Decentralized Poly-generation of Energy: Basic Concepts

Nicolae Badea

Abstract This chapter presents the basic concepts for primary energy forms, energy conversion, delivered energy, and energy needed by consumers to satisfy their needs (useful energy). The conversion of primary energy into useful energy is evaluated on the basis of the energy efficiency factor for separate energy generation, cogeneration, and trigeneration. The difference between the primary energy in the case of separate production and the primary energy in the case of combined production represents the primary energy corresponding to the saved fuel. The energy saving measure is achieved through the *primary energy savings (PES) or percent fuel savings.* Finally, a trigeneration energy conversion is exemplified and the performance indicators of the system are given.

1 Energy

Matter is characterized through two fundamental measures: mass and energy. Mass is the measure of inertia and gravity, and energy is the scalar measure of matter movement. The energy modification of a physical system is known as mechanical work. Mechanical work appears when the state of physical system is modified as result of a transformation, and the latter implies the modification of the system's energy.

Polygeneration describes an integrated process which has three or more outputs that include energy outputs, produced from one or more natural resources.

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1.1 Forms of Energy

There are several forms of energy, the most frequent of which being:

- chemical;
- thermal;
- electrical;
- electromagnetic;
- nuclear.

Chemical energy is stored in the atomic links which form the molecules. When different chemical compounds react among themselves, these links are broken or modified, frequently generating or absorbing energy under the form of heat. At the micro level, the energy of fossil sources of energy (coal, petroleum, natural gases, wood etc.) may be considered as *potential energy* of atomic links which change in the burning of fuel, thus generating energy. When wood burns, the carbon contained by the wooden mass reacts with the oxygen in the air. Through burning, a new chemical product is obtained (the atomic links are modified)—carbon dioxide, CO_2—and energy, under the form of heat and light (radiation), is released simultaneously. Another example may be considered, the cell of an electric accumulator or the combustion cell, where various chemical products react among themselves, producing electric energy and other chemical products.

Thermal energy is the sum of the kinetic and potential energies of all the atoms and molecules which form a certain solid, liquid, or gaseous body. Thermal energy includes both kinetic energy (since atoms and molecules move) and potential energy (since, as a result of the movement of atoms and molecules—oscillatory movement—the linking forces modify, which results in the modification of the potential energy of each atom and molecule forming the respective body). The greater the movement speed of atoms and molecules, the greater the temperature of the body and vice versa. In a boiler, the chemical energy of fossil fuels is transmitted to the steam under the form of thermal energy which, in turn, transmits it to the turbine.

Electrical energy is the kinetic energy of a flux of particles with an electric charge (called electrons and ions), which move inside an electric field. The movement of particles is produced by the force of the electric field. In metals, the charge bearers are the electrons, and in gases and liquids the main charge bearers are the positive and negative ions. Once the electric charge bearers move, it means that they have kinetic energy.

Electromagnetic energy manifests itself under the form of electromagnetic waves, having different values for the wave length, starting with radio waves and ending with X-rays. A particular example of electromagnetic energy is solar energy, which takes the form of an electromagnetic wave spectrum, of different wave length. On the other hand, the electromagnetic wave has particle properties, moving at the speed of light. That is why, essentially, electromagnetic energy is kinetic energy—which indicates the movement of particles without substance transport.

Nuclear energy is the energy obtained following the fission reaction of the atom's nucleus, for instance uranium-235 or plutonium-239. The fission of a nucleus means its splitting into several fragments. The difference between the mass of the initial nucleus and the sum of the fragment masses is found in the kinetic energy that these fragments acquire. In the nuclear reactor, this energy is transformed into thermal energy. In the process of nuclear fission, only 0.1 % of the atom's total energy is emitted, the rest of 99.9 % remaining stored in the mass of the newly created fragments. But this quantity is millions of times larger than that obtained following the oxidation (burning) reaction of a fossil fuel (coal, for instance), where the chemical energy (that is the energy of the atomic and molecular links) is transformed into thermal energy.

1.2 Energy Units

The consumer is interested in being delivered energy to satisfy his needs, such as the heating and lighting of the residence. For him, essential are the quantity of *delivered energy*, the form in which it is delivered, and the amount due. The basic forms of delivered energy are heat and power. Afterward, the energy delivered is converted, transformed, or transmitted to other bodies, the result being called *useful energy*. For example, the heat is transmitted to the radiator in the room, for its heating, and the electricity is converted into light energy, for lighting the house area. These energies are derived from *primary energy* supplied fuel. Figure 1 exemplifies the three notions regarding energy: primary energy (obtained from natural gas, in a thermal station), delivered energy (by the electric energy distributor), and useful energy (necessary for the consumer).

The energy units have been defined either in keeping with the useful energy, or in keeping with the primary energy of the energy source.

(a) When the energy units are defined in keeping with *the useful energy*, the following cases occur:

- If the useful energy is electrical, its unit is the kilowatt-hour (kWh)
- If the useful energy is mechanical, its unit is the Joule (J).

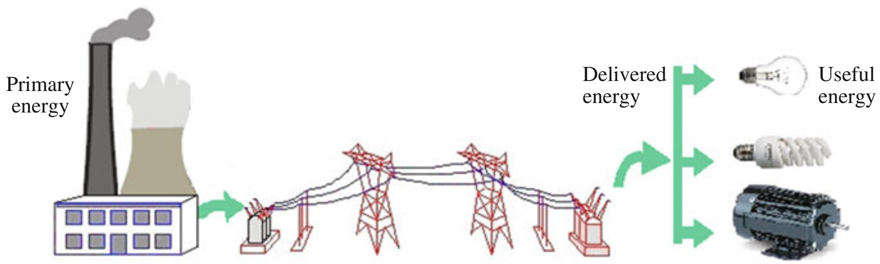

Fig. 1 Primary, delivered, and useful energy

- If it is thermal, the calorie is used additionally. A calorie (cal) is the quantity of energy necessary to raise the temperature of a gram of pure water by a Celsius degree, or the quantity of energy lost by a gram of pure water, in which case temperature decreases by a Celsius degree. The conversion is 1 cal = 4,184 J.

On the other hand, in many areas of the Anglo-Saxon world, especially in the United States, the temperature scale used is that of Fahrenheit (°F). The melting temperature of pure frozen water at sea level is of 32 °F, and the boiling point of pure liquid water is of 212 °F. Thus, 32 °F corresponds to 0 °C and 212 °F corresponds to 100 °C. As a result, 1 °C = (5/9)(F − 32) °F or 1 °F = (1.8–32 °C) °C.

In the same areas, the BTU (British thermal unit) is used to measure thermal energy. A BTU is the energy necessary to raise the temperature of a lb of pure liquid water by a degree Fahrenheit. The conversion is 1 BTU = 1055 J. The energy transfer rate (the power) is defined as 1 BTU/h = 0.293 W. If the useful energy is electric, its unit is Wh. The conversion is 1 Wh = 3600 J.

