Chapter 15
Energy Technologies for Building Supply Systems: MCHP

Sergio Sibilio and Antonio Rosato

Abstract Micro-cogeneration is an emerging technology with the potential to—if designed and operated correctly—reduce both the primary energy consumption and the associated greenhouse gas emissions, when compared to traditional energy supply systems. The distributed nature of this generation of technology has the additional advantages of (1) reducing electrical transmission and distribution losses; (2) alleviating the peak demands on the central power plants; and (3) diversifying the electrical energy production, thus improving the security of energy supply. The micro-cogeneration devices are used to meeting the electrical and heating demands of buildings for space heating/hot water production, as well as potentially (mainly for temperate and hot climates) absorption/adsorption cooling systems. 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 and flux, and the market remains undeveloped, but interest in the technologies by manufacturers, energy utilities, and government agencies remains strong.

15.1 Introduction

The electricity demand of buildings is usually satisfied by large central power plants using combustion-based energy conversion; one 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) that is

S. Sibilio (✉) · A. Rosato
Department of Architecture and Industrial Design "Luigi Vanvitelli",
Second University of Naples, via San Lorenzo, 81031 Aversa, CE, Italy
e-mail: sergio.sibilio@unina2.it

A. Rosato
e-mail: antonio.rosato@unina2.it

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able to recover and use this 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 stream such as oil, coal, natural or liquefied gas, biomass, solar, etc. (ASHRAE Handbook 2000). It allows developing the 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 principle, the concept of cogeneration can be applied to power plants of various sizes, ranging from small-scale for residential buildings to large-scale cogeneration systems for industrial purposes, to fully grid-connected utility generating stations. 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 the transformers; in addition, large cogeneration systems generally utilize the waste heat by piping hot water into the buildings of the surrounding community, a process that involves significant heat loss due to transportation of hot water over long distances, along with the 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 where both energy flows can be used. According to Directive 2004/8/EC, 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_{el}. Some authors use the term “small-scale cogeneration” for the combined heat and power generation systems with electrical power less than 100 kW_{el} (Angrisani et al. 2012; Maghanki et al. 2013), while the term “micro-cogeneration” is sometimes used to denote cogeneration units with an electric capacity smaller than 15 kW_{el} (Angrisani et al. 2012; Maghanki et al. 2013).

Micro-cogeneration may potentially change the traditional roles attributed to the private consumer. Typically, households purchase and consume electricity from the grid and produce heat with a heating unit owned by them. With a micro-cogeneration unit installed in their houses, they become electricity producers and may sell electricity to the grid. Figure 15.1 (Evangelisti et al. 2015) shows the concept of MCHP applied to a home: waste heat is used for space heating and domestic hot water production, while electricity is used within the building (for lighting, consumer electronics, or any other electrical needs the house may have) or exported to the grid.

Micro-cogeneration applications have to satisfy either the electrical and thermal demands, or satisfy the thermal demand and part of the electrical demand, or satisfy the electrical demand and part of the thermal demand. 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 heating needs, while electricity is either used internally or exported to the grid. However, in a

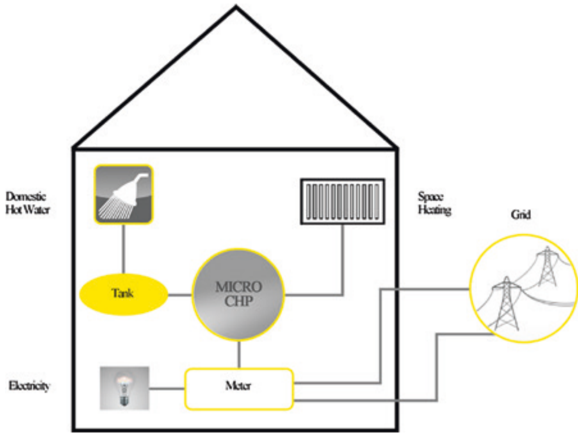

Fig. 15.1 Schematic representation of an MCHP unit for residential use (Evangelisti et al. 2015)

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 heat 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 (as well as the operating strategy), the MCHP system may have to be run at partial 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 plant; the surplus heat produced 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 (Onovwiona and Ugursal 2006).

Micro-cogeneration is emerging as a fast-growing technique to reduce the primary energy consumption in small- or medium-scale applications (Angrisani et al. 2012; Maghanki et al. 2013; Onovwiona and Ugursal 2006; Wu and Wang 2006; Chicco and Mancarella 2009), 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 15.2 (Onovwiona and Ugursal 2006) illustrates how the chemical energy from the fuel is converted into useful thermal energy and electrical energy for a conventional fossil fuel-fired electricity generation and a micro-cogeneration system.

In this figure, α_E is the electric efficiency (ratio between electric output and fuel power input) of the micro-cogeneration unit, α_Q is the thermal efficiency (ratio between thermal output and fuel power input) of the MCHP device, η_E is the electric efficiency of the electrical power plant (production of electricity only), η_Q is the thermal efficiency of the boiler (production of heat only), E is the electricity

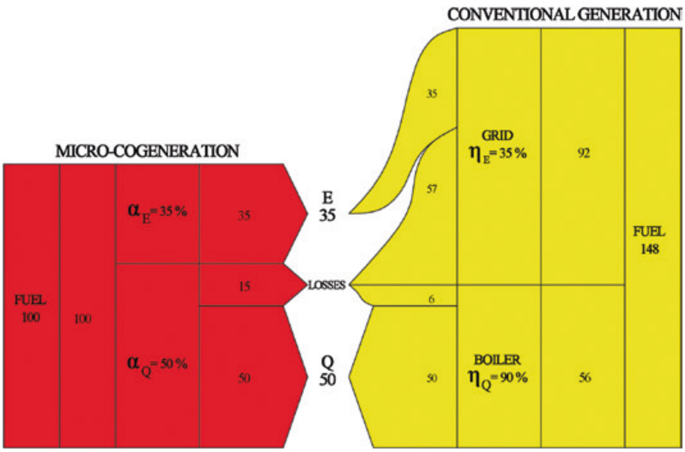

Fig. 15.2 Micro-cogeneration versus conventional separate generation (Onovwiona and Ugursal 2006)

demand, and Q is the heat demand (for space heating and domestic hot water production). This figure 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 separately (in centralized power plants), as recognized also by the European Community (Directive 2004/8/EC, 2004); in addition, it should be stressed that the increase in energy efficiency with micro-cogeneration can result in lower operating costs and reduced greenhouse gas emissions [assisting in meeting Kyoto targets (United Nations, Framework Convention on Climate Change, 2005)]. 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 peak utility 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 can use alternate fuels), thus potentially improving the security of the energy supply in the event of problems occurring with the main electricity grid.

