# Combined Micro-Systems

**Nicolae Badea**

**Abstract** This chapter presents the technologies for achieving Combined Heat and Power (CHP) and micro-Combined Cooling Heat and Power (mCCHP) micro-generation systems. Section 1 presents based on the relevant data from literature the main primary thermal motors used in CHP micro systems. A comparative analysis of cogeneration technologies based on performance indicators is presented in Sect. 2. Section 3 describes the mCCHP systems from the points of view of architectural achievement and operation modes in order to satisfy the residential consumers' energy needs.

## 1 The Micro-CHP Technologies

CHP technologies refer to the energy conversion, recuperation, and management in view of obtaining heat and power from burning a fuel. The term CHP (Cooling, Heating, and Power) describes all electrical power generation systems that utilize recoverable waste heat for space heating, cooling, and domestic hot water purposes (Fig. 1). The term CHP describes all electrical power generation systems that utilize recoverable waste heat for space heating, cooling, and domestic hot water purposes. Micro-CHP encompasses all systems in the range of 15–35 kW of electrical production or less. These systems range from single family homes to small apartment complexes to small office buildings. In a typical micro-CHP system, electricity is generated on-site from the combustion of a fuel source in an electrical generation set (prime mover and generator). This combustion produces recoverable heat in the form of heated engine coolant and high temperature exhaust. The use of the recoverable thermal energy for space heating and cooling purposes is the driving factor behind the increased overall energy usage from conventional power generation systems. Cogeneration system [1] consists of four basic elements: a prime mover (engine), an electricity generator, a heat recovery system and a control system. In the systems based on these technologies, primary engines play an extremely important role; they

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N. Badea (ed.), *Design for Micro-Combined Cooling, Heating and Power Systems*,
Green Energy and Technology, DOI 10.1007/978-1-4471-6254-4_3

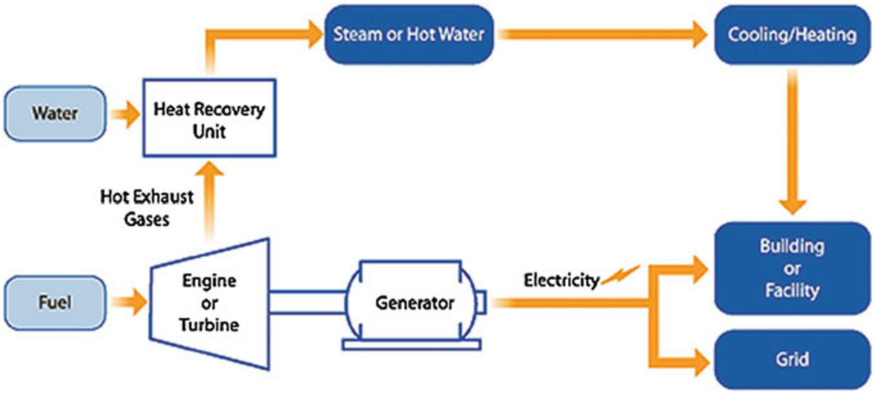


**Fig. 1** CHP technologies requirements [1]

represent the basic components and, to a certain extent, determine the architecture of these systems.

The performance characteristics of a CHP system are overall efficiency, electric efficiency, power, power-to-heat ratio, and start-up time. The overall efficiency is dependent on many factors, such as technology used, fuel types, operation point, size of the unit, and also on the heat potential. All these characteristics are closely linked to the primary engine of the CHP system. That is why cogeneration technologies for residential, commercial, and institutional applications can be classified according to their prime mover and to where their energy source is derived from.

Present day technologies of cogeneration in mCHP systems [2] are based on the recuperation of the thermal energy of the following prime movers:

- Steam turbines, which are capable of operating over a broad range of steam pressures. They are custom designed to deliver the thermal requirements of CHP applications through use of backpressure or extraction steam at the appropriately needed pressure and temperature.
- Gas turbines, which produce a high quality (high temperature) thermal output.
- Reciprocating engines, which are well suited for applications that require hot water or low-pressure steam.
- Stirling engines.
- Fuel cells, where the waste heat can be used primarily for domestic hot water and space heating applications.

### *1.1 Steam Turbines*

Steam turbines represent the widest used technology in industrial electric plants [3]. The thermodynamic cycle which lies at the basis of conventional steam plant functioning may be the one with overheated steam (the Hirn cycle) or the one with

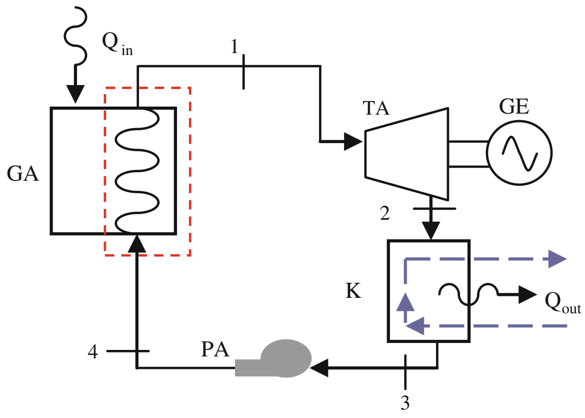


**Fig. 2** CHP with a condensation steam turbine [3]

saturated steam (the Rankine cycle). In Fig. 2 is present a CHP system with a steam turbine [3],

where

GA—steam generator, TA—steam turbine, GE—electric generator, K—condenser, PA—charging pump.

The steam generator has the role of vaporizing water and transforming it into saturated or overheated steam. This process is achieved using the heat from burning a fuel. The steam is released in the turbine, producing mechanical energy, which the electric generator transforms into electric energy.

The condenser ensures the condensation of the water vapors released from the turbine and represents the cold source of the thermodynamic cycle. To evacuate the heat toward the exterior, water or, rarely, atmospheric air may be used as cooling agents.

The thermal efficiency can also be expressed in terms of the heat transfer terms or in terms of temperatures in the following manner:

$$\eta = \frac{\dot{Q}_{\text{in}} - \dot{Q}_{\text{out}}}{\dot{Q}_{\text{in}}} \tag{1}$$

or

$$\eta = 1 - \frac{\vartheta_{\text{out}}}{\vartheta_{\text{in}}} \tag{2}$$

where:

$\vartheta_{\text{out}}$—is the temperature on the steam side of the condenser

$\vartheta_{\text{in}}$—is the average temperature of heat addition at the boiler.

To increase the turbine thermal efficiency, the methods presented in what follows are used.

### 1.1.1 Method Based on Increasing the Pressure and Temperature in the Warm Source

Increasing the pressure and temperature of the thermal agent delivered by the warm source leads directly to the increase in thermal efficiency. However, this method of increasing efficiency is subject to a series of technological restrictions, such as the mechanical resistance of the thermal circuit components (especially those of the steam generator). Increasing the initial pressure has the effect of increasing the steam humidity in the final area of the turbine. The presence of a large number of water drops in the steam released at high speed (>200 m/s) leads to a phenomenon of accentuated erosion and destruction of rotor blades in the final area of the turbine.

Increasing the initial temperature has a contrary effect on the release humidity in the steam turbine. Consequently, increasing the initial pressure must be accompanied by increasing the initial temperature.

This method of increasing efficiency is achieved through the intermediary overheating of the thermal agent, which comes from the warm source of the thermodynamic cycle. The method presupposes the interruption of the steam release in the turbine, for it to be then sent back to the steam generator. Here, it is overheated once again, up to a temperature comparable with the initial one and then it continues to be released in the steam turbine. Figure 3 presents the simplified scheme of an intermediary overheating system, where: GA—steam generator, SÎI—intermediary over-heater, CIP—high pressure body, CMJP—medium and low pressure body, GE—electric generator, K—condenser, PA—circulation pump, PR—regenerative pre-heater.

Intermediary overheating presupposes a complication of the thermal circuit and of the steam generator, with direct effects on the initial investment. Consequently, the scheme is generally justified only for high power groups (>100 MW) with a sufficiently high annual duration of installed power use.

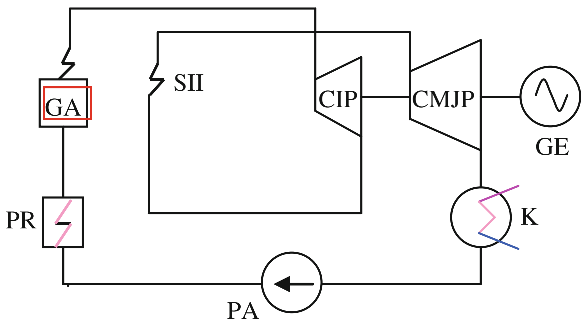


**Fig. 3** Intermediary overheating system scheme

### 1.1.2 Method Based on Decreasing the Temperature and Pressure in the Cold Source

Decreasing the condensation temperature and/or pressure represents a method of increasing efficiency, since the lower the steam temperature in the condenser, the higher the thermal efficiency is. We are positing that the effect produced by a decrease (by 1 °C) of the condensation temperature may be equivalent with the effect produced by the increase (by 10–15 °C) of the initial temperature of the thermal agent. Therefore, this method of increasing thermal efficiency is very productive. A low condensation temperature is conditioned by the existence of several cooling fluids, with an appropriate flow and thermal level.