(b) If the energy units are defined in keeping with *the primary energy* of the source, they depend on the calorific power of the fuel used as reference. Thus, if it is petroleum, the unit is the petroleum equivalent kg, whose symbol is kg oe. Changing the nature of the reference fuel changes the energy unit. For example, kg is used for coal and m^3 *gas equivalent* is used for pit gas. Table 1 presents the conversion factors for energy units in different systems of measurement.

1.3 Energy Conversion

One of the fundamental laws of physics is the law of energy conservation, according to which, in physical processes, energy cannot be created or destroyed, increased or

Table 1 Conversion factors for energy

Units	kJ	kcal	kWh	kg ce	kg oe	m^3 gas	BTU
1 kilojoule (kJ)	1	0.2388	0.000278	0.000034	0.000024	0.000032	0.94781
1 kilocalorie (kcal)	4.1868	1	0.001163	0.000143	0.0001	0.00013	3.96831
1 kilowatt-hour (kWh)	3,600	860	1	0.123	0.086	0.113	3412
1 kg coal equivalent (kg ce)	29,308	7,000	8.14	1	0.7	0.923	27,779
1 kg oil equivalent (kg oe)	41,868	10,000	11.63	1.428	1	1.319	39,683
1 m^3 natural gas	31,736	7,580	8.816	1.083	0.758	1	30,080
1 British thermal unit (BTU)	1.0551	0.252	0.000293	0.000036	0.000025	0.000033	1

decreased, but only transformed (converted) from one form of energy into another. The most common energy conversion processes are presented in Fig. 2.

The few possibilities of direct conversion of energy from one form to another are shown on Table 2 and Figure 2

According to energy conservation law, a system's total quantity of energy remains constant and is called the primary energy of that system. The elements that the primary energy of a system is stored in are called sources of energy.

Quantitatively, the primary energy of a system represents the sum of the quantities of energy contained in all its sources of energy.

- Today, the main sources of energy are:
- fossil fuels (coal, petroleum, and natural gases);
- bio fuels (firewood, wood residue, agricultural residue etc.);
- renewable as hydraulic, geothermal, solar, wind energy;
- nuclear energy.

In the case of fuels (whether fossil or bio), primary energy is obtained through burning and is evaluated by multiplying the quantity of burned fuel by its calorific power. Numerically, the calorific power of a fuel is the energy resulting from burning a unitary quantity of fuel (for example, a kg—if the fuel is solid or liquid, or an m^3—if it is gaseous).

The great majority of fuels contain water which, in the burning process, is released under the form of vapors. That is why, in the burning process, part of the energy resulting from the chemical reactions is used to evaporate the water. Consequently, the primary energy which is converted into heat during the burning of the fuel cannot be measured directly; it can only be evaluated, and the evaluation is done relative to the reference state of the water in the fuel.

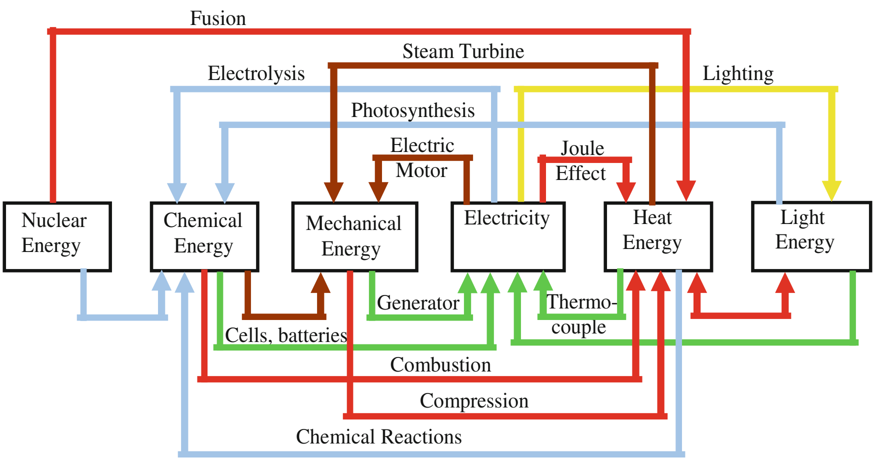

Fig. 2 Conversion processes

Table 2 A few possibilities of direct conversion of energy

Energy type	In chemical	In heat	In electricity	In electromagnetic	In mechanical
From chemical	Plants food products	Burning anaerobic fermentation	Battery fuel cell	Fluorescence lamp	Human muscle and animals
From heat	Pyrolytic gasification	Heat pump heat exchanger	Thermocouple	Fire	Gas turbine steam turbine
From electricity	Battery electrifier	Hob toaster flat iron	Transformer frequency converter	Fluorescent bulb light emitting diode	Electric motor electromagnet
From electromagnetic	Photosynthesis	Solar collector	Photovoltaic cell	Laser	Solar radiation pressure
From mechanical	Crystallization	Brake friction	Generator	Flint	Propeller wind Volant

Table 3 Heating values of fuels

	Units	LHV	HHV	LHV/HHV
Natural gas	BTU/CubicFoot	950	1,050	0.905
Fuel oil	BTU/Gallon	130,000	138,300	0.940
Propane	BTU/Gallon	84,650	92,000	0.920
Sewage/landfill	BTU/CubicFoot	350	380	0.921
Coal-bituminous	BTU/lbs	13,600	14,100	0.965

Standardized reference states may vary, and that is why several calorific powers of the same fuel have been defined. The most commonly used are the Lower Heating Value (LHV) and the Higher Heating Value (HHV) shown in Table 3.

For the inferior calorific power, the reference state of the water is the gaseous one, and for the superior calorific power, the reference state is the liquid one. For this reason, the inferior calorific power decreases with the increase in the water content (ignoring the fact that a large content of water implies a smaller content of combustive substances). (3) In practice, to be able to light the fuel and extract its energy, the maximum content of water is of 55 % (of the humid mass).

2 The Concept of Cogeneration

Today's energy supply system is still dominated by central generation connected to the high voltage level. Cogeneration is the combined production of two forms of energy—electric or mechanical power plus useful thermal energy—in one technological process. The electric power produced by a cogenerator can be used on-site or distributed through the utility grid, or both. The thermal energy usually is used on-site for space conditioning, and/or hot water. But, if the cogeneration system produces more useful thermal energy than is needed on-site, distribution of the excess to nearby facilities can substantially improve the cogeneration's economics and energy efficiency. Cogeneration is an old and proven practice. Because cogenerations produce two forms of energy in one process, they will provide substantial energy savings relative to conventional separate electric and thermal energy technologies. The principal technical advantage of cogeneration systems is their ability to improve the efficiency of fuel use. A cogeneration facility, in producing both electric and thermal energy, usually consumes more fuel than is required to produce either form of energy alone. However, the total fuel required to produce both electric and thermal energy in a cogeneration system is less than the total fuel required to produce the same amount of power and heat in separate systems. Hence, cogeneration is most likely to be competitive with conventional separate electric and thermal energy technologies when it can use relatively inexpensive, plentiful fuels.

