

Fig. 16. PES as a function of electric grid efficiency.

Finally, in [117], a numerical analysis, based on design operating conditions and on nominal characteristics of the devices, is carried out in order to compare the performance, in terms of primary energy consumptions, annual operating costs and greenhouse gas emissions, of the MCHP/HVAC-DW system with respect to conventional cooling dehumidification HVAC systems powered by separate electric and thermal "production".

On an annual basis, the MCCHP system can guarantee a primary energy saving of 8.30% and a reduction of equivalent CO_2 emissions of about 17.8%.

In terms of economic viability, a reduction of about € 900 in terms of annual operating cost, can be obtained. However, the high initial cost of both the MCHP and the desiccant wheel still determines a very long payback period, but government grants may

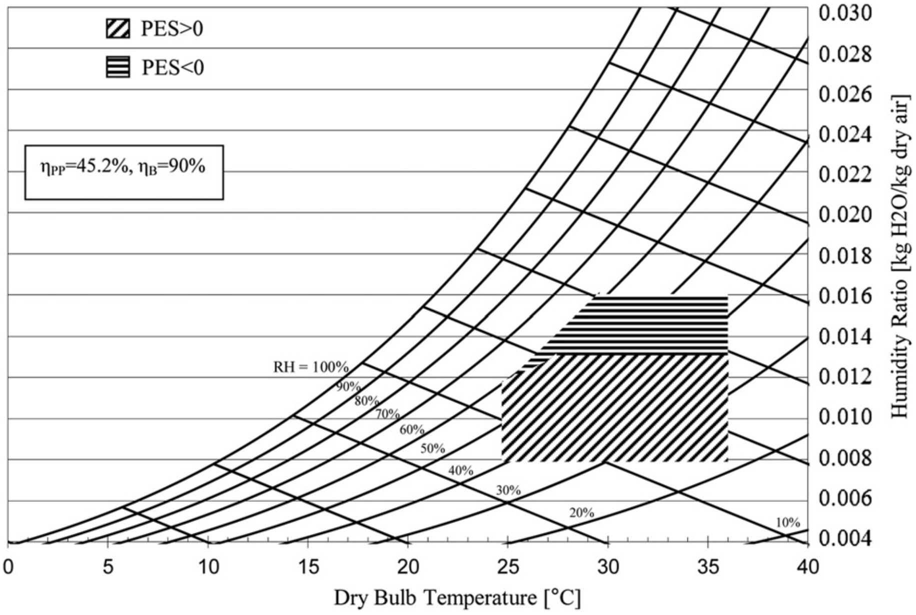

Fig. 15. Psychrometric chart showing the area where PES is <0 and that where PES is >0.

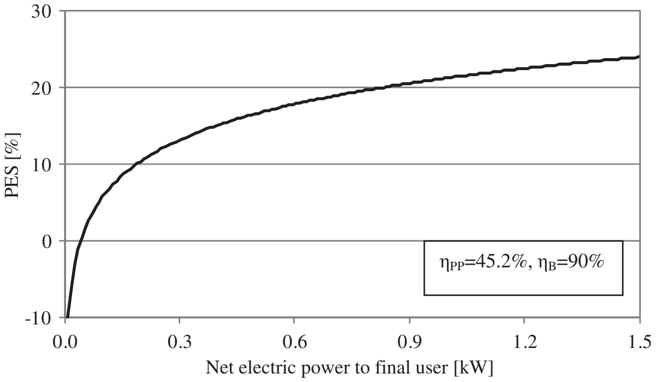

Fig. 17. PES as a function of net electric power supplied to the final user.

significantly encourage MCHP and desiccant dehumidification market penetration.

Further researches are involved on activities on this trigeneration system, but there are no experimental data available, [118].

2.5. *MCHP/EJEC*

A trigeneration system could be based on a thermally activated device such as the ejector, EJEC. This technology was first introduced in 1901 and is based on the ejector cycle, in which the compression effect is achieved by an ejector [119].