MCHP systems could also provide new commercial opportunities for manufacturers as well as for partnerships between manufacturers, energy suppliers, financiers, and others. In addition, 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 in the market, providing solutions to exploit the price elasticity to the electrical demand.

In order to obtain that include energy savings, reduction of pollutant emission, and short payback-periods, residential cogeneration units must be appropriately designed and managed in response to variations in 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 for obtaining high levels of overall energy efficiency, along with the associated environmental benefits (IEA/ECBCS Annex 42 2007). When designing an MCHP system, it should be also taken into account that the efficiency of a cogeneration unit is strongly related to the type of the 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 (Angrisani et al. 2012), the utilization level of the unit typically has to be more than 4000 running hours per year (Onovwiona and Ugursal 2006).

Together with a lot of potential benefits, some drawbacks still limit the large diffusion of micro-cogeneration systems (Angrisani et al. 2012; Sonar et al. 2014; DECENT project 2002; Mancarella and Chicco 2009; Angrisani et al. 2014a):

- 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
- High first-capital costs
- 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 a good price)
- Insufficient political support mechanisms and administrative hurdles, such as electric network grid connection
- Components that are in the R&D phase or in a pre-selling 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 optimum system performances
- The diffusion of distributed cogeneration within urban areas, where air quality standards are quite stringent, brings about environmental concerns regarding local emissions (such as NO_x, CO, SO_x, particulate matter, unburned hydrocarbons, etc.).

Today, leading governments from the countries of Europe, Japan, and the United States have taken roles in promoting and advancing this technology (IEA/ECBCS Annex 42 2007; IEA/ECBCS Annex 54 2013) and micro-cogeneration has a significant market potential. MCHP devices are especially interesting for small and medium family houses, buildings and enterprises, hotels, hospitals, university campuses, etc. The Micro-Map Project (MICRO-MAP 2002) reported that in Europe between 5 and 12.5 million homes could have MCHP systems installed by 2020, which would result in a CO_2 emissions savings of between 3.3 and 7.8 million tons per year.

With respect to the potential utilization of micro-cogeneration technology, it is very important to emphasize that in many countries in the last few years, there has been an increasing demand for cooling energy during the warm season, generally satisfied by electrically-driven units, with this trend having 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 and environmental 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 electrically driven cooling systems allows setting up a "micro-trigeneration system" (MCCHP = micro combined cooling heat and power) (Angrisani et al. 2012; Maghanki et al. 2013; Onovwiona and Ugursal 2006; Wu and Wang 2006; Chicco and Mancarella 2009), that represents the production in situ of a threefold energy vector requested by the user from a unique source of fuel with significant potential benefits from energy and environmental points of view. MCCHP is an upgrade of the 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 decreases, due to the larger amount of operating hours per annum (Angrisani et al. 2012).

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 (IEA) (IEA/ECBCS Annex 42 2007; IEA/ECBCS Annex 54 2013).

15.2 Prime Mover Technologies and Market Survey

Today, there are several technologies that 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 the photovoltaic conversion of radiation.

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

1. Reciprocating internal combustion engines (ICE)-based MCHP systems
2. Reciprocating external combustion Stirling engines (SE)-based MCHP systems
3. Fuel cells (FC)-based MCHP systems
4. Gas and steam micro-turbines (MT)-based MCHP systems
5. Photovoltaic thermal (PVT) MCHP systems

Table 15.1 shows the most important scientific papers focused on the above-listed micro-cogeneration technologies. The references reported in this table highlight and describe many significant examples referred on them.

At the moment, micro-cogenerators based on reciprocating internal combustion and Stirling engines are already available on the market for the single- and multi-family residential building market; small-scale commercial applications and

Table 15.1 Manufacturer's data on main ICE-based micro-cogenerators

	Proposed literature
Reciprocating internal combustion engines (ICE)-based MCHP systems	Onovwiona and Ugursal (2006), Wu and Wang (2006), Angrisani et al. (2012), Maghanki et al. (2013), Sonar et al. (2014).
Reciprocating external combustion Stirling engines (SE)-based MCHP systems	Onovwiona and Ugursal (2006), Wu and Wang (2006), Angrisani et al. (2012), Maghanki et al., (2013), Sonar et al. (2014)
Fuel Cells (FC)-based MCHP systems	Onovwiona and Ugursal (2006), Wu and Wang (2006), San Martin et al. (2010),Angrisani et al. (2012),Maghanki et al. (2013), Sonar et al. (2014).
Gas and steam micro-turbines (MT)-based MCHP systems	Onovwiona and Ugursal (2006), Wu and Wang (2006), Maghanki et al. (2013), Sonar et al. (2014).
Photovoltaic thermal (PVT) MCHP systems	Chow (2010), Bianchi et al. (2012), Maghanki et al. (2013), Ferrari et al. (2014), Kumar et al. 2015

a large R&D operation that aims at producing, in the medium and long run, small, commercially available units based on fuel cells, gas, and steam micro-turbines, are already in progress (Angrisani et al. 2012). When selecting micro-cogeneration systems, one should consider some important technical parameters that assist in defining the type and operating scheme of the various alternative cogeneration systems to be selected:

- Electric and thermal load patterns of the end-users
- Heat-to-power ratio of the end-users
- Fuels available
- System reliability
- Permission of power export to the central electric grid
- Temperature levels
- Local environmental regulations

In the following sections, the various technologies suitable for micro-cogeneration are described and compared in terms of capacity range, fuel, electricity efficiency, thermal efficiency, overall efficiency (sum of electric and thermal efficiencies), noise level, dimensions, weight, life service, pollutant emissions, capital, and maintenance costs.

15.2.1 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, coolants and 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 (Angrisani et al. 2012)], a capital cost of between €2000 and 6000/kW$_{el}$ depending on the size (Angrisani et al. 2012), and a typical maintenance cost from 0.010 to 0.015 €/kWh (Onovwiona and Ugursal 2006). ICE-based MCHP systems occupy small installation spaces and also have satisfactory electric (20–34 %) and thermal (50–65 %) efficiencies. In addition to fast start-up capability and good operating reliability, they are characterized by high efficiency at partial load operation and can be fired on a broad variety of fuels with excellent availability, allowing for a range of various energy applications, especially emergency or standby power supplies.