Cogeneration unit in turn, can be large-scale centralized near big cities and small or medium scale nears the final consumer.

2.1 Centralized Versus Distributed Energy Generation

The importance of the cogeneration system is showing in 2012/27 EC Directive EED in which the MS for 2014 by National Energy Efficiency Action Plan must provide a description of measures, strategies, and policies, including programs and plans, at national, regional, and local levels to develop the economic potential of high-efficiency cogeneration and efficient district heating and cooling and other efficient heating and cooling systems as well as the use of heating and cooling from waste heat and renewable energy sources, including measures to develop the heat markets (EED Article 14(2), Article 14(4), Annex VIII 1(g)). In this, programs and plans include number of new micro-CHP and small-scale CHP installed and number of other new efficient heating systems and trends in their market uptake, (e.g., heat-pumps efficient boilers, solar equipment and), new or as replacement of old systems installed either as new installations or as replacement for old systems. In the Energy Efficiency Directive are given two types of energies, namely:

- "Primary energy consumption" means gross inland consumption, excluding nonenergy uses (Article 2.2)
- "Final energy consumption" means all energy supplied to industry, transport, households, services, and agriculture. It excludes deliveries to the energy transformation sector and the energy industries themselves (Article 2.3).

The conversion of primary energy into useful energy (or final energy consumption) is evaluated on the basis of the efficiency factor EFF, defined as a percentage ratio between the useful energy and the primary energy.

$$\mathrm{EFF} = (\mathrm{Eu}/\mathrm{Ep})100\,\% \tag{1}$$

where

- Eu is the useful energy and
- Ep is the primary energy.

Energy efficiency has a major role to play in economically, environmentally, and socially sustainable energy policies. Energy efficiency can play a vital role in reducing the energy intensity of economic activity and avoiding the need for significant new supply. Energy savings are among the fastest, highest impacting and most cost-effective ways of reducing greenhouse gases (GHG) emissions. Over the years, the European Union has introduced a number of directives, regulations, and initiatives to encourage and support Member States, regional authorities, individuals, and so on to increase energy efficiency in the different sectors, including buildings, transport, and products. The span of policies, have yet to change our combined thinking, capacity, and ambition to capture significant savings. Although everyone agrees with the importance of saving energy, it has enjoyed little high level political attention and as such we are a long way from achieving the indicative 20 % energy savings target by 2020.

Energy saving means producing a larger quantity of material goods and offering a larger number of services, consuming a smaller quantity of primary energetic resources, to obtain useful energy, that is to increase the efficiency factor EFF.

Different terms are used, often with little precision or accuracy, to express targets in the area of energy efficiency policy. The definitions provided in the Energy Efficiency Directive establish a clear relation between "energy savings" and "energy efficiency".

The following definitions from Article 2 of the EED are worth recalling here as they are relevant:

- "Energy efficiency" means the ratio of output of performance, service, goods, or energy to input of energy (Article 2.4).
- "Energy savings" means an amount of saved energy determined by measuring and/or estimating consumption before and after implementation of an energy efficiency improvement measure, whilst ensuring normalization for external conditions that affect energy consumption (Article 2.5).

Specifically, energy savings are defined as the result of improvements of energy efficiency. Savings are measured as the difference in energy consumption before and after the efficiency improvement has taken place.

For years, the model of the electric energy industry development has been based on the idea that energy must be produced in a centralized way, in large electric plants, then delivered to the large consumption areas through electric transport lines and, finally, delivered to the consumers through the distribution infrastructure, at the lowest voltage levels. Thus, energy circulates in a unidirectional way, from high voltage to low voltage. This situation is indicated in Fig. 3a.

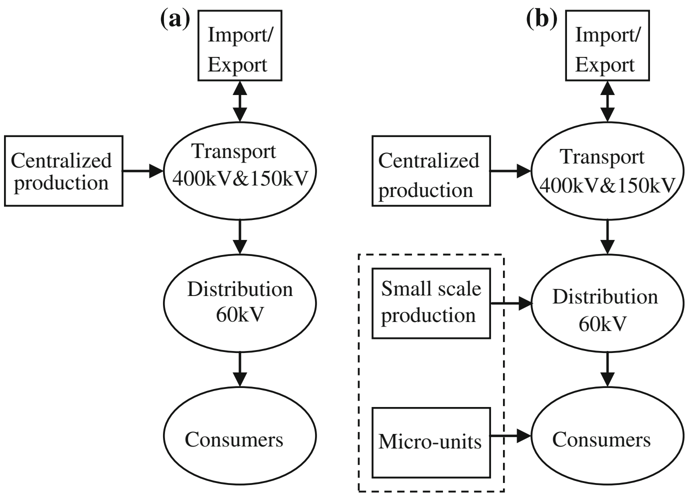

Fig. 3 Models of energy generation

In the first case, the cogeneration unit operates with high efficiency in winter when electricity production is injected into the grid and heat distribution is done to final consumers. Efficiency during the warm season, of the centralized cogeneration units is low, same as power separate systems, because the heat production is not used.

A very important role in the conversion of primary energy into useful energy is played by the capacity of each component of conversion, transformation, and the distribution. For example, the conversion of fuel primary energy into electric energy, in a thermal station, is achieved with an efficiency of maximum 35 %. The electric energy produced by the station is transported along the energy distribution line and reaches the consumer as delivered energy, with an efficiency of 85 %. Then, the consumer uses it to supply various devices, becoming useful energy. For example, the consumer converts electric energy into useful energy under the form of light, with an efficiency of 5 %—in the case of using an incandescent light bulb, of 20 %—in the case of using a fluorescent light bulb, or converts it into mechanical energy, with the aid of an electric engine, with an efficiency of 90 %.

In its turn, the efficiency factor is dependent on the efficiency of converting the energy into different component elements of the chain of energy production, distribution, and use.

Increasing the energy efficiency factor may be achieved in two different ways:

1. by *reducing the energy losses*, as a result of increasing the energy conversion efficiency in each component element of the chain of converting primary energy into useful energy;
2. by *recuperating the energy losses* in the component elements of the chain of converting primary energy into useful energy and transforming these losses into useful energy.

The first applies to systems of separate heat and power generation (SHP systems), where the effort is concentrated on achieving efficient systems (technologies) of energy conversion. This may be achieved in the case of centralized generation, as indicated in Fig. 3a.

The second implies modifying the management of primary energies and their conversion into useful energy. This may be achieved in the case of distributed generation, as indicated in Fig. 3b.

