NOTE eNOTE IIR Information

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Cogeneration/Trigeneration

The IIR publishes Informatory Notes designed to meet the needs of decision-makers worldwide, on a regular basis. These notes summarize knowledge in key refrigeration-technology and refrigeration-application domains. Each note puts forward future priority developmental axes and provides IIR recommendations in this context.

Offering high efficiency through the recovery of thermal waste, cogeneration and trigeneration are valuable alternative technologies for producing energy. However, they should be further developed across the world in order to control the exploitation of fossil fuels and reduce greenhouse gas emissions. This Informatory Note discusses the operating principles of these technologies, their benefits as well as the obstacles hampering their development. In conclusion, the IIR provides some recommendations on the conditions required for the implementation of these technologies.

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Introduction

The energy issue is a major challenge for the future. Fossil fuels resources are limited, so their exploitation has to be monitored closely. Many countries still do not have access to a sufficient level of energy, allowing to improve their quality of life and development.

This energy problem is related to environmental issues: global warming in particular is a key issue that has to be addressed by the cooling sector, whose energy demand increases constantly.

Therefore, a more reasonable use of energy and the development of new technologies for the production of energy are necessary. The development of cogeneration, which consists of the production of two energies simultaneously, is a viable option for raising the effectiveness of energy use. Generally, power and heat are produced, and in this case the cogeneration is called Combined Heat and Power (CHP). Trigeneration, also called Combined Cold Heat and Power (CCHP), adds a third energy: cooling. These technological solutions offer many environmental and economic benefits. Each of these technologies has advantages, both economically and environmentally.

This Informatory Note discusses the operating principles of cogeneration and trigeneration as well as their benefits and challenges.

Operating principles

Cogeneration (CHP and CCP)

Cogeneration consists of the simultaneous production of two different energy forms from a single resource. CHP is the most common application: the heat produced during power production is recovered, for instance by a heat exchanger, and can then be used to produce steam, hot water, hot air or another hot fluid. Combined Cold and Power (CCP) exists as well: cooling is produced along with electricity from the recovered heat.

In order to promote heat production, the CHP scheme can also produce heat first and then use a part of it to produce power [1]. Later in this Informatory Note, we will focus on the most common cogeneration type: the recovery of thermal wastes during power production.

Trigeneration (CCHP)

Trigeneration extends the cogeneration principle by coupling heat and power production with cooling production. This technique is used when cooling is needed on top of power and heat. Its principle is presented in Figure 1: the excess of recovered heat is converted into cooling by way of thermally driven refrigeration system [2, 3].

A trigeneration system can be implemented to improve the management of the different energy forms depending on the demand and its variation during the day and the year. Thus, the electricity production can be adjusted via exchanges with the public grid. In addition, a boiler can be installed to manage the heat needs and their variation. For this purpose, a heat and cold storage system can be set up (sensible or latent heat storage, chemical storage...) [3, 4, 5]. To match the cooling production with the needs, complementary cooling can also be produced from power or from fuel combustion.