Although they are a mature technology, reciprocating internal combustion engines have obvious drawbacks: (1) relatively high vibrations that require shock absorption and shielding measures to reduce acoustic noise [<60 dB(A) at a 1 m distance (Angrisani et al. 2012)]; (2) a large number of moving parts and frequent maintenance intervals that increase maintenance costs; and (3) 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 (Angrisani et al. 2012)], which are the underlying aspects of this technology and need to be improved. Major manufacturers around the world continuously develop new engines with lower emissions; at the same time, emissions that 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 15.2 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),

Table 15.2 Manufacturers' data on main ICE-based micro-cogenerators

	SENERTEC Dachs G 5.5	YANMAR CP5WN-SN	YANMAR CP10WN-SN
Input power (kW)	20.5	17.8	31.5
Electric power (kW)	5.5	5.0	9.9
Thermal power (kW)	12.5	10.0	16.8
Electric efficiency (%)	26.8	28.1	31.4
Thermal efficiency (%)	61.0	56.2	53.3
Overall efficiency (%)	87.8	84.3	84.8
Fuel	Natural gas	Natural gas	Natural gas
Weight (kg)	530	400	756
L (mm)	720	1100	1470
H (mm)	1000	1500	1790
D (mm)	1060	500	800
No. of cylinders	1	3	3
Displacement (cm^3)	579	699	1642
Noise (dB(A))	56	53	56

(continued)

Table 15.2 (continued)

	TEDOM micro T7 AP	COGENGREEN ecoGEN-12AG	EC POWER XRGI 9
Input power (kW)	25.9	43.0	31.0
Electric power (kW)	7.0	12.0	9.0
Thermal power (kW)	17.2	28.0	20.0
Electric efficiency (%)	27.0	27.9	29.0
Thermal efficiency (%)	66.4	65.1	64.5
Overall efficiency (%)	93.4	93.0	93.5
Fuel	Natural gas	Natural gas, LPG	Natural gas, propane, butane
Weight (kg)	645	700	440
L (mm)	1315	1340	920
H (mm)	1480	1218	960
D (mm)	700	780	640
No. of cylinders	3	4	4
Displacement (cm^3)	962	1600	2237
Noise (dB(A))	58	55	49

	HONDA Ecowill	AISIN SEIKI GECC 46 A2	AISIN SEIKI GECC 60 A2
Input power (kW)	3.8	18.0	20.8
Electric power (kW)	1.0	4.6	6.0
Thermal power (kW)	2.5	11.7	11.7
Electric efficiency (%)	26.3	25.6	28.8
Thermal efficiency (%)	65.8	65.0	56.3
Overall efficiency (%)	92.1	90.6	85.1
Fuel	Natural gas, LPG	Natural gas, LPG	Natural gas, LPG
Weight (kg)	71	465	465
L (mm)	580	1100	1100
H (mm)	750	1500	1500
D (mm)	298	660	660
No. of cylinders	1	3	3
Displacement (cm^3)	163	952	952
Noise (dB(A))	43	54	54

	VAILLANT Ecopower e4.7	SENERTEC Dachs G 5.0
Input power (kW)	18.9	19.6
Electric power (kW)	4.7	5.0
Thermal power (kW)	12.5	12.3
Electric efficiency (%)	24.9	25.5
Thermal efficiency (%)	66.1	62.8
Overall efficiency (%)	91.0	88.3

(continued)

Table 15.2 (continued)

	VAILLANT Ecopower e4.7	SENERTEC Dachs G 5.0
Fuel	Natural gas, propane	Natural gas
Weight (kg)	390	530
L (mm)	760	720
H (mm)	1080	1000
D (mm)	1370	1070
No. of cylinders	1	1
Displacement (cm^3)	270	579
Noise (dB(A))	56	56

overall efficiency (sum of electric and thermal efficiencies), fuel, weight, dimensions (L = Length, H = Height, D = Depth), number of cylinders, displacement, and noise (at a 1 m distance), based on the manufacturers' nominal data.

15.2.2 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, usually helium or hydrogen (but also oxygen, nitrogen, and carbon dioxide), is not exchanged during each cycle (but within the device), 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 that facilitates the control of the combustion process and results in low emissions (emissions from current Stirling burners can be 10 times lower than those emitted from reciprocating internal combustion engines with a catalytic converter, making the emissions generated from Stirling engines comparable to those from modern gas burner technology (Onovwiona and Ugursal 2006)). Compared to the ICE-based systems, Stirling engines have fewer moving parts and lower vibrations, longer lives service, lower noise levels, and longer maintenance-free operating periods. The global efficiency is higher than 80 %, and it may even go beyond 95 %, with a good performance at partial load. The capital costs depend on the size, ranging from €2,700 to 5500/kW_{el} (Angrisani et al. 2012); an estimated maintenance cost for the unit is around €0.013/kWh (Onovwiona and Ugursal 2006). Despite many advantages, the Stirling engine has not found the expected applications due to low electric efficiency (ranging from 12 to 28 %), difficult power control system because of the presence of various heat exchangers (heater, cooler, regenerator, and auxiliary heat exchangers), high pressure level of working gas, low durability of parts, and long start-up time.

Various small-scale Stirling-based cogenerators are commercially available or under development. Table 15.3 describes the main SE-based MCHP systems available 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

Table 15.3 Manufacturers' data on main SE-based micro-cogenerators

	WHISPERGEN	BAXI Ecogen	Qnergy QCHP7500
Input power (kW)	8.3	7.4	38.0
Electric power (kW)	1.0	1.0	7.5
Thermal power (kW)	7.0	6.0	30.0
Electric efficiency (%)	12.0	13.5	19.7
Thermal efficiency (%)	84.3	81.1	78.9
Overall efficiency (%)	96.4	94.6	98.7
Fuel	Natural gas	Natural gas, biogas	Wood pellets, biomass, liquid fuels, natural gas, propane
Weight (kg)	137	110	200
L (mm)	480	450	630
H (mm)	840	950	770
D (mm)	560	426	1380
No. of cylinders	4	–	–
Displacement (cm3)	–	–	–
Working gas	Nitrogen	–	–
Maximum pressure (bar)	–	–	–
Noise (dB(A))	–	45	65

	SUNMACHINE	SOLO 161
Input power (kW)	12.0	38.8
Electric power (kW)	3.0	9.5
Thermal power (kW)	7.8	26.0
Electric efficiency (%)	25.0	24.5
Thermal efficiency (%)	65.0	67.0
Overall efficiency (%)	90.0	91.5
Fuel	Wood pellets	Natural gas, LPG, biogas, biomass
Weight (kg)	410	460
L (mm)	1160	1280
H (mm)	1590	980
D (mm)	760	700
No. of cylinders	1	2
Displacement (cm3)	520	160
Working gas	Nitrogen	Helium, hydrogen
Maximum pressure (bar)	36	150
Noise (dB(A))	–	–

fuel input power), thermal efficiency (ratio of thermal power to fuel input power), overall efficiency (sum of electric and thermal efficiencies), fuel, weight, dimensions (L = Length, H = Height, D = Depth), number of cylinders, displacement, working gas, maximum working pressure, and noise (at a 1 m distance) based on manufacturers' nominal data.