Decentralized power generation combined with heat supply (CHP) is an important technology for improving energy efficiency, security of energy supply, and reduction of CO_2 emissions. The need to introduce several "environment friendly" installations (like microturbines, fuel cells, photoelectric installations, small wind turbines, and other advanced technologies for distributed generation) have determined an increase in the interest for distributed generation, particularly for local ("on-site") generation. Introducing environment friendly installations implies the implementation of two concepts: distributed energy resources (DER) and renewable energy sources (RES). In fact, the DER concept encompasses three main aspects, whose focus is set on the electrical standpoint:

- *Distributed generation* (*DG*) that is local energy production from various types of sources [1–5]. Distributed generation has emerged as a key option for promoting energy efficiency and use of renewable sources as an alternative to the traditional generation.
- *Demand response* (*DR*) that is energy saving brought by the customer participation to specific programs for reducing the peak power or the energy consumption [6–9]. Demand response (DR implies not only satisfying the consumer's electric energy demand, but ensuring any form of energy demanded by the consumer (heat, air conditioning, etc.) also, at any moment, and in the specific quantities necessary to the consumer.
- *Distributed storage* (*DS*) local energy storage with different types of devices [10–13].

In the case of a residence, implementing the DER concept [14] consists in achieving the system for energy production on the basis of the convenient association of three key ideas:

- combined production of heat and power*, from the same fuel, in the same system*, resulting in a so-called Combined Heat and Power system (CHP system);
- the simultaneous use of *more sources of energy* (fossil fuel, sun, wind, geothermal sources, etc.) and their integration in a system;
- placing the cogeneration installations *as close to the final consumer* as possible and dimensioning them so that they may offer the amount of heat and electricity necessary for the consumer, resulting in a *local system* for producing electric and thermal energy, in the *specific quantities* necessary to satisfy the useful energy needs of each consumer *at any given moment in time* (Fig. 4);
- smart metering, with bidirectional way of energy in low voltage to create smart grid concept.

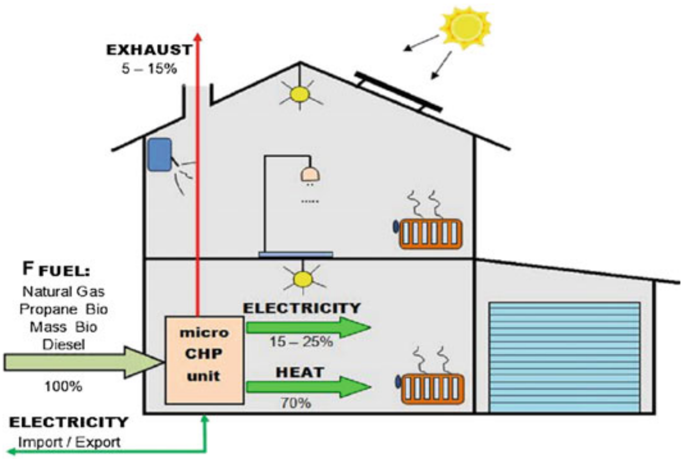

Fig. 4 Energy system for residences, based on the DER concept [15]

Usually, distributed generation uses low power generation units situated with the consumer or in his proximity. These units are installed so as to cover all of the consumer's needs, to ensure an economical functioning of the electric distribution grid, or to satisfy both conditions. Distributed generation complements the traditional centralized generation and distribution of electric energy. It ensures a favorable answer (as regards the cost of capital) to the increase in the energy demand, avoids the installation of supplementary transport and distribution capacities, localizes the generation of electric energy where it is necessary and has the flexibility of delivering it to the grid in the consumer's proximity.

Technological developments, the progressive rise of distributed generation, and the increasing need to manage the system close to consumption points all require a *shift towards* a more decentralized electricity system. Therefore, decentralized and centralized generation can coexist; smart grid development will enhance their complementarities. In this transition, a new figure appeared: the "prosumer", producing and consuming his/her own electricity. By covering on-site part of the final user's electricity needs, PV systems will generate new opportunities. Such decentralized electricity generation will have to be better incorporated in future strategies.

Small-scale power producers are also giving rise to new ownership structures and business models, some of which directly compete with conventional utilities. "More than 3 million households have started producing their own electricity with solar PV", says Eurelectric, while 133 "bio-villages" have emerged in Germany since 2000, generating more than 50 % of their electricity and heat from bioenergy resources.

In Italy, at the end of 2011, PV [16] already covered 5 % of the electricity demand, and more than 10 % of the peak demand. In Bavaria, a federal state in southern Germany, the PV installed capacity amounts to 600 W per inhabitant, or three panels per capita. In around 15 regions in the EU, PV covers on a yearly basis close to 10 % of the electricity demand; in Extremadura, a region of Spain, this amount to more than 18 %.

Market trends across Europe indicate that liberalization is bearing fruit, with wholesale markets becoming more *competitive and customers* increasingly benefiting from new types of products and energy-related services.

Customers use today, an ever larger number of electronic appliances (TV, computers, tablets, smart phones), heating systems (thermostats, air conditioning, heat pumps), green goods (washing and drying machines, dishwashers, ovens, refrigerators), for reasons linked to comfort, entertainment, environment, and security. This increase of appliances in and around the home combined with the progressive introduction of new loads such as heat pumps and electric vehicles is likely to cause electricity demand from households to rise. At the same time, new technologies such as micro-CHP and solar photovoltaic have made power generation at household level a real economic possibility. Customers with such installations no longer only consume energy, but produce electricity as well. This is the way customers will more and more benefit from new services, be able to save on their energy bill and potentially become electricity producers themselves. But these developments also pose new challenges to the electricity industry, which has to cope with a higher share of variable and decentralized generation, in which customers will progressively move to the center of the electricity system.

Competitiveness of the new technologies can be analyzed from three points of view:

- “Wholesale competitiveness”, which compares PV’s generation cost (the Levelised Cost of Electricity, or LCOE) with wholesale electricity prices, requires examining much more complex boundary conditions (such as market design);
- “Dynamic grid parity”, when comparing PV’s LCOE with PV revenues (earnings and savings);
- “generation value competitiveness”, when comparing PV’s generation cost to that of other electricity sources.

A meaning of these terms is as follows:

“Dynamic grid parity” is defined as the moment at which, in a particular market segment in a specific country, the present value of the long-term net earnings (considering revenues, savings, cost, and depreciation) of the electricity supply from a PV installation is equal to the long-term cost of receiving traditionally produced and supplied power over the grid.

“Generation value competitiveness” is defined as the moment at which, in a specific country, adding PV to the generation portfolio becomes equally attractive from an investor’s point of view to investing in a traditional and normally fossil fuel based technology.

“Wholesale competitiveness” is defined as the moment at which—in a particular segment in a country—the present value of the long-term cost of installing, financing, operating, and maintaining a PV system becomes lower than the price of electricity on the wholesale market.

Competitiveness of the PV is analyzed in EPIA study [15] for the residential, commercial, and industrial segments—involving the local consumption of PV electricity, when a user goes from being a consumer to a “prosumer” as “dynamic grid parity”, when comparing PV’s generation cost (the Levelised Cost of Electricity, or LCOE) with PV revenues (earnings and savings).

In the future, decentralized electrical generation units (DG units) of small size will be connected to the low voltage grid with an increasing number and generation capacity. With a rapidly increasing number of DG units, also the rated power installed increases. In the future, the consumer (operator of DG unit) will decide at which time and at which level electric power is fed into the grid.