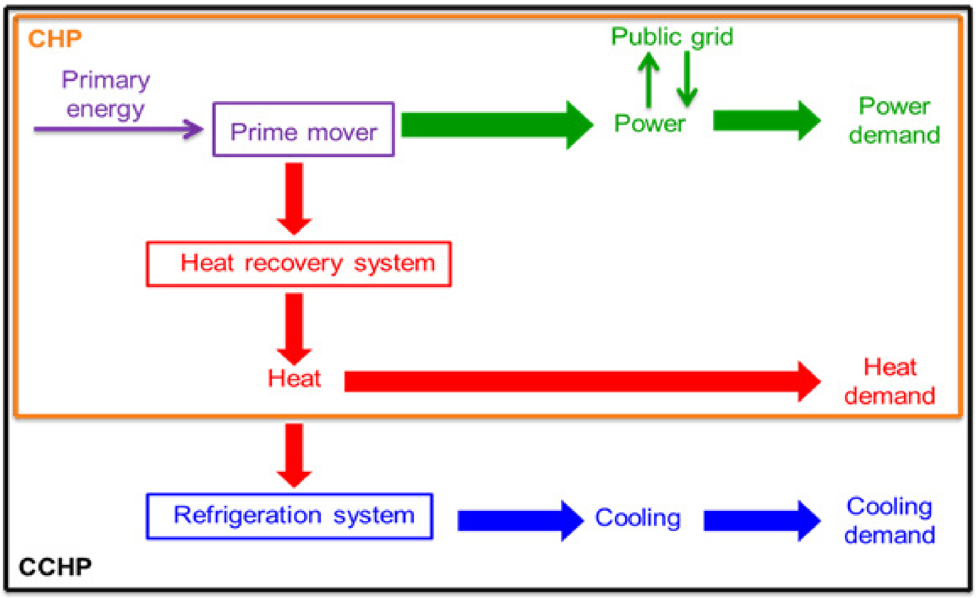

Figure 1: *CCHP principle*

In buildings, the heat demand is usually higher in winter than in summer and vice versa for cooling, except in tropical regions where the cooling demand is extended all year long. Therefore, a trigeneration system can focus on cooling production or on heat production, depending on the demand and the seasons.

Polygeneration

Polygeneration extends the trigeneration principle: it is an integrated process which provides three types of production or more from one or several primary energy resources (including renewables). For instance, a polygeneration system can be set up in order to produce power, heat for two needs (heating and hot water), and cooling and purified drinking water. Purified or desalinated water can be produced with reverse osmosis using power, or through distillation using heat. Several other applications can also be considered as the recovery, the purification and the usage of CO_2 (for example for industrial process) from the exhaust gas of a combustion engine integrated into a trigeneration system.

State-of-the-art and latest developments

Many technical solutions are offered to investors who can choose the most appropriate technology for their project, depending in particular on the form of energy (electrical or thermal) they need to produce in priority. The clear assessment of heat or electricity needs and their daily, monthly and annual changes is thus essential.

Used fuels

Several fuels are used as the primary energy for cogeneration and trigeneration. Natural gas is the most commonly used fuel for cogeneration and trigeneration (around 40% in the European Union (EU) between 2005 and 2013 for example). Moreover, solid fossil fuels (such as coal and peat), which emit more CO_2, are being gradually replaced by renewable energies. As far as cogeneration is concerned, their consumption dropped from 35% in 2005 to 21% in 2013 in EU countries, whereas the consumption of renewable energies has doubled at the same time (from 10% to 18%). Oil and oil-based products are also used as fuel for co/trigeneration and accounted for 4% in 2013, whereas other fuels account for 12% in the European Union [6].

Main prime movers

Different technologies are used and developed to convert primary energy into power. The main ones are thermal engines, which convert the thermal energy of fuel combustion into mechanical energy. In the following paragraph, we will consider that each prime mover is coupled with an alternator to convert the resulting mechanical energy into power. Thus, in order to compare these technologies, we will discuss electrical efficiency (conversion factor of consumed primary energy into power), thermal efficiency (conversion factor of consumed primary energy into heat) and about overall efficiency (conversion factor of consumed primary energy into useful energy, i.e. power and heat). The power/heat ratio (ratio between power and heat produced by the cogeneration system) is also a useful parameter to choose the most suitable technology according to the required energy form [7]. Four major technologies stand out and their parameters are shown below in Table 1 [1, 7, 8, 9].

Table 1: *Parameters of major prime movers* [7, 9]

Technologies	Internal combustion engines (ICEs)*	External combustion engines (Stirling)	Gas turbines	Steam turbines
Capacity range	Tens of kW to a few MW	A few tens of kW	Several hundreds of kW to several hundreds of MW	A few tens of kW to several hundreds of MW
Power/heat ratio	0.4-0.9	0.3-0.4	0.3-0.8	0.1-0.33
Electrical efficiency	0.25-0.45	0.20-0.30	0.25-0.40	0.07-0.25
Overall efficiency	0.8-0.9	0.5-0.7	0.5-0.8	0.85-0.90
Fuels	Natural gas, propane, gasoil, biogas	All kinds	Natural gas, biogas, gasoil	Different types of fuels used in the boiler
Investment costs	400-6,800 (€/kW installed)	5,000-10,000 (€/kW installed)	400-900 (€/kW installed)	900-2,100 (€/kW installed)
Maintenance costs	0.44-3.25 (€cents/kWh)	0.35-1.7 (€cents/kWh)	0.48-0.53 (€cents/kWh)	0.15-0.23 (€cents/kWh)
Lifespan	80,000-100,000 h	50,000-60,000 h	130,000 h	175,000 h
Noise	High	Moderate	High	High
Applications	Heat needs at low temperature, small-sized facilities (residential, commercial, hospitals, buildings…)	Small-sized applications (residential, commercial, small industries…)	Industries and tertiary sector	High needs in steam (food industries, paper mills…)