Figure 4 presents the simplified thermal scheme corresponding to such a system, which uses a backpressure steam turbine. In such a turbine, the release pressure is much higher than in the case of condensation turbines and depends on the type of consumer, as 0,7…2,5 bar for urban consumers (heating, sanitary hot water preparation, etc.);

Steam exits the turbine at a pressure higher or at least equal to the atmospheric pressure, which depends on the needs of the thermal load. This is why the term back—pressure is used. After the exit from the turbine, the steam is fed to the load, where it releases heat and is condensed. The condensate returns to the system with a flow rate which can be lower than the steam flow rate, if steam mass is used in the process or if there are losses along the piping. Make–up water retains the mass balance.

Being a mature technology, long studied and improved, steam turbines have a large life cycle and, if properly maintained, are very reliable. However, there are aspects which limit the use of these turbines: the thermo-electric conversion efficiency, the relatively long barring process, and the weak charge performances.

The characteristics and performance indicators of CHP systems with industrial turbines and of mCHP systems with steam micro-turbines are synthetically given in Table 1.

Based on an Rankine cycle engine, the new existing technology [5] produces clean and cost-effective heating and electricity from a low temperature solar thermal system. The product provides households with 1 kW of electricity and 8.8 kW of heating from free solar energy (Fig. 5).

**Fig. 4** Backpressure steam turbines

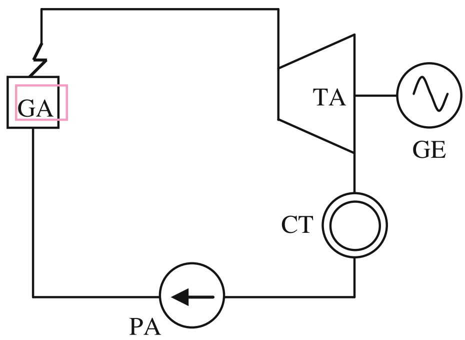

**Table 1** Turbines—indicators of performance [4]

| Features | Industrial steam turbines | Micro steam turbines |
|---|---|---|
| Electrical efficiency | 15–38 % | 18–27 % |
| Thermal efficiency | 80 % | 65–75 % |
| Global efficiency | 75 % | 50–75 % |
| Power to Heat ratio | 0.1–0.3 | 0.4–0.7 |
| Start-up time | 1 h–1 day | 60 s |
| Power range | 50 kW–250 MW | 5–250 kW |
| Using thermal energy | Low and high pressure steam | Heat, hot water, low pressure steam |
| Advantages | Report electricity /heat depending flexible operating system; | High reliability (few moving parts); easy installation; |
| | | Compact; Light weight; |
| | | Acceptable noise level |
| | Ability to adapt to the requirements of several types of heat consumers; variety of types and sizes; long life | High temperature heat recovery |
| Disadvantages | High report heat/electricity; | High costs |
| | High investment cost; | |
| | Slow start | |

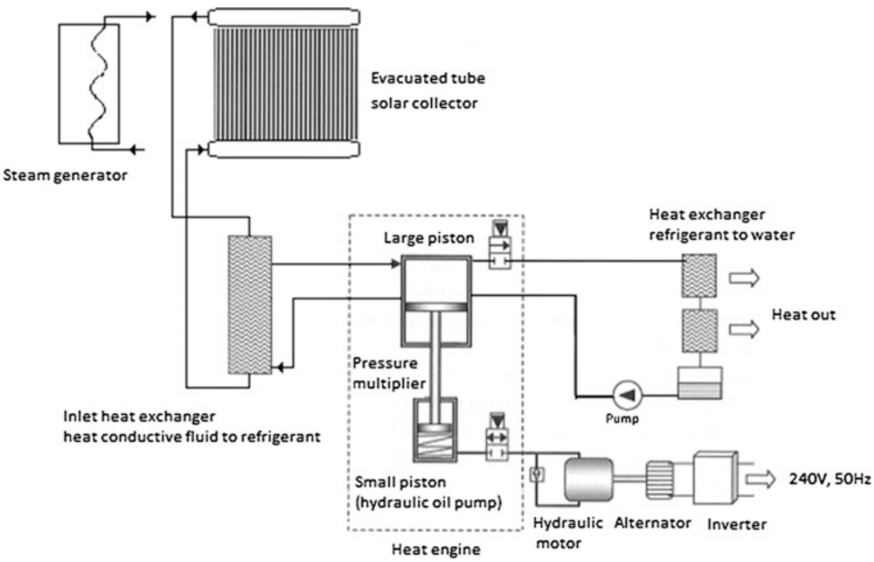


**Fig. 5** Solar thermal heating and power [5]

### 1.2 Gas Micro Turbines

Internal combustion turbines are primary engines, frequently used in cogeneration due to the high level of safety and reliability and to the wide power range.

A CHP system with a gas turbine contains a compressor, a combustion chamber and a turbine on the same axis with the compressor. On this axis, the turbine provides the useful mechanical work.

Microturbines are small gas turbines in which hot and pressurized gases (obtained from the combustion of fuel added to compressed air) are expanded through a rotating turbine, thereby acting on the motor shaft. These are used to produce electricity. The majorities of microturbines have an exit power between 25 and 300 kW and may be fuelled with natural gas, diesel, petrol or alcohol.

The process of a microturbine is similar to that of an industrial turbine, which has a recovery to recuperate part of the exhaust heat and to use it to preheat the combustion air. The scheme in Fig. 6 shows the main components of a microturbine.

Most turbines have a rotation speed of 90,000–120,000 rpm [7] Most producers use one shaft (with the compressor, the turbine and the electric generator on it), for which bearing greasing is easy. The electric generator has permanent magnets, and a group redresser-converter is needed to adapt the electric charges to the grid. The air in the compressor is preheated and, in the combustion chamber, the air combines with the fuel and the resulting combustion mix burns and expands in the turbine. The rotation of the turbine engages the compressor and generator shaft. The gases exhausted from the turbine are sent back, through the recovery, to preheat the combustion air.

Nonrecuperative turbines produce electricity from natural gas, with an efficiency of approximately 15 %. Microturbines equipped with a recovery have an electric efficiency between 20 and 30 %. The difference in electric efficiency is generated by the air preheating achieved in the recovery, which reduces the quantity of necessary fuel. The global efficiency of the system may be of 85 % and may be reached when

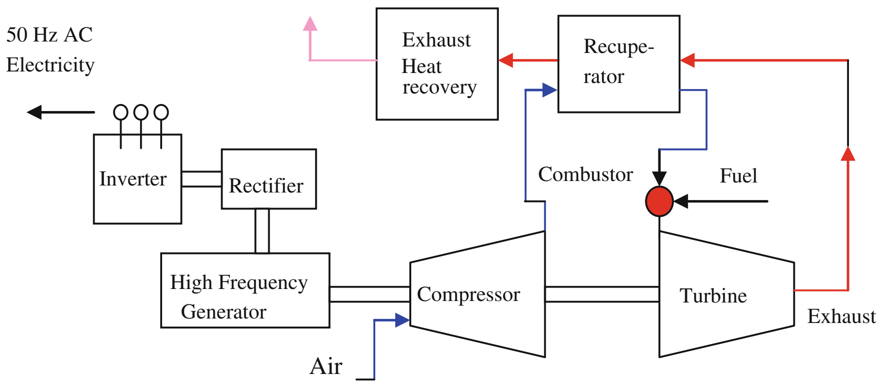


**Fig. 6** Scheme of a gas turbine [6]

the microturbines are coupled to thermal components to recuperate the heat. The heat lost in a microturbine is mainly contained in the hot exhaust gases. This heat should be used to fuel a steam generator, to heat a residence or to fuel various cooling absorption systems. The way in which the heat lost may be used depends on the configuration of the turbine. In a nonrecuperative turbine, the exhaust gas comes out at a temperature of 538–594 °C. A recuperative turbine capitalizes the heat lost by using it to heat spaces or for the thermal agent in a cooling absorption system where the exhaust temperature is around 271 °C.