Cogeneration (CHP) solutions can exhibit excellent overall energy efficiency and allow for significant primary energy saving with respect to the separate production of heat and electricity. As a consequence of the primary energy saving, CHP systems can also be an effective means to pursue the objectives of the Kyoto’s Protocol in terms of greenhouse gas emission reduction

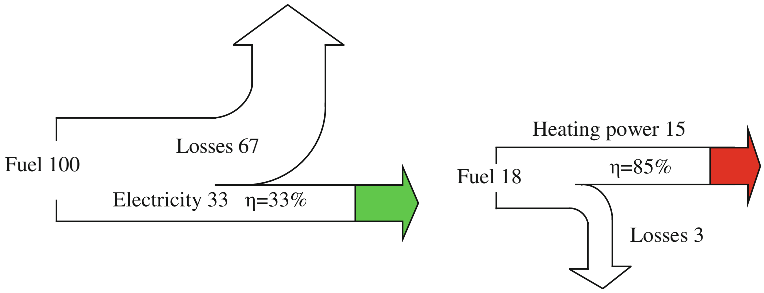

Fig. 5 Energetic balance of separate energy production

2.2 Performance Indicators of Cogeneration Systems

To define the performance indicators of cogeneration systems, let us firstly analyze the energetic efficiency in the case of the separate production of heat and power (Fig. 5).

Heat may be produced with the aid of a boiler, through the transformation of the primary energy of a fuel (chemical energy) into thermal energy useful to the consumer. Boilers (both condensing and noncondensing) are by far the most widely adopted technology for separate production (i.e., excluding district heating) of space heating and domestic hot water heating.

The efficiency of transforming fuel energy into heat (EFF_H) can be defined by means of the First Law of Thermodynamics as the net energy output (Q_H) divided by the fuel consumed (Q_F) in terms of kWh thermal energy content.

$$EFF_H = \frac{Q_H}{Q_F} \tag{2}$$

The efficiency of transforming fuel energy into heat is dependent on the type of fuel used and the performance of the burning chamber. If the boiler uses pit gas, the standard efficiency is of 85 %, and if it uses biomass, the efficiency is considered to be of 65 %, assuming that the heat of condensation cannot be recovered (Fig. 5).

Power is generated through the multiple transformation of energy: the primary energy of a fuel (chemical energy) is transformed into thermal energy (Q_H) which, in turn, is transformed into mechanical energy (W_M), to be then transformed into electric energy (E). The efficiency of electric energy generation (EFF_P) is defined by the relation:

$$EFF_P = \frac{E}{Q_F} = \frac{Q_H}{Q_F}\frac{W_M}{Q_H}\frac{E}{W_M} \tag{3}$$

Its value is much lower (of approximately 33 %) than that of the efficiency of thermal energy generation.

On the other hand, according to the Directive 2012/27/EC, the overall efficiency shall mean the annual sum of electricity and mechanical energy production and useful heat output divided by the fuel input used for heat and electricity and mechanical energy, produced in a cogeneration process (for heat produced in a cogeneration process and gross electricity and mechanical energy production, produced in a cogeneration process).

In the case of energy generation with a SHP system (Fig. 5), the overall efficiency (EFF_{SHP}) is defined as the sum of net power (E) and useful thermal energy output (Q_H) divided by the sum of fuel consumed to produce each and may be calculated with the relation:

$$EFF_{SHP} = \frac{E + Q_H}{\frac{E}{EFF_P} + \frac{Q_H}{EFF_H}} \tag{4}$$

where: E = Net power output from the SHP system; Q_H = Net useful thermal energy from the SHP system; EFF_P = Efficiency of electric generation; EFF_H = Efficiency of thermal generation.

2.2.1 Energy Efficiency

In the case of cogeneration in a CHP system, the overall efficiency (EFF_{CHP}) is defined as the sum of the net power (E) and net useful thermal output (Q_H) divided by the total fuel (Q_F) consumed, in terms of kWh thermal energy content, and may be calculated with the relation:

$$EFF_{CHP} = \frac{E + Q_H}{Q_F} \tag{5}$$

What may be observed is that, as compared to a SHP system, the energetic efficiency of a CHP system is greater, as a result of recuperating the lost energy and transforming it into useful energy. For example, let us consider the situation presented in Fig. 6, where the consumer needs 33 units of electric energy and 15 units of thermal energy. In the case of a SHP system, 118 units of primary energy are needed, while only 100 units are needed if the cogeneration is implemented in a CHP system.

It results that the *effect of recuperating energy losses using the concept of cogeneration is the increase in overall efficiency*. To evaluate this effect, two indicators are used: fuel utilization efficiency and percent fuel savings.

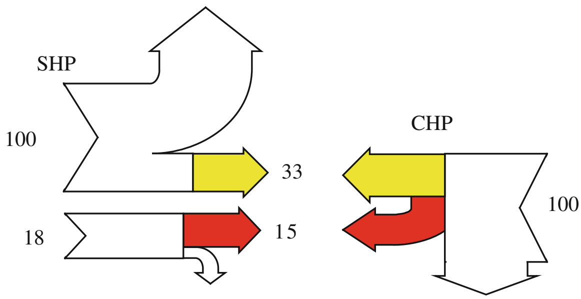

Fig. 6 Energy balance of separate vs. combined production

2.2.2 Fuel Utilization Efficiency

Fuel utilization efficiency (*FUE*) is defined as the ratio of net power output to net fuel consumption, where net fuel consumption excludes the portion of fuel used for producing useful heat output. Fuel used to produce useful heat is calculated assuming that the typical boiler efficiency, EFF_H, is 85 %. FUE can be calculated with the relationship:

$$FUE = \frac{E}{Q_F - \frac{Q_H}{EFF_H}} \tag{6}$$

The difference between the primary energy in the case of separate production and the primary energy in the case of combined production represents the primary energy corresponding to the saved fuel.

2.2.3 Primary Energy Saving

Primary energy saving or Percent fuel savings (*PES*) with combined production is obtained relating this energy to the primary energy in the case of separate production and is calculated with the relation:

$$PES = \left(1 - \frac{Q_F}{\frac{E}{\eta_{Eref}} + \frac{Q_H}{\eta_{Href}}}\right) \times 100\,\% \tag{7}$$

Similarly, fuel saving compares the fuel used by the CHP system to a separate heat and power system. Positive values represent fuel savings, while negative values indicate that the CHP system is using more fuel than SHP.

Recoverable thermal energy from the various prime movers is available in one or both of the following two forms, namely hot exhaust gases and hot water.

Two options for recovering heat from the hot exhaust gases from the prime movers could be considered:

1. Direct use of the exhaust for providing process heat;
2. Indirect use via heat exchangers for producing hot water. Hot water produced can be used to meet the needs for space heating. In applications that require more thermal energy or higher temperatures than that available from power generation equipment, supplementary heat is supplied using a duct burn .The possibilities and the level of energy loss recuperation are dependent on the energy conversion technology for CHP systems.