** Except gas turbines (see 3rd column)*

- **Internal combustion engines (ICEs) using gas or gasoil.** Heat is recovered from the exhaust gases at a high temperature (around 450 °C) and from cooling liquid (mainly water and oil) at a low temperature (around 95 °C). Their electrical efficiency is high but they require regular maintenance (Table 1), including monitoring and periodic change of lubricating oil. Furthermore, they are noisy, they vibrate strongly and emit greenhouse gases.

- **External combustion engines** (like Stirling engines). They use different fuels and emit less greenhouse gases than internal combustion engines. They are less noisy but they are less efficient and more expensive.
- **Combustion turbines** (gas turbines). These are ICEs whose exhaust gases are expanded in a turbine, and their heat is then recovered at a high temperature (over 500 °C). A post-combustion system can be used downstream of the turbine, in order to raise the temperature of exhaust gases up to 900 °C [8].
- **Steam turbines**. Their thermodynamic cycle is based on an external combustion, and operates on the principle of the Hirn cycle. In this technology, the working fluid is steam and not an organic fluid as for the organic Rankine cycle, which can also be used for thermal engines. The high pressure vapour produced by a boiler is expanded in the turbine, and the heat is then available as low pressure steam. Several primary energies can be used in the boiler: fuels from the recovery of industrial waste, from the incineration of Municipal Solid Waste (MSW) or from biomass.

Alternative technologies have been developed [1, 7, 8, 9, 10]:

- **Combined cycles** consist of a gas turbine and a steam turbine: the heat recovered by the turbine exhaust allows to produce the steam to drive a steam turbine, simultaneously allowing a larger heat recovery or another operation (typically in summer) when all the recoverable heat is used to produce power. As a result, the electrical efficiency is higher but the thermal efficiency drops consequently [8].
- **Micro turbines** have an energy range of a few tens of kW. These compact, small-sized and light combustion turbines require very little maintenance. They are increasingly used and enable to reject heat at a higher temperature than internal combustion engines. However, their price is high for a relatively low electrical efficiency (about 25-30%), and their lifespan is limited (about 80,000 hours).
- **Micro Internal Combustion Engines** (ICEs) are a variation of micro turbines for small scale applications. Indeed, their lifespan and investment costs are similar, and their electrical efficiency is generally slightly higher (about 30%). However, they are noisier, they need a more regular maintenance and reject more greenhouse gases.

Other prime movers and development of new technologies

Other technologies exist to convert primary energy into electricity. Fuel cells [1, 8, 10] offer a higher electrical efficiency than turbines or internal combustion engines. They directly and silently convert hydrogen (used in most cases) into power without combustion. This technique is less polluting and, as soon as hydrogen is obtained, only heat and power are produced [7]. However, their price is high, their lifespan is limited, and they require regular maintenance. Nowadays, this technology is generally used for small-sized applications requiring a high power/heat ratio, and is gradually replacing Stirling engines for this energy range.

The cogeneration principle can also be applied to geothermal plants. The heat at the outlet end of the cycle of power production can indeed be recovered [11]. Today, studies focus on the application of this technique to plants with resources at low temperature in order to extend its use.

New forms of cogeneration are being developed, such as “solar” cogeneration, which consists of producing simultaneously both thermal and photovoltaic energy on the same area. These are quiet and non-polluting techniques. The solar energy, which is not converted into power and not reflected by photovoltaic cells, is transformed into heat at a very low thermal level. The recovery of this heat allows it to be used in many applications. Exhausting this heat can also allow the cooling of photovoltaic cells, thus improving the electrical efficiency of the system [12]. Moreover, solar energy is free and inexhaustible even though depending on sunlight. "Solar" cogeneration requires a high investment and is limited to small capacity applications. The cogeneration principle can also be applied to solar thermal systems alone: thermal energy is then converted into power and the output heat is recovered [11].