15.2.3 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 a relatively high efficiency with a significant reduction of greenhouse gas emissions.

In a fuel cell, the chemical energy within the fuel is converted directly 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 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 the time and costs required for installation, maintenance, repair, and durability of fuel cells (Angrisani et al. 2012). Additional types of fuel cells are available: alkaline fuel cells (AFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), and, as of late, direct methanol fuel cells (DMFC).

Fuel cells have several benefits, such as high electric efficiency (30–60 %) and overall efficiency (80–90 %), near zero emissions [due to their lack of a combustion process, FCs have extremely low emissions of NO_x and CO; their CO_2 emissions are also generally lower than other technologies due to their higher efficiency (Onovwiona and Ugursal 2006)], a good match with the residential thermal to power ratio, reliability, quiet operation, potential for low maintenance, and excellent partial load management.

Nevertheless, the high costs [varying from €6700/kW_{el} for PEMFC to €60,000/kW_{el} for SOFC (Angrisani et al. 2012)] 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 an ancillary (5–15 %) (Angrisani et al. 2012). Fuel cell maintenance costs vary with the type of fuel cell, size, and maturity of the equipment. A major overhaul of fuel cell systems involves shift catalyzer replacement, reformer catalyzer replacement, and stack replacement; for example, the cost of replacing the stack of a 10 kW PEMFC is estimated to be €0.0188/kWh (Onovwiona and Ugursal 2006).

Ongoing research to solve technological problems and develop less expensive materials and mass production processes are expected to result in advances in technology that will reduce the cost of fuel cells. At this moment there are few fuel

Table 15.4 Manufacturers' data on main FC-based micro-cogenerators

	KYOCERA (SOFC)	PANASONIC ENE FARM (PEMFC)	HEXIS Galileo 1000 N (SOFC)
Electric power (kW)	0.70	0.75	1.00
Thermal power (kW)	0.65	1.08	1.80
Electric efficiency (%)	42.0	35.2	30.0
Thermal efficiency (%)	39.2	50.6	62.0
Overall efficiency (%)	81.2	85.8	92.0
Fuel	Natural gas	Natural gas	Natural gas, biogas
Weight (kg)	94	95	170
L (mm)	600	400	620
H (mm)	935	1850	1640
D (mm)	335	400	580

	BlueGEN (SOFC)	VAILLANT FCU 4600 (PEMFC)	VIESSMAN Vitovalor 300-P (PEMFC)
Electric power (kW)	1.50	4.60	0.75
Thermal power (kW)	0.54	7.00	1.00
Electric efficiency (%)	60.0	35.0	37.0
Thermal efficiency (%)	25.0	50.0	53.0
Overall efficiency (%)	85.0	85.0	90.0
Fuel	Natural gas, propane, butane, ethanol, biodiesel	Natural gas	Natural gas
Weight (kg)	–	–	125
L (mm)	600	–	516
H (mm)	1010	–	1667
D (mm)	660	–	480

cell-based MCHP systems available commercially. Table 15.4 describes the main FC-based micro-cogeneration units on the market (with electric output lower than 15 kW_{el}) in terms of electric output, thermal output, electric efficiency (ratio of electric power to fuel input power), overall efficiency (sum of electric and thermal efficiencies), fuel, weight, and dimensions (L = length, H = height, D = depth) based on manufacturers' nominal data.

15.2.4 Gas and Steam Micro-turbines (MT)

Micro-turbines 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.

Table 15.5 Manufacturers' data on main FC-based micro-cogenerators

	FLOWGROUP (steam MT)	OTAG (steam MT)	MTT(steam MT)
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
L (mm)	–	62	610
H (mm)	–	126	970
D (mm)	–	83	1120
Noise (dB(A))	–	54	<58

In comparison to internal combustion engines, they offer a number of advantages such as more compact size, lower weight, shorter delivery time, smaller number of moving parts, and lower vibration and lower noise, with minimum maintenance requirements [maintenance costs are in the €0.006–0.01/kWh range (Onovwiona and Ugursal 2006)]. Additionally, micro-turbines have a significant advantage over reciprocating internal combustion engines in terms of emissions: current expectations for NO_x emissions from micro-turbines are already below those of ICEs. However, in the lower power ranges, micro-turbines have a lower overall efficiency (up to 80 %) when compared to reciprocating internal combustion engines. Their limitations are mainly due to high first-capital costs and a relatively short life. Other issues include relatively low electrical efficiency and sensitivity of efficiency to changes in ambient conditions. This technology has only recently been commercialized and is offered by a small number of suppliers. The electric capacity of micro-turbines currently on the market is usually 25 kW_{el} or above. Research is ongoing for systems with capacities less than 25 kW_{el}, which will be suitable for single-family residential buildings.

Table 15.5 describes the main MT-based micro-cogeneration units available on the market (with electric output lower than 15 kW_{el}) in terms of electric output, thermal output, electricity efficiency (ratio of electric power to fuel input power), overall efficiency (sum of electric and thermal efficiencies), fuel, weight, dimensions and noise level based on manufacturer nominal data.

15.2.5 Photovoltaic Thermal (PVT) Generators

Solar energy conversion to electricity and heat with a single device is obtained with the "photovoltaic thermal (PVT) collectors." A PVT collector is a module in which the photovoltaic (PV) system not only produces electricity, but also serves as a thermal absorber. PV cells utilize a fraction of the incident solar radiation to produce electricity and the remainder is turned mainly into waste heat in the cells and substrate raising the temperature of PV. The photovoltaic thermal (PVT) technology recovers part of this heat and uses it for practical applications (Chow 2010). In this way, both heat and power are produced simultaneously (Maghanki et al. 2013). 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 collector, and thus enable a more effective use of solar energy. Different types of PVT collectors are currently being used, such as PVT/air, PVT/water, and PVT concentrated collectors (Chow 2010). Currently, there are various PVT applications on the commercial level but it is 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 (Kumar et al. 2015).