3 The Trigeneration Concept

Trigeneration is a basic and most popular form of polygeneration. The term describes an energy conversion process with combined heat, cooling, and power generation. Today, availability of CHP technologies with good electrical and excellent overall efficiency has been adopted on a small-scale [17] and even on a microscale [18] basis, with suitable applications ranging from residential houses to schools, restaurants, hotels, and so forth. The trend toward distributed micro-cogeneration could be significant in terms of increasing the local energy source availability, reducing both the energy dependency [19] and the vulnerability of the electrical system to the effects of grid congestions, reducing service interruptions, blackouts, vandalism or external attacks [19, 20] through the formation of self-healing energy areas [21, 22]. The advantage of combined production of heating and power in a cogeneration (or CHP) system is obvious: the waste heat which is always produced when electricity is generated using thermodynamic cycles is not released into the environment—as in large-scale centralized power plants—but can be used. Typical use of this heat is to heat buildings or to produce domestic hot water. Depending on the building site and building standard, the heating season often lasts for only 6 months or less. But for the economic viability of CHP systems, it is important that they are used as much as possible. Therefore, other uses of the waste heat are awakening more interest. One of the possible uses of waste heat during the nonheating season is cooling. The concept of trigeneration is an extension of the CHP concept through adding cold producing equipment for the summer. Classical trigeneration solutions are represented by coupling a CHP prime mover to an absorption chiller fired by cogenerated heat. In this scheme, the produced thermal power is exploited also in the summertime to produce cooling. In this way, one of the biggest shortcomings that often make cogeneration unprofitable, that is the lack of adequate thermal request throughout the whole year, is made up for by transforming the cooling demand into thermal demand.

One difference between various CCHP systems resides in the connection mode of the cold producing device (Fig. 7), where: PM-primary mover; EG-electrical generator; MCP-monitoring control and protection system; PC-personal computer.

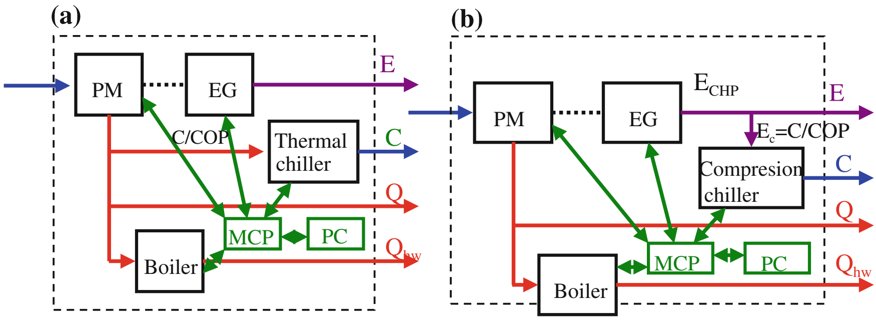

Fig. 7 Trigeneration processes

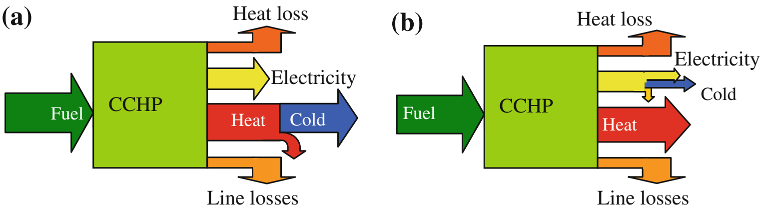

Fig. 8 Energy balance of trigeneration processes

The first version presupposes transforming heat into cold (thermally activated chiller) and the second presupposes obtaining cold by transforming electric energy (mechanical compression chiller). The energy balance related to these two trigeneration processes is given in Fig. 8.

A standard mode of achieving CCHP system does not exist but, generically, such a system consists of a cogeneration unit CHP (Fig. 9), a refrigerating device (a Thermal Driven Chiller—TDC or a Mechanical Compression Chiller—MCC), heat storage unit (hot water storage—HW), and electricity storage unit.

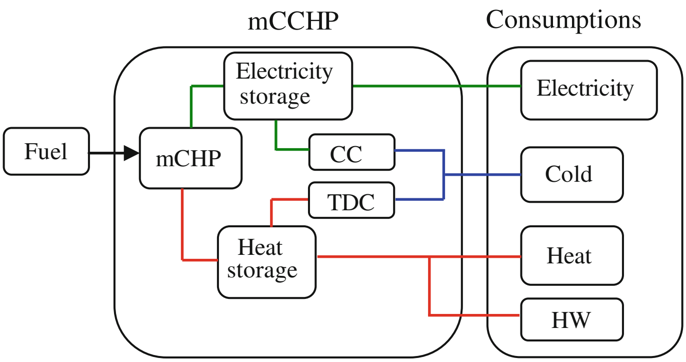

Fig. 9 Trigeneration system

The energies produced by the CCHP system are dependent on the type of refrigerating device, but also on whether the system is connected to the national electricity grid or not.

3.1 Energy Conversion in the Trigeneration

Note electric energy as E, the thermal energy for heating the residence as Q, the energy necessary for the air conditioning of the residence as C, and the thermal energy for preparing domestic hot water as Q_{hw}. To satisfy the demand for electric energy of the residence, the following systems may be used:

- *Centralized energy producing system*. In this case, the residence is connected to the electricity grid. The thermal energy demand for heating the residence or for cooling the air in the residence must be ensured with a system which contains equipment installed in the residence. This system includes a conventional condensing boiler (with 90 % thermal efficiency) providing heat for space heating and sanitary uses (hot water), and a conventional compressing refrigerator which supplies cold for air conditioning (Fig. 10).

Regarding the cooling equipment, performance is usually described by means of the specific coefficient of performance (COP). The COP_C can be generally defined as the ratio of the desired cooling energy output to the relevant input (electrical energy for electric chillers).

The energetic balance of this system is:

- for the electric subsystem:

$$E_{\text{grid}} = E + \frac{C}{\text{COP}_C} \tag{8}$$

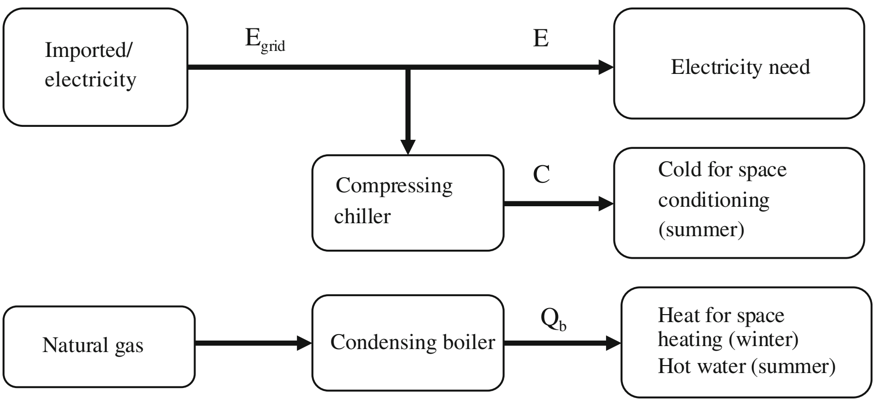

Fig. 10 Centralized energy producing system

- for the thermal subsystem:

$$Q_b = Q + Q_{\text{hw}} \tag{9}$$

where:

E_{grid} the quantity of electricity consumed from the grid;
COP_C the coefficient of performance of the compression chiller;
Q_b the heat produced by the boiler

- *Decentralized energy producing system*. In the case of the decentralized system, two solutions are applied for the supply with electricity:

(a) On-grid (or open) system

This solution produces combined heat and power by using a CHP technology [23, 24], and cold for air conditioning is generated by means of an absorption refrigerator making use of the “cogenerated” heat (Fig. 11). The CHP are sized in order to satisfy the maximum heat demand, so that they generate power in excess of customer needs. This excess power is exported to the utility grid.