On the basis of experimental analysis performed on a trigeneration system that consists of a natural gas-fired MCHP and an ejector cooling device, EJEC, an energy and environmental analysis has been carried out in [120] by UK researchers. The system is based on a RIC cogenerator and ejector cooling device that can deliver, as a function of different operating variables, cooling power in the range 1.2–3.5 kW. The results of a simulation of four different MCHP/EJEC systems were examined. In the first one, thermal energy available from an MCHP is used to operate the ejector while the other systems (2, 3, and 4) are based on different operating modes. Part of the MCHP output is used for heating purposes, and/or part of the electric power is used to increase the ejector generator temperature.

On Table 8, the simulation results of the different operating modes of the ejector-based trigeneration system show low PER, that attains a value of 55.4% for systems 2 and 4.

MCHP/EJEC systems due to low performance of the ejector cannot compete with conventional system (power plant: $\eta_{PP} = 45\%$, $CO_2 = 0.53$ kgCO$_2$/kWh$_{el}$, electric heat pump: $COP_{EHP} = 3.5$; boiler: $\eta_b = 90\%$, $CO_2 = 0.22$ kgCO$_2$/kWh$_p$) both in terms of primary energy savings and equivalent CO_2 emissions reduction.

Table 8
Comparison of four variants of trigeneration systems.

System	1	2	3	4
Primary power input (LHV) [kW]	20.5	20.5	20.5	20.5
Thermal power from MCHP [kW]	12.5	12.5	12.5	12.5
Thermal power output [kW]	0	5	0	5
Additional electric power input to ejector [kW]	0	0	1	1
Electric power output [kW]	5.34	5.34	4.34	4.34
Generator temperature inlet [°C]	70	70	84.3	93.5
Ejector cooling COP [−][a]	0.134	0.135	0.201	0.236
Cooling power output [kW]	1.68	1.01	2.72	2.01
MCCHP Electric efficiency [%]	26.0	26.0	21.2	21.2
PER [%]	34.2	55.4	34.4	55.4

[a] This parameter includes for cases 3 and 4 electric input.

3. Conclusion

The transition from conventional centralized energy systems, based on separate “production”, to the incoming decentralized ones is currently in progress. This is due to the market availability of a wide variety of small scale power and heat pump systems, allowing for a satisfaction of different energy requirements (electricity, cooling and heating) with a great potential of primary energy saving and reduction of greenhouse gas emission.

The opportunity of introducing trigeneration system in small scale applications, such as residential and commercial market, derives from the energy weight of these sectors in the overall energy balance of developed countries. In Italy, these sectors were responsible for about 35.6% of the global energy consumption in 2005 while in 1999 their consumption was about the 30% of the total. In 1999, a potential energy saving of about 200,000 toe per year, about 16% of the total energy requirements, was evaluated if 500,000 micro-CHP units will replace the usual energy-supply equipments in Italy. Furthermore about 71 million European houses are supplied with natural gas, and the European Commission recognizes the advantages of cogeneration and has made the increased cogeneration capacity a key part of its CO_2 reduction strategy.

Some micro-cogenerators, based on reciprocating internal combustion engine (manufactured in Europe and Japan) and Stirling engine, are already available in the market. About thirty years ago, FIAT group built TOTEM, an RIC gas fuelled cogenerator (15 kW$_{el}$, 39 kW$_{th}$, $\eta_{el} = 26.7\%$, $\eta_{th} = 69.4\%$), and since 1981 a district heating system based on 31 TOTEMs operates in Vicenza, in the North of Italy. The strong R&D activity on fuel cells will resolve, in the medium and long term, their main limitations such as short lifetime and high initial cost. At the same time, small scale absorption and adsorption heat pumps are in R&D phase at the moment and only few and expensive models are in the presale phase. A strong effort towards the diffusion of THP systems will be due to the development of solar cooling plants in which the heat is supplied by efficient solar collectors.

In this paper a simplified 3-E (Energy, Economic and Environmental) approach has been carried out to compare the performance of complex CCHP plants.