The exploitation of a microturbine has several advantages. The first is that it has less moving parts than a combustion engine. The limited number of moving parts and the reasonable demands regarding the greasing make microturbines have a long life cycle. Consequently, microturbines have low exploitation costs (seen as cost per kW of power produced). The second advantage of microturbines is their relatively small size, as compared to the power produced. Microturbines are light and have a low level of noxe. The third, and maybe the most important advantage of microturbines, is their capacity to use more types of fuel, including recuperated fuel or bio fuel. The main disadvantages of microturbines are due to the fact that they have low levels of electric efficiency. Moreover, in conditions of increased altitude and environment temperature, microturbines observe a decrease in exhaust power and efficiency. Environment temperature directly affects the intake air temperature. A gas turbine will work more efficiently when colder air is available at intake. The performance characteristics of microturbines are given in Table 2.

Micro Turbine Technology (MTT) is developing recuperated micro turbines up to 30 kW electrical powers for CHP and other applications [9]. Automotive turbocharger performance and efficiency have increased significantly during recent

**Table 2** Micro-turbine cogeneration system performance characteristics [8]

| | Capstone model 330 micro-turbine | IR energy systems 70LM (two shafts) | Turbec T 100 |
|---|---|---|---|
| Nominal electricity capacity (kW) | 30 | 70 | 100 |
| Electrical heat rate (Btu/kWh) HHV | 15,075 | 13,540 | 12,639 |
| Electrical efficiency (%) HHV | 22.6 | 25.2 | 27.0 |
| Fuel input (MMBtu/h) | 0.422 | 0.948 | 1.264 |
| Required fuel gas pressure (psig) | 75 | 55 | 75 |
| Exhaust flow (Ibs/s) | 0.69 | 1.40 | 1.74 |
| GT exhaust temperature (F) | 530 | 435 | 500 |
| Heat exchanger exhaust temperature (F) | 150 | 130 | 131 |
| Heat output (MMBtu/h) | 0.17 | 0.369 | 0.555 |
| Heat output (kW equivalent) | 51 | 108 | 163 |
| Total overall efficiency (%) HHV | 73 | 64 | 71 |
| Power/heat ratio | 0.47 | 0.65 | 0.62 |
| Net heat rate (Btu/kWh) | 5509 | 6952 | 5703 |
| Effective electrical efficiency (%) HHV | 46.7 | 49 | 60 |

years, even for very small sizes. This has created an opportunity to develop low-cost micro turbines that can be produced in large volumes at low prices. Coupled with a generator electric power can be produced. By adding a recuperator, a large portion of the exhaust gas heat is recovered and electrical efficiency can be substantially increased. With low-cost configurations, 16 % electrical efficiency can be realized offering an excellent solution for a micro CHP application. With more advanced versions, levels up to 25 % can be realized opening a wide variety of additional applications. Based on the MTT, a 3 kW electrical/15 kW thermal micro CHP system is being developed to replace heating boilers for small business and households. Major focus is given to low-cost price, reliability, noise reduction, and low maintenance.

## *1.3 Thermal Engines with Internal Combustion*

Internal combustion engines based on fossil fuel are widely spread and have diverse uses. An internal combustion engine is activated by the explosion of the fuel mix which burns in direct contact with the engine. To function, internal combustion engines need fuel, air and a mechanism which can achieve the compression of the air-fuel mix.

The basic elements of a reciprocating internal combustion engine based on a cogeneration system are the engine, generator, heat recovery system, exhaust system, and controls and acoustic enclosure. The generator is driven by the engine, and the useful heat is recovered from the engine exhaust and cooling systems. The main scheme of a CHP device with thermal combustion engines is shown in Fig. 7.

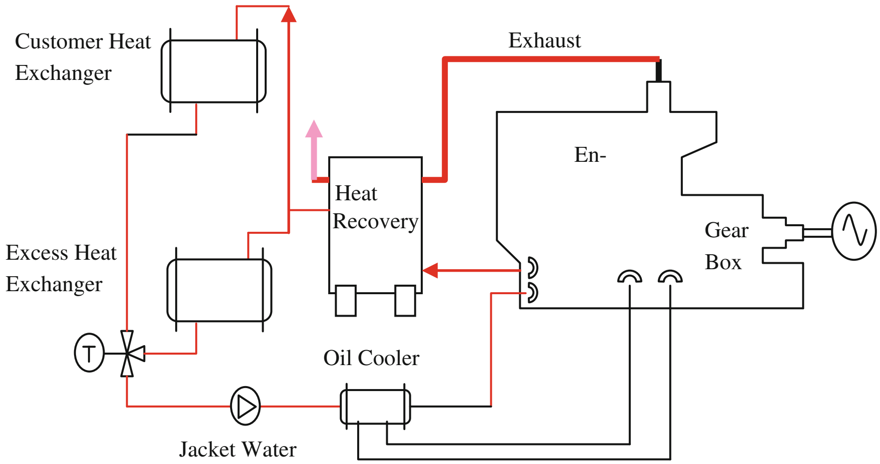


**Fig. 7** CHP system with internal combustion engines

Two types of internal combustion engines are used to generate energy:

- spark ignition engines (with plugs, Otto);
- internal combustion engines ignited by compression, where the mix is brought to a high pressure before entrance into cylinders (Diesel).

Piston engines are available, from those coupled to small generators (0.5 kW) to those coupled to large generators (3 MW). These use common fuels like petrol, natural gas, diesel, and are convenient in a multitude of applications, due to their small sizes and their low costs. In energy production, the functioning of piston engines includes both continuous functioning and functioning at peak charges, as spare source. Piston engines are ideal for applications where there is a substantial need for hot water or for low pressure steam.

In the case of a CHP system used for producing electricity on a wide scale, efficiency is around 30 % while, during a combined exploitation cycle, efficiency is of approximately 48 %. The heat in the burning gases is lost, together with their exhaust into the atmosphere. Unlike this case, with a mCHP system based on internal combustion thermal engines, the heat from the cooling water, from the machine oil and from the exhaust circuit of burning gases is recuperated. From the recuperated heat, low pressure steam or hot water may be obtained, which may then be used for heating, obtaining domestic hot water and refrigerating.

The heat from the cooling circuit is able to produce hot water at 90 °C and represents approximately 30 % of the fuel input energy. Engines which work at high pressure are equipped with a cooling system for very high temperatures and can work to up to a temperature of 455–649 °C. Since the temperature of the exhaust gases must be kept above the condensation limit, only part of the heat contained by these gases can be recuperated. Heat recuperation units are generally designed for a temperature of 150–175 °C, to avoid corrosion and condensation in the exhaust pipes. Low pressure steam and hot water 110 °C is produced using the machine's heat exhaust. The heat recuperated from the cooling fluid and from the gases resulted from the burning process may reach approximately 70–80 %.

The performance characteristics of internal combustion engines are given in Table 3.

**Table 3** The performance characteristics of the CHP systems with internal combustion engines as prime mover [10]

| Power range ($kW_e$) | 10 | 100 | 3,000 |
|---|---|---|---|
| Power to heat ratio | 0.50 | 0.79 | 0.97 |
| Electrical efficiency (%) | 25–28 | 34 | 36 |
| Total efficiency (%) | 79 | 78 | 73 |
| Fuel Input (MMBtu/hr) | 0,5 | 4,9 | 28 |
| Engine Speed (rpm) | 1,500 | 1,500 | 750 |
| Fuel type | A variety of gaseous and fluid fuels | | |

## *1.4 Stirling Engines*

Stirling engine is the most promising technology on the short medium term. It can be installed in urban environment every type of fuel can be utilized (methane, hydrocarbons, hydrogen, biomass, or heat from renewable sources). The Stirling technology is mainly mechanical, is well established, does not require special infrastructure.

A Stirling engine is an internal combustion engine which uses a difference in temperature to create movement in the shaft. The functioning of a Stirling engine is based on the behavior of a fixed quantity of air or gas (like helium or hydrogen) inside the engine cylinders. Two properties of gases lie at the basis of a Stirling engine functioning.

- in the case of a constant quantity of gas, with a fixed volume, the more the temperature increases, the more the pressure increases also;
- when a fixed quantity of gas is compressed, the temperature of that gas will increase.

The applications for the Stirling engine (an example being given in Fig. 8) include units of energy generation for space ships, small planes, refrigeration, mCHP systems and, on a smaller scale, residential or portable energy generators.

Main characteristics of the CHP systems with Stirling engine is given in Table 4.

Stirling engines have an electric efficiency of 10–25 %. If, however, the heat lost is recuperated in CHP type systems, the overall efficiency of these systems may increase significantly. Typical normal temperatures for operating vary between 650 and 800 °C. The heat may be recuperated by using the heat exchanger in the cold source of the engine, as well as by using the heat exchanger through which the burnt gases are exhausted into the atmosphere.