The characteristics of the CHP prime movers can be effectively and synthetically described by means of the electrical efficiency and the thermal efficiency. For an absorption refrigerator, the COP_a can be defined as the ratio of the desired cooling energy output to the relevant input (thermal energy for steam-fed, hot water-fed, or exhaust-fed absorption chillers).

The energetic balance of this system is:

- for the electric subsystem:

$$E_{\text{CHP}} = E - E_{\text{grid}} \tag{10}$$

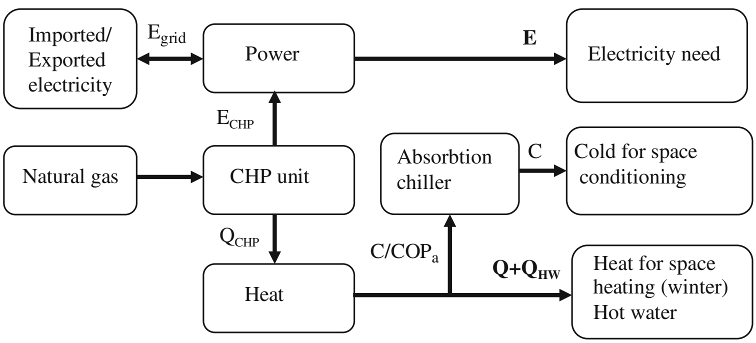

Fig. 11 Decentralized on-grid energy producing system

- for the thermal subsystem:

$$Q_{\mathrm{CHP}} = Q + Q_{\mathrm{hw}} + \frac{C}{\mathrm{COP}_a} \tag{11}$$

where:
COP_a the coefficient of performance of the ad/absorption chiller;

(b) Off-grid (or "isolated") system

Since they do not involve importing/exporting electricity from/to the utility grid, small power plants are sized in order to satisfy the maximum customer needs of electricity. This implies that the amount of "cogenerated" heat is yes or not sufficient to satisfy energy needs for domestic heating and air conditioning. Heat and cold demands of the residence can be covered by adding a boiler and an absorption chiller (Fig. 12). Energy balance of the system is the following:

- for the electric subsystem:

$$E_{\mathrm{CHP}} = E + \frac{C'}{\mathrm{COP}_C} \tag{12}$$

- for the thermal subsystem:

$$Q_b + Q_{\mathrm{CHP}} = Q + Q_{\mathrm{hw}} + \frac{C - C'}{\mathrm{COP}_a} \tag{13}$$

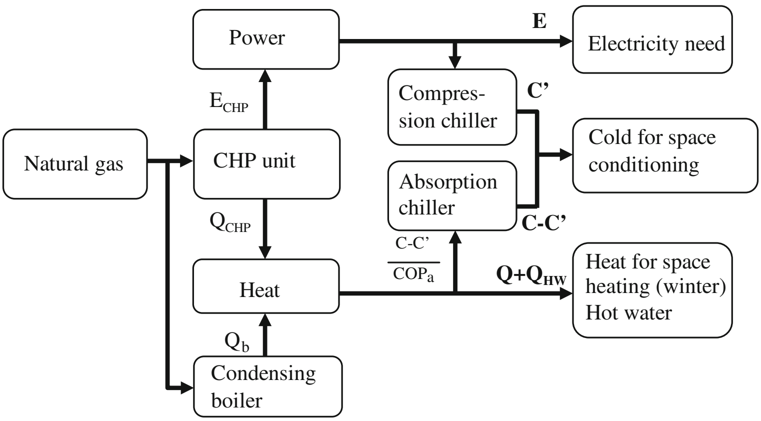

Fig. 12 Decentralized system with off-grid energy production

where:

C' is the quantity of cold produced by the mechanical compression chiller.

The term "cogeneration" is traditionally adopted with reference to the combined production of heat and electricity from fossil fuels. However, other types of cogeneration sources can be adopted [24, 25], for example from solar power, that allow for clean high-performance solutions. In this respect, increasing interest is being lately gained by applications of solar technologies for multigeneration. More specifically, photovoltaic (PV) modules, thermal collectors, and hybrid photovoltaic/thermal (PV/T) systems can be effectively coupled to bottoming cooling/heating equipment. In particular, although in theory electricity can be produced in a PV system and then utilized to feed an electric chiller, it results more energetically and economically effective to adopt heat-fired cooling technologies (namely adsorption, absorption, or desiccant systems) to be fed by cogenerated heat in a PV/T solar system (solar trigeneration), or by heat produced in a solar collector. In particular, PV/T solar units for cogenerative and trigenerative applications bear the additional intrinsic energy benefit that the optimized cooling of the solar modules brought by the heat recovery system brings along an increase in the PV electrical generation efficiency owing to decrease of the module temperature. The rationale of the utilization of solar systems for both heating and cooling generation is the same as for adopting conventional CHP unit in trigeneration applications. In fact, the solar thermal power is optimally exploited throughout the year, namely, in the summertime for cooling generation, and in the wintertime for heat generation.

What results from the presentation of these systems is that the applications developed in the decentralized energy production area can be categorized in structural and functional terms and in the increasing order of complexity, as:

(a) classical cogeneration (single input fuel, double output, single site);
(b) trigeneration (single/multiple input fuel, manifold output energy vectors, single site);
(c) distributed multigeneration (single/multiple input fuel, manifold output energy vectors, multiple sites).

From a generalized point of view, with trigeneration planning [25] it is possible to look at the plant as a black box (Fig. 13) with an array of inputs and manifold outputs. The core of the system is represented by two main physical blocks:

the CHP block, containing a cogeneration prime mover. It produces electricity (E) and heat (Q) for various possible final uses,

the additional generation plant (AGP) may be composed of various equipments for cooling and/or heat production and/or electricity production.