An MCHP/HP system (56 kW of cooling power, 22 kW of thermal output for domestic hot water and 1.35 kW of electric power) performs a primary energy saving of about 28% and a $\Delta CO_2 = 36\%$. Another trigeneration system, MCHP/EHP (5.8 kW of cooling power, 11.7 kW of thermal output and 3.6 kW of electric power), can provide 21% savings in primary energy and a 29% reduction of equivalent CO_2. A system (4.7 kW of cooling power, 14.1 kW of thermal output and 12 kW of electric power), based on a micro-cogenerator operating an adsorption heat pump, could achieve a PES equal to 9%. Finally an HVAC system, based on a desiccant wheel coupled to a cogenerator, allows a primary energy saving of about 20%.

The key factors that can sustain the diffusion of CCHP systems are:

- primary energy savings;
- reduction of greenhouse gas emissions;
- transition to gas cooling technologies; the HVAC market is largely dominated by electrically-driven units, which involves an increased power generation capacity of electric utilities and a summer peak load of electric energy consumption, with the related problem of electric black-out. Japan and USA were involved in this problem 20 years ago and it is currently very pressing in Mediterranean area. The GCT can shift energy demand in summer from electricity to gas, at the same time

permitting the utilization of natural gas surplus during the warm season;
- shifting from centralized to decentralized energy “production” systems to avoid network losses, thus assuring high quality power supply and finally increasing the network availability.

The energy and the environmental benefits of small scale and on-site trigeneration cannot be disputed, but some obstacles, such as high initial cost are still very prominent. In fact a support action which allows for a short payback period is necessary. There are a great number of subjects involved in the definition of the economic variables including the public sectors and the private sectors (gas utilities, manufacturers, and so on). For example, the possibility of obtaining funds as well as selling the electric surplus to the grid at good price, could strongly contribute to CCHP market penetration. As it is also well known, legislative initiatives play a basic role to support very efficient technologies. For example EU has introduced directives that can strongly contribute to the diffusion of small scale cogeneration and/or trigeneration systems, such as the directives on emission trading, on electricity and gas and on the energy performance of building.

Further incentives, such as low tax rates on gas, carbon tax exemption, dispatch priority in the transmission grid and economic instruments to support high energy efficiency systems, could be introduced by governments.

Acknowledgements

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Nomenclature

ABHP	ABsorption Heat Pump
AC	Alternating Current
ADHP	ADsorption Heat Pump
AFC	Alkaline Fuel Cell
AS	Alternative System
B	Boiler
CHP	Combined Heating and Power
CCHP	Combined Cooling, Heating and Power
COP	Coefficient of Performance, [−]
CS	Conventional System
DG	Decentralized or Distributed Generation
DHW	Domestic Hot Water
DMFC	Direct Methanol Fuel Cell
DT	Decentralized Trigeneration
DW	Desiccant Wheel
E	Energy, [kJ]
EHP	Electric Heat Pump
EJEC	Ejector
G	electricity Generator
GCT	Gas Cooling Technologies
GHP	Gas engine driven Heat Pump
HHV	Higher Heating Value
HP	Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
LPG	Liquefied Propane Gas
LHV	Lower Heating Value
MC	Molten Carbonate
MCHP	Micro Combined Heat and Power
MCCHP	Micro Combined Cooling Heating and Power
MEMS	Micro Electro Mechanical Systems
ODP	Ozone Depletion Potential
PAFC	Phosphoric Acid Fuel Cell
PM	Prime Mover
PEMFC	Proton Exchange Membrane Fuel Cell
PER	Primary Energy Ratio, [%]
PES	Primary Energy Savings, [%]
PP	Power Plant
RIC	Reciprocating Internal Combustion
SOFC	Solid Oxide Fuel Cell
SPB	Simple Pay-Back period, [year]
THP	Thermally activated Heat Pump
r_e	rate of electric energy delivered by MCHP and used in electrically-driven cooling equipments
r_m	rate of mechanical energy delivered by MCHP and used in mechanically-driven cooling equipments
r_t	rate of thermal energy delivered by MCHP and used in thermally-driven cooling equipments

Greek symbol

ΔCO_2	Avoided equivalent CO_2 emissions, [%]
η	efficiency, [%]

Subscript

AS	Alternative System
B	Boiler
co	cooling
CS	Conventional System
EHP	Electric Heat Pump
el	electric
g	electricity generator
m	mechanical
p	primary input
PP	Power Plant
th	thermal

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