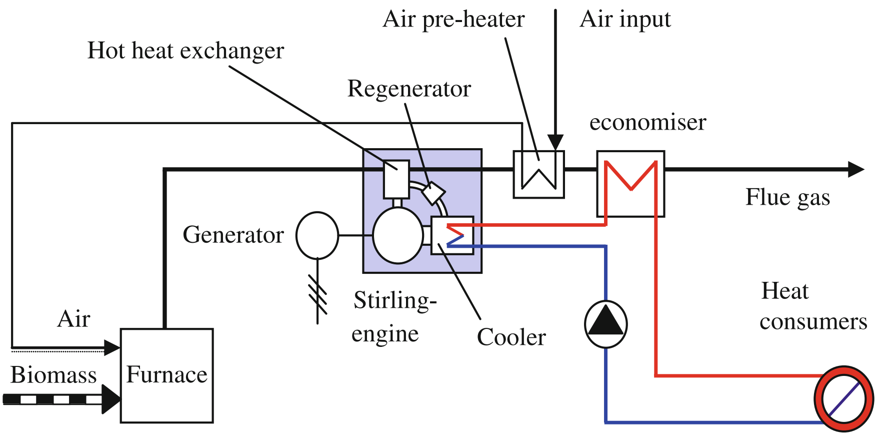


**Fig. 8** Scheme of a biomass CHP system based on a Stirling engine [11]

**Table 4** Main characteristics of the CHP systems with Stirling engine

| | |
|---|---|
| Power range ($kW_e$) | 0.003–100 |
| Power to heat ratio | 0.33 |
| Electrical efficiency (%) | 10–25 |
| Thermal efficiency (%) | 40–80 |
| Total efficiency (%) | 70–90 |
| Fuel type | All fuels |

## *1.5 Fuel Cell*

Fuel cells use an electrochemical process that release the energy stored in natural gas or hydrogen fuel to create electricity. Heat is a by-product. Fuel cells that include a fuel reformer use hydrogen from any hydrocarbon fuel. Fuel cells transform the electrochemical energy into electricity and heat, through combining hydrogen with oxygen in the presence of a catalyst (Fig. 9).

Through a catalytic reaction, the hydrogen at the anode produces ions and electrons. Ions may pass through the electrolyte and reach the cathode through the external electric circuit. The reaction at the cathode leads to heat and water generation.

Besides hydrogen, other gases (like pit gas) may be used, especially for high power cells. The scheme for this case is shown in Fig. 10. The fuel–oxygen mix may be achieved outside or inside the cell, depending on the work temperature of the fuel cell.

Fuel cells are similar to electric batteries and have the capacity to produce continuous current through an electro-chemical process. While an electric battery produces energy during a time span which is limited by the stored chemical energy, fuel cells may operate indefinitely.

Five main types of cells are known today, being classified according to the type of the electrode used:

- alkaline (AFC)
- with phosphoric acid (PAFC)
- with melted carbonate (MCFC)
- with solid oxide (SOFC)
- with a proton exchange membrane fuel cell (PEMFC).

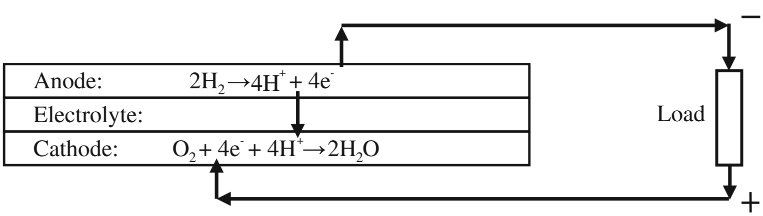


**Fig. 9** Electro-chemical conversion in a fuel cell [12]

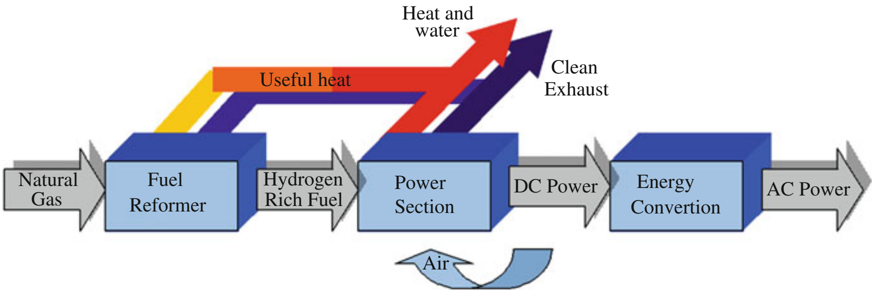


**Fig. 10** Conversion system with a fuel cell [13]

Fuel cells offer the advantage of nearly 1-to-1 power—to-heat ratio, suited for modern low-energy buildings. Fuel cells provide a higher proportion of electricity than other CHP technologies. The fuel cell systems most widely commercially deployed are PAFC and PEMFC, with 5,000 PEMFC fuel cells having been installed in Japan [14] in 2009 alone. Most operational experience is therefore limited to these fuel cells, although there are increasing numbers of SOFC and MCFC systems installed. Combined heat and power systems of building scale is 1–10 kWe. Traditional CHP systems are mature and a useful transitional technology, while micro-CHP, biomass CHP and even fuel cell systems (using $CO_2$-free hydrogen) may emerge as abatement option. The advantages of fuel cell CHP over traditional mechanical CHP are the greater degree of modulation and the heat-to power ratio is typically much lower. In general, fuel cells have high electric efficiency, under variable charge, and reduced emissions. However, energy generation seems to represent another promising market that fuel cells could conquer. Actually, with the exception of PAFC cells, fuel cells are not completely viable for sale yet. World wide, there is a total capacity of over 40 MW, PAFC fuel cells. A detailed comparison of the characteristics of these fuel cells is given in Table 5.

**Table 5** Performance characteristics for representative commercially available and developmental natural gas fuel cell based cogeneration systems [15]

| *Fuel cell type* | PEM | PEM | PAFC | SOFC | MCFC |
|---|---|---|---|---|---|
| Nominal electricity capacity (kW) | 10 | 200 | 200 | 100 | 250 |
| Electrical efficiency (%) HHV | 30 | 35 | 36 | 45 | 43 |
| Fuel input (MMBtu/hr) | 0.1 | 2.1 | 1.9 | 1.0 | 2.4 |
| Operating temperature [°C] | 70 | 70 | 200 | 950 | 650 |
| *Cogeneration characteristics* | | | | | |
| Heat output (MMBtu /hr) | 0,42 | 0,76 | 0,85 | 0,34 | 1,9 |
| Heat output (kW equivalent) | 11,7 | 211 | 217 | 100 | 556 |
| Total overall efficiency (%) HHV | 65 | 72 | 81 | 77 | 65 |
| Power/heat ratio | 0.85 | 0.95 | 0.81 | 1.25 | 1.95 |
| Effective electrical efficiency (%) | 55 | 65.0 | 81 | 65.6 | 56.5 |

## 2 Comparative Analysis of Cogeneration Technologies in mCHP Systems

A variety of types of cogeneration systems are available, or under research and development, for single- and multifamily residential buildings and small scale commercial applications. These technologies could replace or supplement the conventional boiler in a dwelling and provide both electricity and heating to the dwelling, possibly with the surplus electricity exported to the local grid and surplus heat stored in a thermal storage device.

A review of existing residential cogeneration systems performance assessments and evaluation can be found in [16] and the main advantages and disadvantages of each of the prime mover options for cogeneration can be found in [17]. A summary of typical cost and performance characteristics by CHP technology type [18] is presented in Table 6. Data represent illustrative values for typically available systems.