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 an array of photovoltaic cells (Ferrari et al. 2014). 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 (1) high fuel utilization factor (close to the unit, thanks to the recovery of most of the thermal losses); (2) low noise levels (due to the absence of moving parts); (3) easy maintenance (similar to a common domestic boiler); and (4) great fuel flexibility. According to the values reported in the literature associated with realized prototypes, the electric efficiency of TPV systems is low [from 0.6 to 11.0 % (Ferrari et al. 2014)], but the potential overall efficiency is always higher than 90 % (Ferrari et al. 2014). At present, the capital cost of thermophotovoltaic generators is high [around 6,000 €/m^2 (Bianchi et al. 2012)] and it does not ot appear very favorable for the development of this technology.

15.3 Operating Schemes

In this section the main operating schemes of MCHP applications are discussed. Figure 15.3 (Mohamed et al. 2014) presents a typical schematic diagram [thermal connections of the MCHP unit, and electrical connections of both the MCHP device and the photovoltaic (PV) modules (when used)] under the thermal load following control strategy, while Fig. 15.4 (Mohamed et al. 2014) presents a typical schematic diagram (electrical connections of the MCHP unit, and thermal connections of both the MCHP device and the solar thermal collectors (STC) modules (when used)) under the electric load, following control strategy. Both schemes can be used for domestic hot water (DHW) production, space heating, and electricity production.

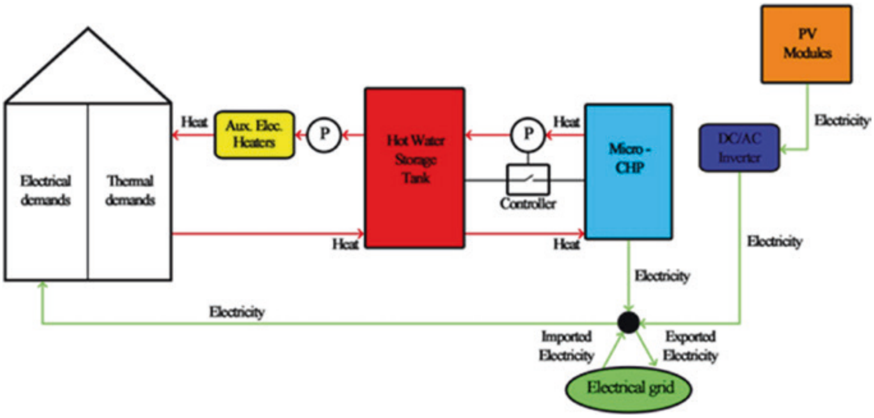

Fig. 15.3 The typical control principle of MCHP systems under thermal load following strategy (Mohamed et al. 2014)

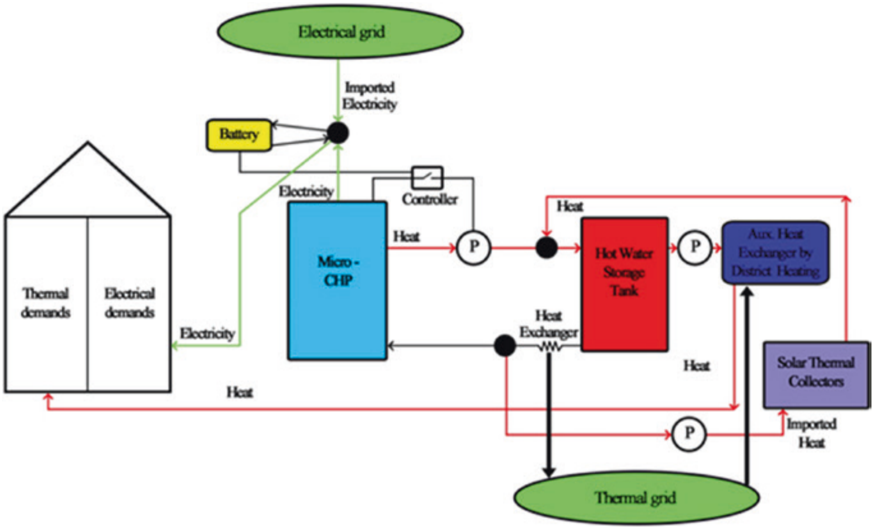

Fig. 15.4 The typical control principle of MCHP systems under electric load following strategy (Mohamed et al. 2014)

Some authors proposed micro-cogeneration plants using two separate tanks for space heating and domestic hot water (Fig. 15.5; Dorer and Weber 2009; González-Pino et al. 2014).

Additional operating schemes are suggested by the main manufacturers of the MCHP units, such as VAILLANT (Fig. 15.6), BOSCH (Fig. 15.7), and AISIN SEIKI (Fig. 15.8).

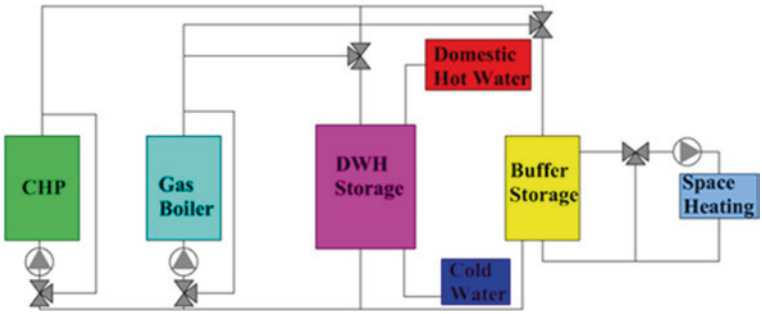

Fig. 15.5 Schematic of MCHP systems with two separate tanks (Dorer and Weber 2009)

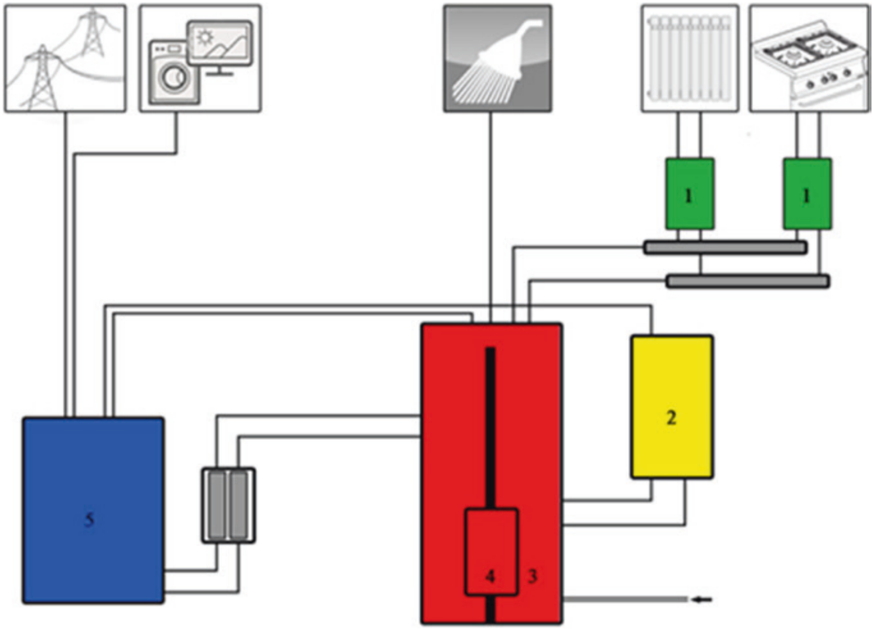

Fig. 15.6 Operating diagram of the MCHP scheme proposed by VAILLANT (*1* distribution and control system of the heating circuit; *2* boiler; *3* storage tank for space heating; *4* storage tank for DHW production; *5* MCHP unit)