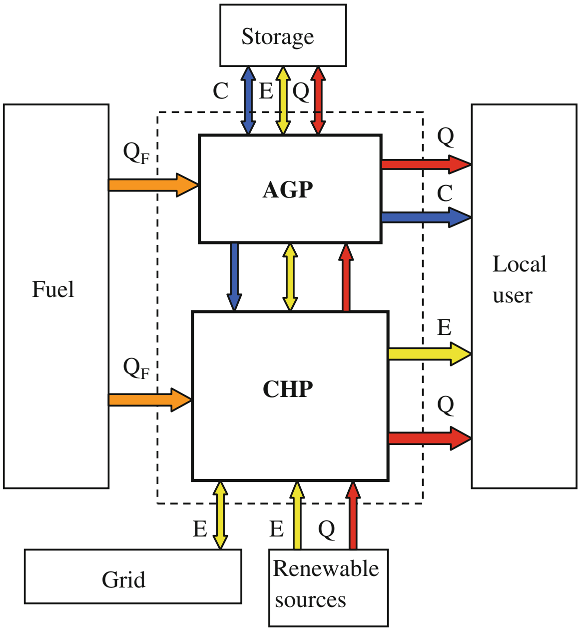

Fig. 13 Trigeneration black box system

3.2 Performance Indicators of the Trigeneration Systems

3.2.1 Primary Energy Saving to Trigeneration Systems

The CCHP system is compared to separate heat and power (SHP) systems in order to define its efficiency. This comparison is similar to the one between CHP and SHP systems. For SHP systems, Directive 2012/27/EC defines primary energy saving (PES), which may be calculated with the relation:

$$\mathrm{PES} = 1 - \frac{1}{\frac{\eta_H}{\eta_{\mathrm{Href}}} + \frac{\eta_E}{\eta_{\mathrm{Eref}}}} \tag{14}$$

where:

η_H is the heat efficiency of the cogeneration production, defined as annual useful heat output divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration;

η_{Href} is the efficiency reference value for separate heat production;

η_E is the electrical efficiency of the cogeneration production defined as annual electricity from cogeneration divided by the fuel input used to produce the sum of useful heat output and electricity from cogeneration;

η_{Eref} is the efficiency reference value for separate electricity production.

Where a cogeneration unit generates mechanical energy, the annual electricity from cogeneration may be increased by an additional element representing the amount of electricity which is equivalent to that of mechanical energy.

On the other hand, primary energy saving may also be calculated with the relation:

$$\mathrm{PES} = 1 - \frac{Q_F}{\frac{E}{\eta_{\mathrm{Eref}}} + \frac{Q_H}{\eta_{\mathrm{Href}}}} \quad (15)$$

where Q_F is the fuel consumption of the cogeneration plant, E is the electricity generated, Q_H is the heat generated, and η_{Href}, η_{Eref} are the two reference efficiencies for electricity and heat generation, defined separately.

The efficiency reference values are calculated according to fuel categories and the climatic differences between Member States.

For CCHP systems, no standardized relation for calculating the primary energy saving has been found, but in some countries [26] where this technology is used, PES is calculated with the relation:

$$\mathrm{PES} = \left(1 - \frac{Q_F}{\frac{E}{\eta_{\mathrm{Eref}}} + \frac{Q_H}{\eta_{\mathrm{Href}}} + \frac{C}{\mathrm{COP}_{\mathrm{ref}}\eta_{\mathrm{Eref}}}}\right) \times 100 \quad (16)$$

where C is the cooling energy generated and $\mathrm{COP}_{\mathrm{ref}}$ is the performance reference chiller. Reference thermal efficiency is set to 0.8 for civil cogeneration and 0.9 for other cases. The reference chiller performance $\mathrm{COP}_{\mathrm{ref}}$ is set to 3.0. Reference values for electrical efficiency used to calculate the energy saving index [26] is presented in Table 4.

The relation for calculating PES may be rearranged as:

$$\mathrm{PES} = \left(1 - \frac{Q_F}{\frac{E + \frac{C}{\mathrm{COP}_{\mathrm{ref}}}}{\eta_{\mathrm{Eref}}} + \frac{Q_H}{\eta_{\mathrm{Href}}}}\right) \times 100 \quad (17)$$

Table 4 Reference values for electrical efficiency [26]

Electrical efficiency for Italian regulation energy calculation				
Nominal power (MW)	Natural gas, liquid gas	Oil, naphtha, diesel fuel	Solid fossil fuels	Solid refuse fuels (organic and inorganic)
<1 MWe	0.38	0.35	0.33	0.23
>1–10 MWe	0.4	0.36	0.34	0.25

Or

$$\mathrm{PES} = \left(1 - \frac{Q_F}{\frac{E_{\mathrm{sys}}}{\eta_{\mathrm{Eref}}} + \frac{Q_{\mathrm{sys}}}{\eta_{\mathrm{Href}}}}\right) \times 100$$

where:

$$E_{\mathrm{sys}} = E + \frac{C}{\mathrm{COP_{ref}}}$$

Under this form, the relation is similar to the relation for calculating PES defined in cogeneration, when the cooling energy is generated through electric energy consumption. Generalizing to thermal systems (activated thermally), where cooling energy is generated through thermal energy consumption, we may define PES with the similar cogeneration relation:

$$\mathrm{PES} = \left(1 - \frac{Q_F}{\frac{E}{\eta_{\mathrm{Eref}}} + \frac{Q_H + \frac{C}{\mathrm{COP_{ref}}}}{\eta_{\mathrm{Href}}}}\right) \times 100\,\% \tag{18}$$

or

$$\mathrm{PES} = \left(1 - \frac{Q_F}{\frac{E_{\mathrm{sys}}}{\eta_{\mathrm{Eref}}} + \frac{Q_{\mathrm{sys}}}{\eta_{\mathrm{Href}}}}\right) \times 100\,\%$$

where:

$$Q_{\mathrm{sys}} = Q_H + \frac{C}{\mathrm{COP_{ref}}}$$

3.2.2 Energy Efficiency of the Trigeneration Systems

PES refers basically to the percentage of fuel saved from the energy production of the CCHP system compared to the same energy produced separately. PES does not point if this production of the CCHP system is useful or not. Energy can be exceedingly produced and dissipated in the environment (especially for thermal energy). The second indicator sets the correlation between the produced and useful energy. This is also called CCHP efficiency. The second performance indicator is CCHP system efficiency given by relation:

$$\mathrm{EFF}_{\mathrm{CCHP}} = \frac{E_{\mathrm{sys}} + Q_{\mathrm{sys}}}{Q_F + E_{\mathrm{PV}} + Q_{\mathrm{TP}}} \times 100\,\%$$

where:

E_{PV} is the annual specific electricity production from photovoltaic panels (PV);
Q_{TP} is the annual specific heat production from thermal panels (TP);
E_{sys} is the annual specific electricity production from CCHP system;
Q_{sys} is the annual specific heat production from CCHP system;
Q_F is the specific fuel consumption of CCHP system (sum of useful fuel input for CHP unit and additional boiler)

If we use the renewable energy, the primary energy is considered the amount of energy produced. In other words, if the electricity production is from renewable sources, is not taken into account the efficiency of the conversion process.

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