**Table 6** Typical cost and performance characteristics by CHP technology type [18]

| Technology | Steam turbine | Diesel engine | Nat. gas engine | Gas turbine | Microturbine | Fuel cell |
|---|---|---|---|---|---|---|
| Power efficiency (HHV) | 15–38 % | 27–45 % | 22–40 % | 22–36 % | 18–27 % | 30–63 % |
| Overall efficiency | 80 % | 70–80 % | 70–80 % | 70–75 % | 65–75 % | 65–80 % |
| Typical capacity ($MW_e$) | 0.2–800 | 0.03–5 | 0.03–5 | 1–500 | 0.03–0.35 | 0.01–2 |
| Typical power to heat ratio | 0.1–0.3 | 0.5–1 | 0.5–1 | 0.5–2 | 0.4–0.7 | 1–2 |
| CHP Installed costs ($\$/kW_e$) | 300–900 | 900–1,500 | 900–1,500 | 800–1,800 | 1,300–2,500 | 2,700–5,300 |
| Availability | near 100 % | 90–95 % | 92–97 % | 90–98 % | 90–98 % | >95 % |
| Hours to overhauls | >50,000 | 25,000–30,000 | 24,000–60,000 | 30,000–50,000 | 5,000–40,000 | 10,000–40,000 |
| Start-up time | 1 h–1 day | 10 s | 10 s | 10 min–1 h | 60 s | 3 h–2 day |
| Fuels | all | Diesel, residual oil | Gas, biogas, propane, landfill gas | Natural gas, biogas, propane, oil | Natural gas, biogas, propane, oil | Hydrogen, natural gas, propane, methanol |
| Uses for thermal output | LP-HP steam | Hot water, LP steam | Hot water, LP steam | Hot water, LP–HP steam | Heat, hot water, LP steam | Hot water, LP–HP steam |

From among the CHP technologies presented, the most appropriate for residential use are the technologies presented in Table 7. The electric efficiency of reciprocating internal combustion engines is higher compared to micro-turbines and Stirling engines. On the other hand, fuel cells promise to offer the highest electric efficiency for residential and small-scale cogeneration applications in comparison with the other technologies, but are challenged by lack of demonstrated performance.

To better understand the potential benefits of different micro-CHP technologies, a comparative study [19, 20] involved a major field trial of micro-CHP units in domestic applications, with a corresponding trial of A-rated condensing boilers to provide a baseline for comparison.

As expected, the measured thermal efficiencies for the micro-CHP units are around 10–15 % lower than for the condensing boilers. This is primarily a consequence of some of the heat generated by the engine being used to generate electricity.

**Table 7** Technical features of small-scale CHP Devices [8, 10, 15, 19]

| | Reciprocating engines | Microturbines | Stirling engines | PEM fuel cells |
|---|---|---|---|---|
| Electric power (kW) | 10–200 | 25–250 | 2–50 | 2–200 |
| Electric efficiency, full load (%) | 24–45 | 25–30 | 15–25 | 40 |
| Electric efficiency, half load (%) | 23–40 | 20–25 | 25 | 40 |
| Total efficiency (%) | 75–85 | 75–85 | 75–85 | 75–85 |
| Heat/ electrical power ratio | 0.9–2 | 1.6–2 | 3–3.3 | 0.9–1.1 |
| Output temperature level (°C) | 85–100 | 85–100 | 60–80 | 60–80 |
| Fuel | Natural or biogas, diesel fuel oil | Natural or biogas, diesel, gasoline, alcohols | Natural or biogas, LPG, several liquid or solid fuels | Hydrogen, gases, including hydrogen, methanol |
| Interval between maintenance (h) | 5,000–20,000 | 20,000–30,000 | 5,000 | N/A |
| Investment cost ($/kW) | 800–1,500 | 900–1,500 | 1,300–2,000 | 2,500–3,500 |
| Maintenance costs ($/kW) | 1.2–2.0 | 0.5–1.5 | 1.5–2.5 | 1.0–3.0 |

The net carbon benefit of the electricity generated by the domestic micro-CHP systems is significantly higher than for the condensing boilers at 88 %. Conclusion on market potential [20] is micro-CHP can be competitive with condensing boiler if their investment costs and maintenance are comparable.

An important characteristic of mCHP cogeneration systems is the ratio between the electrical energy and the thermal energy of the primary engine. Between these powers depends on the primary thermal engine and is called cogeneration index:

$$\gamma = \frac{E}{Q} \tag{3}$$

where

- E—is the amount of electricity from cogeneration, γ is the power to heat ratio, and
- Q—is the amount of useful heat from cogeneration (calculated for this purpose as total heat production minus any heat produced in separate boilers or, in case of turbines, by live steam extraction from the steam generator before the turbine).

The power to heat ratio is of special importance, since the calculation of electricity from cogeneration is based on the actual power to heat ratio.

An over-unitary value of the cogeneration index shows the predominance of the electricity produced by the mCHP system as compared to the thermal one. The majority of cogeneration technologies have a subunitary cogeneration index.

The dependence of the mCHP system electric and thermal power on this index may be determined by imposing that the cogeneration index should vary between 0.1 and 4, and assuming that the sum of electric power and thermal power is the power unit.

$$E + Q = 1 \tag{4}$$

Measured with this unit, electric power may be calculated in keeping with this ratio, with the relation:

$$E = \frac{\gamma}{\gamma + 1} \tag{5}$$

and the thermal power with the relation:

$$Q = \frac{1}{\gamma + 1} \tag{6}$$

The cogeneration index has a great influence on the mCHP performance indices (PES and overall efficiency). If we assume that the cogeneration system has a fuel saving of 5 % then, to produce the same output power and admitting an electric efficiency of 40 % and a thermal one of 80 %, the input energy has the following dependency on the cogeneration index:

- in the case of separate production:

$$Q_{\mathrm{SHP}} = \frac{E}{\eta_e} + \frac{Q}{\eta_{th}} = \left(\frac{10}{4}\frac{\gamma}{\gamma+1} + \frac{10}{8}\frac{1}{\gamma+1}\right) \tag{7}$$

- in the case of cogeneration using relation:

$$\mathrm{PES} = 1 - \frac{Q_{\mathrm{CHP}}}{Q_{\mathrm{SHP}}} \tag{8}$$

Resulting is the following dependency:

$$Q_{\mathrm{CHP}} = 0,95 \cdot Q_{\mathrm{SHP}} = 0,95\left(\frac{10}{4}\frac{\gamma}{\gamma+1} + \frac{10}{8}\frac{1}{\gamma+1}\right) \tag{9}$$

Figure 11 presents the dependence of powers on the cogeneration index. What may be noticed is that, practically, for high indices, the cogeneration system produces only electric energy, and for very low indices, it produces only thermal energy.

The efficiency of the separate energy production may be compared to the efficiency of the combined system only on the basis of the cogeneration index value.

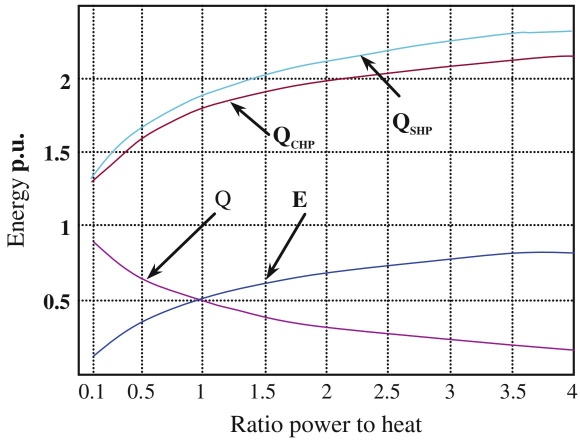


**Fig. 11** Power dependence of the cogeneration index

Thus, the dependency of the overall efficiency of separate energy production on the cogeneration index may be mathematically expressed with the relation:

$$EFF_{\mathrm{SHP}} = \frac{1+\gamma}{\frac{\gamma}{\eta_e} + \frac{1}{\eta_{th}}} \tag{10}$$

The overall cogeneration efficiency, defined by the relation:

$$EFF_{\mathrm{CHP}} = \frac{E+Q}{Q_{\mathrm{CHP}}} = \frac{E+Q}{Q_{\mathrm{SHP}}}\frac{Q_{\mathrm{SHP}}}{Q_{\mathrm{CHP}}} = \eta_{\mathrm{SHP}}\frac{Q_{\mathrm{SHP}}}{Q_{\mathrm{CHP}}} \tag{11}$$

leads to the following dependency on the cogeneration index:

$$EFF_{\mathrm{CCHP}} = \frac{1}{0,95}\frac{1+\gamma}{\frac{\gamma}{\eta_e} + \frac{1}{\eta_{th}}} \tag{12}$$

Figure 12 represents the dependency of efficiency on the power ratio.

According to the Directive 2012/27/EC, the promotion of high-efficiency cogeneration based on a useful heat demand is a Community priority given the potential benefits of cogeneration with regard to saving primary energy, avoiding network losses and reducing emissions, in particular of greenhouse gases. In addition, efficient use of energy by cogeneration can also contribute positively to the security of energy supply and to the competitiveness of the European Union.