Another interesting option is using the MCHP units under the so-called "load-sharing approach" (Cho et al. 2013). This approach mainly consists of combining opposing thermal load profiles in order to increase the operating hours of the micro-cogeneration devices and operate efficiently most of the time with improved part load conditions. This kind of operation is suggested in view of the fact that in residences, the main thermal loads are in the evening through the early morning, whereas the main thermal loads in offices are during the daytime. In this case, a

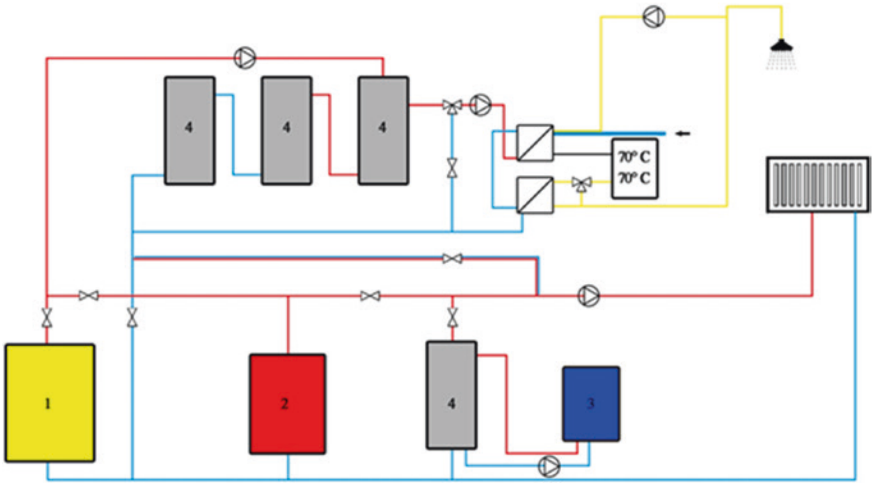

Fig. 15.7 Operating scheme of MCHP systems proposed by BOSCH (*1* MCHP unit; *2* condensing boiler; *3* air-to-water electric heat pump; *4* tanks)

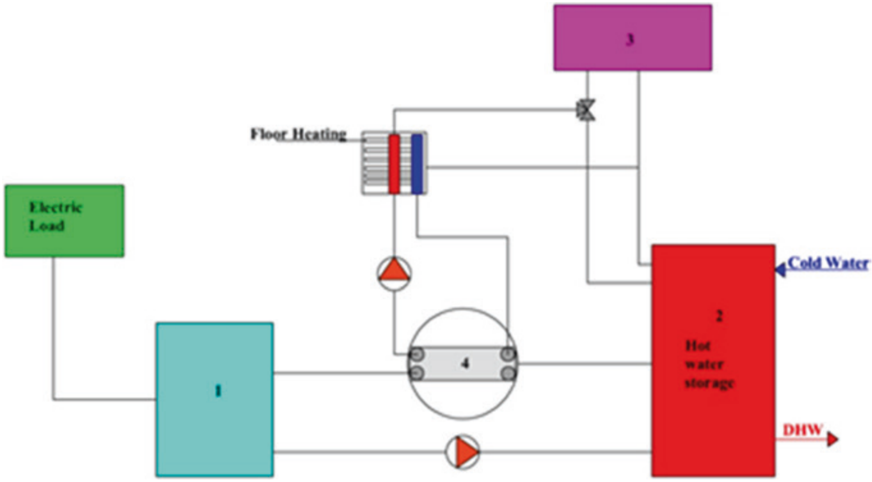

Fig. 15.8 Operating scheme of MCHP systems proposed by AISIN SEIKI (*1* MCHP unit; *2* combined tank; *3* air-to-water electric heat pump)

possible operating scheme for heating purposes is reported in Fig. 15.9 (Angrisani et al. 2014b).

Some authors (Canelli et al. 2015) investigated the "load-sharing approach," using a hybrid system composed of a fuel cell-based MCHP unit integrated with a ground source heat pump (GSHP) to satisfy the combined DHW, heating, and cooling demands of a residential application coupled with a typical office (Fig. 15.10).

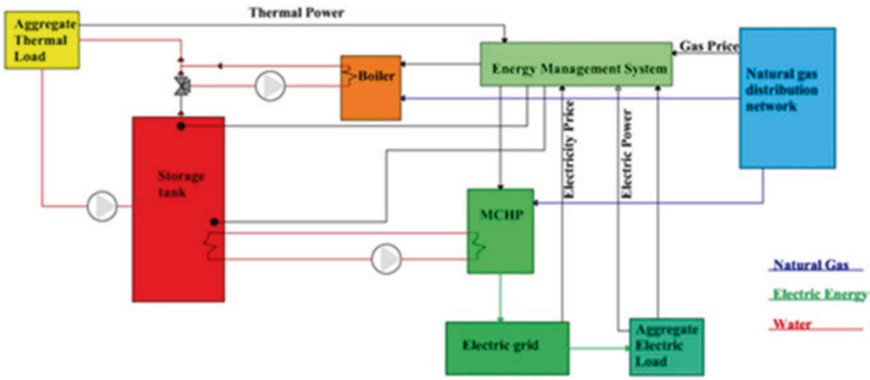

Fig. 15.9 Operating scheme of MCHP system for heating purposes in the case of a "load-sharing approach" (Angrisani et al. 2014b)