Directive 2012/27/EC on the promotion of cogeneration based on a useful heat demand in the internal energy market shows that the power to heat ratio is a technical characteristic that needs to be defined in order to calculate the amount of electricity from cogeneration. Electricity from cogeneration shall mean electricity generated in a process linked to the production of useful heat and is calculated according to the following formula: $E = \gamma \cdot Q$

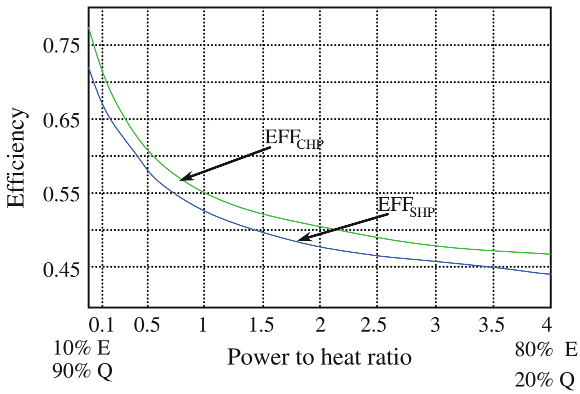


**Fig. 12** Efficiency dependency of the power to heat ratio

**Table 8** The default values of the power to heat ratio [21]

| Type of the unit | Default power to heat ratio $\gamma$ |
|---|---|
| Combined cycle gas turbine with heat recovery | 0.95 |
| Steam backpressure turbine | 0.45 |
| Steam condensing extraction turbine | 0.45 |
| Gas turbine with heat recovery | 0.55 |
| Internal combustion engine | 0.75 |

If the actual power to heat ratio of a cogeneration unit is not known, the default values given in Table 8, may be used.

Cogeneration applications in buildings can be designed to:

- satisfy both the electrical and thermal demands,
- satisfy the thermal demand and part of the electrical demand,
- or satisfy the electrical demand and part of the thermal demand
- or, most commonly, satisfy part of the electrical demand and part of the thermal demand.

In addition, cogeneration in buildings can be designed for peak shaving applications, i.e., the cogeneration plant is used to reduce either the peak electrical demand or thermal demand.

In the case of single-family applications, the design of systems poses a significant technical challenge due to the potential noncoincidence of thermal and electrical loads, necessitating the need for electrical/thermal storage or connection in parallel to the electrical grid.

# 3 The mCCHP Systems

## *3.1 Architecture of the mCCHP Systems*

Trigeneration applications in buildings have to satisfy either both the electrical and the thermal demands, or to satisfy the thermal demand and part of the electrical demand, or to satisfy the electrical demand and part of the thermal demand. Architecture of the mCCHP systems depends on the magnitude of the electrical and thermal loads, whether they match or not, and on the operating strategy.

The trigeneration system can run at part-load conditions, the surplus energy (electricity or heat) may have to be stored or sold, and deficiencies may have to be made up by purchasing electricity from other sources such as the electrical grid [6]. The surplus heat produced may be stored in a thermal storage device, such as a water tank, or in phase change materials, while surplus electricity may be stored in electrical storage devices such as batteries or capacitors.

All these must ensure the necessary heat for the residence. It results that, to achieve a conceptual scheme of a mCCHP system, the energy demand of the residential consumer must be known in advance. Depending on this demand (load curves), the optimal architecture of the mCCHP system may be determined. In establishing the architecture of the mCCHP system, the satisfaction of the residence energy demand and of the system's being connected or not to the electricity grid, must be had in view.

The general architecture of a micro-CCHP system based on renewable energy (Fig. 13) might include the following sources:

- a mCHP cogeneration unit
- auxiliary heating unit/units of the solar collector type and back-up heater
- photovoltaic panels
- thermal and/or electric energy storage unit
- an air-conditioning system thermally/mechanically activated.

In the architecture structure diagram, two subsystems may be identified:

- *Electrical energy supplying subsystem*. The mathematical model of the electrical subsystem is the one that describes the dynamic storage in the battery. It can be written as follows:

$$\frac{dW_B}{dt} = P_{CHP}(t) + P_{PV}(t) - P_{al}(t) - P_{air}(t) \quad (13)$$

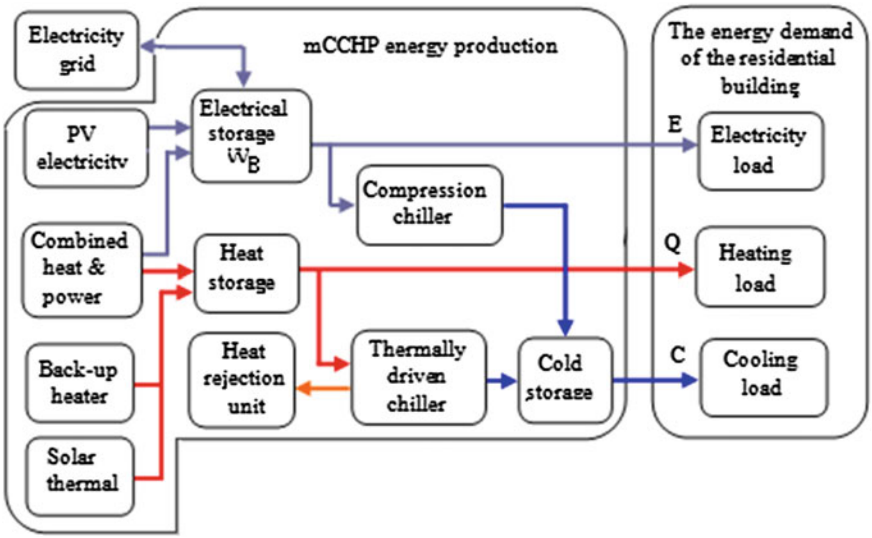


**Fig. 13** General architecture of the mCCHP systems

where $W_B$ is the energy accumulated in the battery [J]; $P_{CHP}$ and $P_{PV}$, are the powers produced by the CHP and photovoltaic source, respectively [W]; $P_{al}$ is the powers corresponding to the useful load and internal intake of the entire system, respectively [W] (the pump engines etc.), and $P_{air}$ is the power consumed by the air-conditioning [W].

- *Thermal energy supplying subsystem*. The mathematical model of the thermal subsystem has as core the thermal balances at the level of the thermal accumulator and of the building. The thermal balance equation for the thermal accumulator is the following:

$$m_w c_w \frac{d\vartheta}{dt} = P_{CHP,t}(t) + P_{PT}(t) + P_{ph}(t) - P_{hl}(t) - P_{acl}(t) - P_{dhw}(t) \quad (14)$$

where: $m_w$, $c_w$ represent the mass and the specific heat of the water accumulated in the heat storage, $\vartheta$—the water temperature in the heat storage,

$P_{CHP,tt}$—the CHP thermal power, $P_{PT}$—the thermal solar collectors power, $P_{ph}$—the power provided by the back-up boiler, $P_{hl}$—the power consumed in the building to cover losses through transmission and ventilation, $P_{acl}$—the power consumed by the air conditioning, $P_{dhw}$—the power consumed by the domestic hot water circuit.

In steady state (equilibrium electric and thermal) by integration of the system of Eqs. (13) and (14) conduct to energy balance equation.

### 3.1.1 The mCCHP System with a Mechanical Compression Chiller

The electricity demand of the residence is composed of the electricity intake of the residence appliances, to which the electricity necessary to produce cold is added. This demand must be satisfied by the mCHP system, according to Fig. 14 and the relation (15):

$$E_{CCHP} = E + \frac{C}{COP_c} - E_{grid} \quad (15)$$

The thermal energy demand of the residence is composed of the energy necessary for heating the residence and preparing domestic hot water, and must be supplied by the CCHP system according to the relation:

$$Q_{CCHP} = Q + Q_{hw} \quad (16)$$

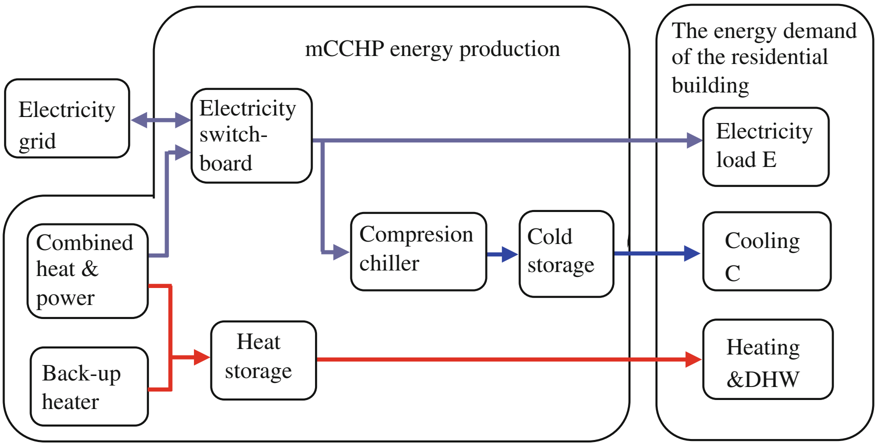


**Fig. 14** The mCCHP system with a mechanical compression chiller

### 3.1.2 The mCCHP System with a Thermal Compression Chiller

The thermal energy demand of the residence (Fig. 15) is composed of the energy intake necessary for heating (heating the residence and preparing domestic hot water), to which the thermal energy necessary to produce cold is added, and must be satisfied by the CCHP system according to the relation:

$$Q_{\text{CCHP}} = Q + Q_{\text{hw}} + \frac{C}{COP_a} \tag{17}$$

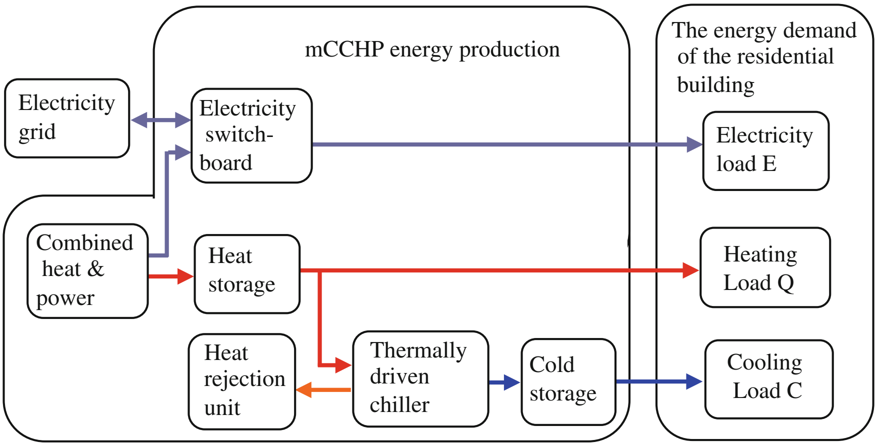


**Fig. 15** The mCCHP system with a thermal compression chiller

The electricity demand of the residence is composed of the electricity intake of the residence appliances. The electricity production of the CCHP system is the difference between the electricity demand of the residence and the energy received from the grid:

$$E_{\mathrm{CCHP}} = E - E_{\mathrm{grid}} \tag{18}$$

## 3.2 Operation Modes of the mCHP Unit

In satisfying these demands, the mCHP unit may have various modes of operation. The mode of operation is characterized by the criterion on which the adjustment of the electrical and useful thermal output of a trigeneration system is based. The following operation modes can be applied:

(a) *Heat-match mode*, where the total thermal energy for the residence is ensured by the cogeneration unit (Fig. 16). As a consequence, the useful thermal output of a cogeneration system at any instant of time is equal to the thermal load (without exceeding the capacity of the cogeneration system), that is:

$$Q_{\mathrm{CHP}} = Q_{\mathrm{CCHP}} \tag{19}$$

If the generated electricity is higher than the load, excess electricity is sold to the grid; if it is lower, supplementary electricity is purchased from the grid.

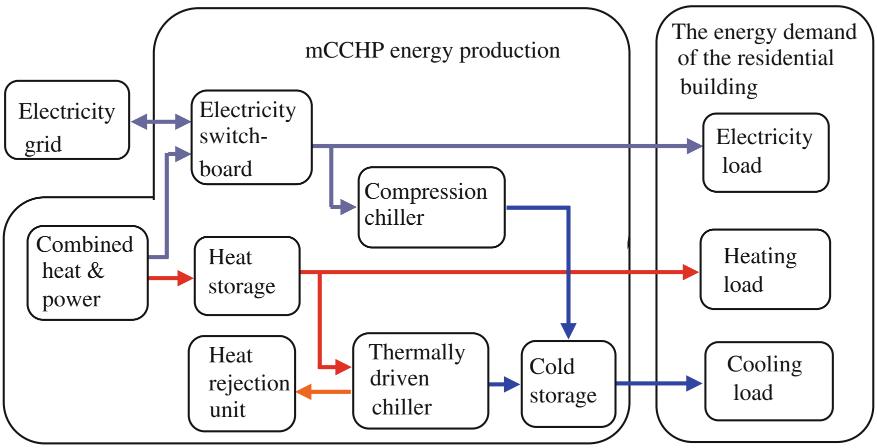


**Fig. 16** Heat-match mode

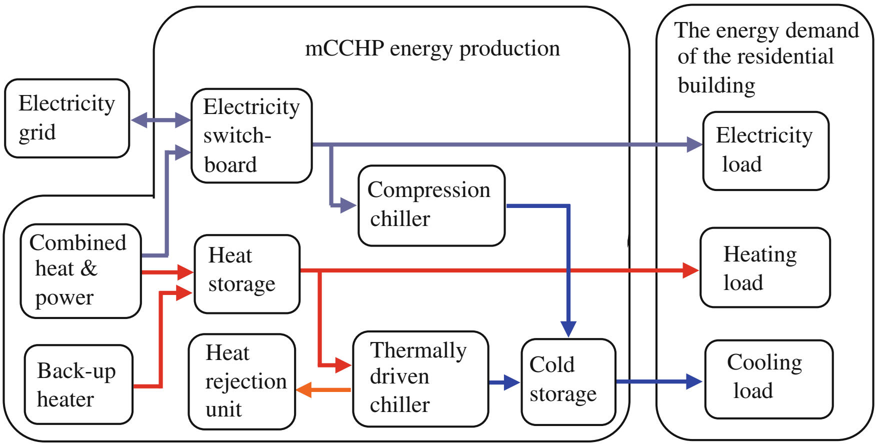


**Fig. 17** Base thermal load matching mode

(b) *Base thermal load matching mode*, (Fig. 17) where the total thermal energy of the residence is provided by the cogeneration unit and by a supplementary boiler which ensures the peak thermal charges, according to the relation:

$$Q_{\mathrm{CHP}} = Q_{\mathrm{CCHP}} - Q_{\mathrm{ad}} \tag{20}$$

Here, the cogeneration system is sized to supply the minimum thermal energy requirement of the site. Stand-by boilers or burners ($Q_{\mathrm{ad}}$) are operated during periods when the demand for heat is higher. The prime mover installed operates at full load at all times. If the electricity demand of the site exceeds that which can be provided by the prime mover, then the remaining amount can be purchased from the grid. Likewise, if local laws permit, the excess electricity can be sold to the power utility.

(c) *Electricity-match mode*, where the total electricity of the residence is supplied by the cogeneration unit (Fig. 18), according to the relation:

$$E_{\mathrm{CHP}} = E_{\mathrm{CCHP}} \tag{21}$$

The generated electricity at any instant of time is equal to the electrical load (without exceeding the capacity of the cogeneration system). If the cogenerated heat is lower than the thermal load, an auxiliary boiler supplements for the needs; if it is higher, excess heat is released into the environment through coolers or the exhaust gases.

$$Q_{\mathrm{CHP}} = Q_{\mathrm{CCHP}} - Q_{\mathrm{ad}} \tag{22}$$

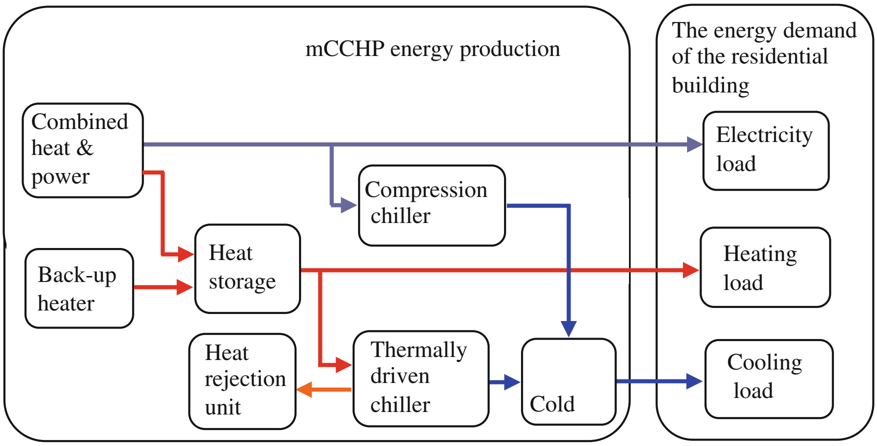


**Fig. 18** Electricity-match mode

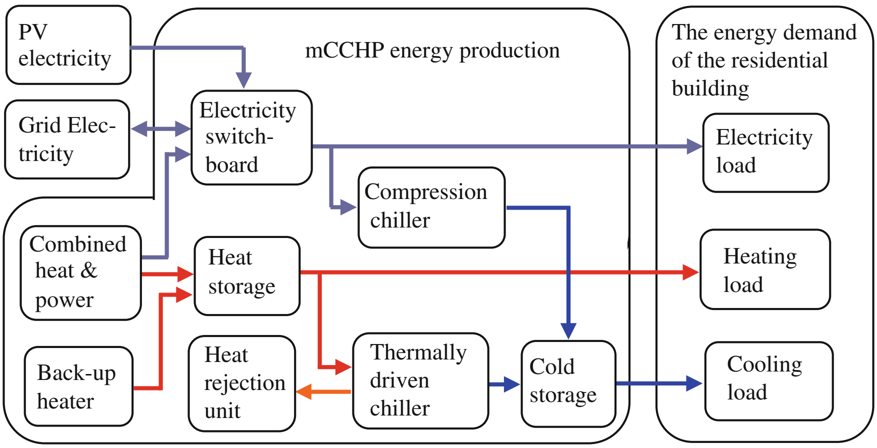


**Fig. 19** Base electrical load matching mode

(d) *Base electrical load matching mode*, where the total electricity of the residence is provided by the cogeneration unit and a supplementary system of producing electric energy, and/or from the grid, which ensures the peak loads (Fig. 19), according to the relation:

$$E_{CHP} = E_{CCHP} - E_{ad} - E_{grid} \tag{23}$$

In this configuration, the CHP plant is sized to meet the minimum electricity demand of the site, based on the historical demand curve. The rest of the power needed is purchased from the utility grid. The thermal energy requirement of the site may be met by the cogeneration system alone or by additional boiler.

$$Q_{\mathrm{CHP}} = Q_{\mathrm{CCHP}} - Q_{\mathrm{ad}} \tag{24}$$

(e) *Mixed-match mode*, In certain periods of time, the heat-match mode is followed, while in other periods, the electricity-match mode is followed. The decision is based on considerations such as the load levels, the fuel price and the electricity tariff at the particular day and time.

(f) *Stand-alone mode*, (Fig. 20). There is complete coverage of the electrical and thermal loads at any instant of time, with no connection to the grid. This mode requires the system to have reserve electrical and thermal capacity, so that in case a unit is out of service for any reason, the remaining units are capable of covering the electrical and thermal load. This is the most expensive strategy, at least from the point of view of the initial cost of the system.

The energetic balance equations are:

$$E_{\mathrm{CHP}} = E_{\mathrm{CCHP}} - E_{\mathrm{ad}} = E + \frac{C'}{COP_c} - E_{\mathrm{ad}} \tag{25}$$

$$Q_{\mathrm{CHP}} = Q_{\mathrm{CCHP}} - Q_{\mathrm{ad}} = Q + Q_{\mathrm{hw}} + \frac{C - C'}{COP_a} - Q_{\mathrm{ad}} \tag{26}$$

where $C$’ is cold produced by compression chiller, $C$ is cooling load.

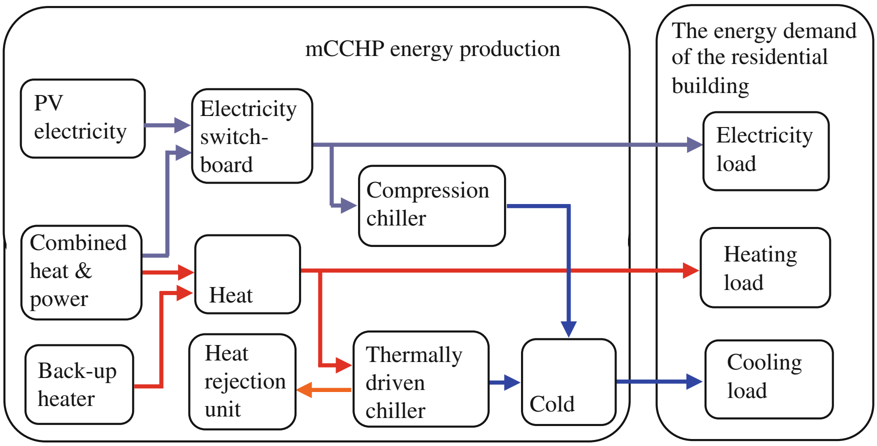


**Fig. 20** Stand-alone mode

In general, the heat-match mode results in the highest fuel utilization rate (fuel energy savings ratio—PES) and perhaps in the best economic performance for trigeneration in the industrial and building sectors.

In the utility sector, the mode of operation depends on the total network load, the availability of power plants and the commitments of the utility with its customers, regarding supply of electricity and heat. However, applying general rules is not the most prudent approach in trigeneration.

Every application has its own distinct characteristics. There is a variety of trigeneration systems (according to the type of the technology, size, and configuration). The design of a trigeneration system can be tailored to the needs of the user. The design of a trigeneration system affects the possible modes of operation, and vice versa. Moreover, the technical and economic parameters may change with the day and time during the operation of the system. For example (Fig. 21), the mCCHP system type off-grid, for satisfy energy need the control can be divided between mCHP unit and boiler. The mCHP is back-up for electricity balance and the boiler is back-up for thermal energy balance. The equilibrium between the power provided by the sources and the power consumed (power consumed for building and the powers corresponding to the useful load and internal intake,

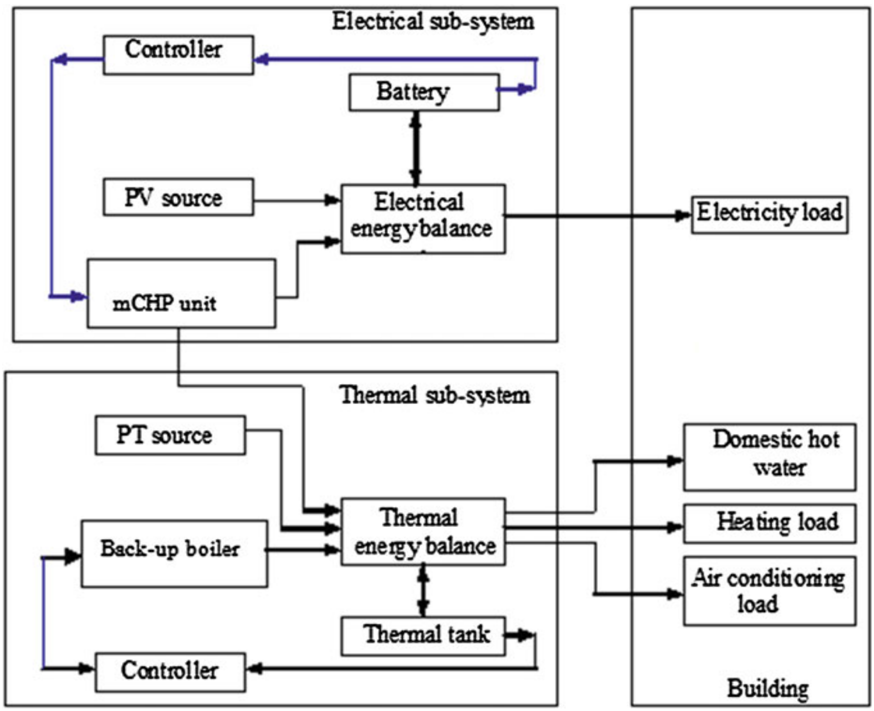


**Fig. 21** Control of the thermal and electrical sub-systems

inclusive for air conditioning) is achieved through the voltage battery control and storage tank temperature, respectively.

All these aspects make it necessary to reach decisions not by rules of thump only, but by systematic optimization procedures, based on mathematical programming, for both the design and the operation of the system. For the operation of cogeneration systems, in particular, microprocessor-based control systems are available.

They may provide the capability to operate in a base load mode, to track either electrical or thermal loads, or to operate in an economic dispatch mode (mixed-match mode).

In the latter mode, the microprocessor can be used to monitor trigeneration system performance, including:

- the system efficiency and the amount of useful heat available;
- the electrical and thermal requirements of the user, the amount of excess electricity which has to be exported to the grid, and the amount of heat that must be released into the environment;
- the cost of purchased electricity and the value of electricity sales, as they may vary with the time of the day, the day of the week, or season.

Using the aforementioned data, the microprocessor can determine which operating mode is the most economical, even whether the unit should be shut down. Moreover, by monitoring operational parameters such as efficiency, operating hours, exhaust gas temperature, coolant water temperatures, etc., the microprocessor can help in maintenance scheduling. If the system is unattended, a telephone line can link the microprocessor with a remote monitoring centre, where the computer analysis of the data may notify the skilled staff about an impending need for scheduled or unscheduled maintenance. Furthermore, as part of a data acquisition system, the microprocessor can produce reports of system technical and economic performance.

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