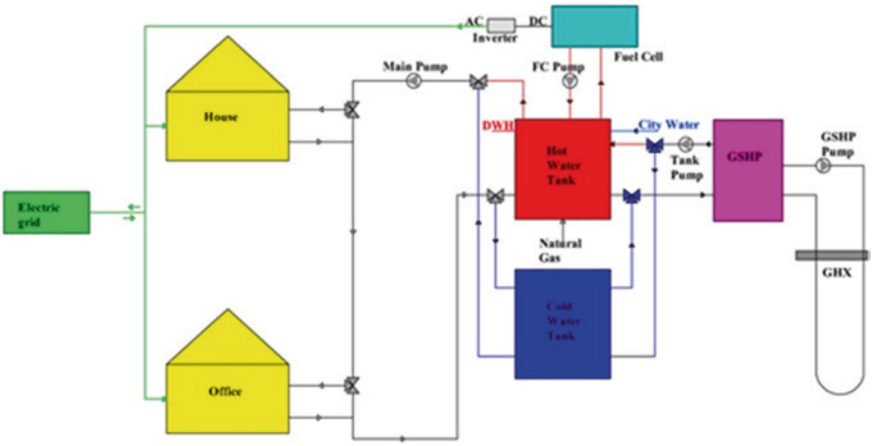

Fig. 15.10 Operating scheme using MCHP and GSHP for domestic hot water production, heating, and cooling demands in the case of a "load-sharing approach" (Canelli et al. 2015)

Integrated energy systems (known as "micro-grids") consisting of distributed generation systems (including micro-cogeneration technologies) and multiple electrical loads operating as a single, autonomous grid either in parallel to, or "islanded" from the existing utility power grid (Asmus 2010; Palizban et al. 2014; Bouzid et al. 2015) are emerging worldwide. Micro-cogeneration systems integrated into an ensemble of other distributed generation systems and load management technologies could also be centrally, remotely, and automatically controlled, forming so-called "virtual power plants" (Asmus 2010; Palizban et al. 2014; Bouzid et al. 2015), maximizing the performance for both end-users and distribution utilities.

15.4 Regulatory Framework

The economic suitability of micro-cogeneration projects are characterized by a high initial investment, the depreciation of which depends heavily on the following factors:

- Fuel price
- Price of electric energy purchased and sold
- Maintenance costs
- Utilization of cogenerated heat
- Yearly hours of operation
- Efficiency of the operating scheme
- Support schemes and other additional incentives

Within the EU member states, a wide variety of financial support mechanisms are in place—or in preparation—that are designed to improve the economics of cogeneration installations. The various European countries designed various support measures to support cogeneration. Table 15.6 summarizes the measures in

Table 15.6 Overview of support measures for CHP in the European Union in 2007 (Moya 2013)

Member state	Tax advantage	Feed-in tariff	Certificates	Grant	Other
Austria	0	1	0	0	1
Belgium	1	0	1	0	1
Bulgaria	0	1	0	0	1
Cyprus	0	0	0	0	1
Czech Republic	0	1	0	0	1
Denmark	0	0	0	0	0
Estonia	0	0	0	0	1
Finland	0	0	0	1	1
France	0	1	0	0	1
Germany	0	1	0	0	1
Greece	1	1	0	0	1
Hungary	0	1	0	0	1
Ireland	0	0	0	0	1
Italy	1	1	0	1	0
Latvia	0	1	0	0	1
Lithuania	0	1	0	0	1
Luxembourg	1	0	0	0	1
Malta	1	0	0	0	1
Netherlands	1	1	0	1	1
Poland	0	0	1	0	1
Portugal	0	0	0	1	1
Romania	0	1	0	1	0
Slovakia	0	1	0	0	0
Slovenia	0	1	0	0	1
Spain	1	1	0	0	1
Sweden	0	0	0	1	1
United Kingdom	1	1	0	1	0

1 measure in place; *0* measure not in place operation in 2007 in the European Union (Moya 2013); they are divided into tax advantages, feed in tariffs, certificates, grants, or other kinds of additional support.

The most widely used support measure is the feed-in tariff. This is a special incentive for electricity supplied to the grid, mainly a generation bonus for total electricity generated in cogeneration mode or a fuel-related concession. Tax advantages are offered in seven countries, or capital grants for specific sizes of projects are offered in eight countries. Obviously, the effectiveness of support measures depends not only on their existence in the first place, but also on their intensity; a deep analysis of the change produced on the payback period—depending on the intensity of support measures—was carried out by Moya (2013).

15.4.1 Micro-cogeneration Testing Procedures

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. Moreover, in some countries, MCHPs may be required to meet certain minimum standards to be marketable (Angrisani et al. 2014c). Therefore, it is useful to define a procedure for testing *ex-ante* the energy performance of a device, representative of a unit type, allowing for classification of the energy performance of the MCHP with experimental tests performed in a test facility, possibly certified by an independent third party. The diffusion of such standards procedures can also support the introduction of energy-labelling schemes for MCHP units, such as those already in place for various electric appliances, which could help potential users understand the achievable energy, and environmental and economic savings.

Standard testing procedures are available or at a discussion stage in many countries around the world. Following are examples of such standard procedures for small-scale cogeneration devices (Angrisani et al. 2014c):

- Italy: prUNI E0204A073: Draft of a proposed UNI standard: microcogeneration devices fuelled by gaseous or liquid fuels—*ex-ante* measurement of energy performance (in stand-by) (Bianchi et al. 2013).
- Germany: DIN 4709 (2011-11): Determination of the standard efficiency factor for micro-CHP-appliances of nominal heat input not exceeding 70 kW.
- UK: Publicly available specification 67 (PAS 67).
- USA: ASHRAE SPC 204—Method of testing for rating micro combined heat and power devices (in progress).
- Europe: prEN 50465: Gas appliances—Combined heat and power appliance of nominal heat input inferior or equal to 70 kW.
- Japan: Industrial standards for performance and safety testing of MCHP.

The principles of the main available national testing procedures are described and summarized in Angrisani et al. 2014c; they have many common general features:

- They require that the MCHP be heat-led.
- They refer to a control volume that includes the whole heating system (MCHP, integration boiler and storage tank).
- They require only a limited number of tests, both under nominal operating conditions and according to appropriate test cycles.
- They specify the equipment and instrumentation to be used, such as sensor accuracy.
- They define the reference testing conditions (supply and return water temperatures, ambient air temperature, etc.).

Nevertheless, some major differences can be detected among the national testing procedures; for example, the analyzed standards differ in terms of the limiting value of power (electric, thermal, or primary) for the applicability. A further dissimilarity can be found in the thermal load profile for testing: the Italian standard defines four day types (three for thermal and one for cooling loads); the German one defines a single profile, representative of an intermediate day; in the UK, the standard heat load profile is represented by the number of days per heating season at 13 part-load bands. A further major difference is that the Italian and German standards use energy-based performance indices to evaluate the stationary nominal and overall annual performance of the MCHP system, while the UK procedure is based on an environmental-based performance assessment parameter.

15.4.2 State of the Art: Experimental Results and Simulation Tools

The opportunity to use MCHP systems depends on factors such as heat and power demand variations, control modes, and the capacity and efficiency of the residential cogeneration system, as well as electricity import/export conditions and modes. Therefore the feasibility of a micro-cogeneration unit is a function of the design and size of the system as well as the building it is intended for. For these reasons, studying and evaluating the performance of various MCHP systems under different operating conditions is mandatory. Two main ways can be considered for this purpose:

- Running field/laboratory experiments.
- Developing accurate simulation models of micro-cogeneration devices.

Many laboratory and field tests of residential micro-cogeneration units have been performed worldwide (Entchev et al. 2004; Torrero and McClelland 2004; Van Herle et al. 2004; Thomas and Wyndorps 2004, 2005; Yagoub et al. 2006; Williams et al. 2006; DePaepe et al. 2006; Hubert et al. 2006; Thomas 2006; Kyocera 2006; Veitch and Mahkamov 2006; Possidente et al. 2006; Rosato and Sibilio 2013a, b) by individual manufacturers and/or by energy utility companies and/or by university researchers. Laboratory test results have been reported from all types of MCHP devices, although detailed results are not often given. Tests were conducted in steady-state mode for several load conditions, and for different supply and return temperature of the heat extraction circuit. Dynamic tests were carried out with MCHP systems including the storage components for typical space heating and domestic hot water load profiles. Measurements have also been taken in demonstration buildings with well-monitored boundary conditions and fully controlled internal loads. Many field trials with MCHP units were also conducted in a joint undertaking of MCHP manufacturers and energy service companies, but few results have been reported. National programs, such as the Carbon Trust in the UK, or the US DOE-DOD Residential PEM Fuel Cell Demonstration Program, promote the development, installation and field-testing of MCHP systems and publish their results.

A detailed review of the literature on the existing residential cogeneration performance assessment studies, on the methodologies and modelling techniques used, and on the assessment criteria and applied metrics, can be also found in Dorer (2007). This review indicated that, on the level of individual buildings, residential cogeneration systems are able to reduce the non-renewable primary energy demand compared to conventional gas boiler systems and grid electricity as the benchmark; the strong dependence of the achievable energy savings and, to an even greater extent, the resulting CO_2 emissions on the grid electricity generation mix is confirmed, as well as the strong dependence of cost savings on factors such as heat and power demand variations, control modes, the capacity and efficiency of the residential cogeneration system, and electricity import/export conditions and modes. The results of the performance assessment studies showed that big discrepancies may occur between the nominal efficiencies of the cogeneration device and the overall efficiency of the cogeneration system if the heat for starting up and cooling down the cogeneration device is not well recovered. In addition, the control mode was shown to have significant effects on the energy and environmental system performance: in many cases, heat load following modes showed the best energy efficiency, while electricity load following control modes reduced costs. In general, base-load control offered better energy savings compared to a peak-load oriented control.

The literature review (Dorer 2007) also emphasized that the potential design and operational combinations of factors affecting MCHP operation are almost limitless. These system integration issues, together considering that experimental analyses are both expensive and time-consuming, led to the need to use accurate and practical simulation models of micro-cogeneration devices as techno-economic analysis tools for studying and evaluating the performance of various systems under different load environments. In the past, it was common to model the performance of micro-cogeneration devices using performance-map methods, wherein the device's electrical and thermal efficiencies are treated as constant or as a parametric function of the device's loading. This approach essentially precludes an accurate treatment of the coupling between the building and MCHP system, and it neglects the inefficiencies associated with the transient operation of the system components. In response to this shortcoming, some authors (Voorspools and D'haeseleer 2002; Haeseldonckx et al. 2007; Onovwiona et al. 2007) recently proposed simple empirical models to simulate the performance of SE and ICE units in building-integrated cogeneration applications. All three of these models are parametric in nature, and all are closely based on empirical data collected for specific cogeneration devices. These models are well-suited for use in building simulations, and designed to predict system fuel use, power generation, and thermal output in response to part-load ratio. However, all three are directly derived from the performance data of specific systems, without the possibility of being readily recalibrated for other cogeneration products.

Recognizing the importance of investigating micro-cogeneration systems, two new generic models that characterize the performance of micro-cogeneration devices were developed (Ferguson et al. 2009; Kelly and Beausoleil-Morrison 2007): one for fuel-cell-based cogeneration systems (SOFC and PEMFC), and a second one for combustion-based systems (SE and ICE). These models rely extensively on parametric equations describing the relationships between key input and output parameters; each of these parametric equations requires empirical constants that characterize aspects of the performance of specific cogeneration devices. Like previous models (Voorspools and D'haeseleer 2002; Haeseldonckx et al. 2007; Onovwiona et al. 2007), the new models (Ferguson et al. 2009; Kelly and Beausoleil-Morrison 2007) are empirical in nature, but were also designed to support calibration with the measurements available during third-party testing of the devices. Instances of new models were independently implemented into source code for four widely used building simulation tools [ESP-r (Clarke 2001), EnergyPlus (Crawley et al. 2001), TRNSYS, and IDA-ICE (Sahlin and Sowell 1989)]. A detailed calibration and validation exercise was undertaken for one fuel-cell-based cogeneration system [SOFC device (Beausoleil-Morrison and Lombardi 2006, Beausoleil-Morrison 2010)], and three combustion-based cogeneration systems [one SE device (Lombardi et al. 2010), two ICE devices (Beausoleil-Morrison 2007, Rosato and Sibilio 2012)].

At present, simulation and optimization tools are emerging as the best option to better understand and control micro-generation systems. The most popular tools used worldwide can be categorized as follows (Sonar et al. 2014):

- Economic tools (RETSCREEN, HOMER)
- Simulation tools (TRNSYS, EnergyPlus (Crawley et al. 2001))
- Optimization tools (EnergyPlan)
- Data-bases (CO2DB)
- Externalities and environment impact calculation tools (Extern E, ECOSENSE)

15.5 Conclusions/Discussion

The opportunity to use micro-cogeneration systems greatly depends on factors such as a building's thermal characteristics, prevailing weather, heat and power demand variations, characteristics and control logic of the MCHP device, unit costs of natural gas and electricity, etc. In order to obtain significant benefits when compared to the traditional energy supply systems, it is imperative that the thermal portion of the cogeneration device's output be well exploited and the utilization level of the units be typically more than 4,000 running hours per year.

Temperate climates are suitable for micro-cogeneration mainly in cases where the thermal or electric energy produced by the micro-cogeneration units is further utilized to provide space or process cooling throughout the year, thus allowing longer annual operating periods.

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