Later in this Note, we will discuss the co/trigeneration based on the main fuel-driven technologies.

Cooling technologies

For CCP (Combined Cold and Power) and CCHP, several technologies are used to convert heat into cooling [2, 3, 7, 9]. In most cases, sorption systems are resorted to. They are less noisy and less polluting than conventional compression systems driven by electrical energy, but they are more expensive and less effective. Indeed, their coefficient of performance (COP), which represents the ratio between the refrigeration effect and the consumed energy, is lower than that of compression systems (which have a COP between 2.5 and 5 [9]). Among these technologies, absorption and adsorption cooling stand out. They operate the same way as the conventional vapour compression refrigeration cycle where the main difference may be that thermal energy is the main driver of the cycle versus the mechanical work. Therefore, instead of a mechanical compressor, a generator/absorber pair or generator/adsorber pair and mechanical pump drive the working fluid [13].

- **Absorption systems.** Several absorbent-refrigerant couples are used. The water-ammonia couple has a low COP (0.2-0.65) [7]. It is suitable for medium and large-scale applications (industrial applications up to a few MW) at cooling temperatures below 5 °C. The lithium bromide-water couple is used for air conditioning (temperature over 5 °C) in buildings; it has a higher COP (0.7-1.2) [9]. Several types of absorption systems exist (single effect, double effect, triple effect...), so choosing different technologies is possible depending on the criteria of the investors, especially in terms of cost and efficiency.
- **Adsorption systems.** The silica gel-water couple is used and applications concern cold water demand up to 3 °C. Their COP is better than that of one-step lithium bromide absorption systems for low temperatures of hot water (65-85 °C) [9].

New technologies are being developed and used. Examples include vapour ejector refrigeration or desiccant cooling.

In order to align the cooling production with its demand, a compression system can be combined with the refrigeration system being used. In this case, the CCP or CCHP system usually ensures the base demand, whereas the compression system ensures the peak demand [8].

Benefits of co/trigeneration

Cogeneration offers many benefits. By recovering heat losses, the overall efficiency of cogeneration is very high and can reach values over 90% [14]. In addition to the power production (with an electrical efficiency of about 35%), a cogeneration unit recovers heat and enhances it. For comparison purposes, power plants have an electrical efficiency between 35 and 40% for coal and oil plants, and up to around 55% for gas combined cycles [9]. However, these conventional plants do not recover heat (their total efficiency and their electrical efficiency are equal). This increase of overall efficiency reduces the exploitation of primary sources, which grows dramatically with the boom in global energy consumption. Cogeneration allows fuel savings between 15 and 40% compared to a separate production of power and heat (an index is used in order to assess these savings and thus compare cogeneration with conventional production methods [15]). Moreover, the emission of greenhouse gases is lower than for a plant that produces heat and thermal power separately. Thus, the reduction of CO_2 emissions is significant. CHP saves around 200 million tonnes of CO_2 per year in Europe [16]. Furthermore, a recent study by the Oak Ridge National Laboratory revealed that cogeneration accounted for 9% of total U.S. electricity generating capacity in 2008, and estimated that increasing that share to 20% by 2030 would lower U.S. greenhouse gas emissions by 600 million metric tonnes of CO_2 (equivalent to taking 109 million cars off the road), compared to a more conventional production [1].

In order to demonstrate these benefits, we can compare the efficiency of a CHP plant with that of a separate production plant consisting of a power plant and a boiler (Figure 2). The cogeneration unit chosen is driven by natural gas and has an overall efficiency of 90% (electrical efficiency of 35% and thermal efficiency of 55%) and a power/heat ratio of 0.64. The separate production plant consists of a gas power plant with an electrical efficiency of 50% and a gas boiler with a thermal efficiency of 90%. To produce the same quantity of electricity and heat, the CHP plant chosen saves 24% [15] of primary energy (natural gas) compared to the separate production system, thanks to a major reduction of losses.

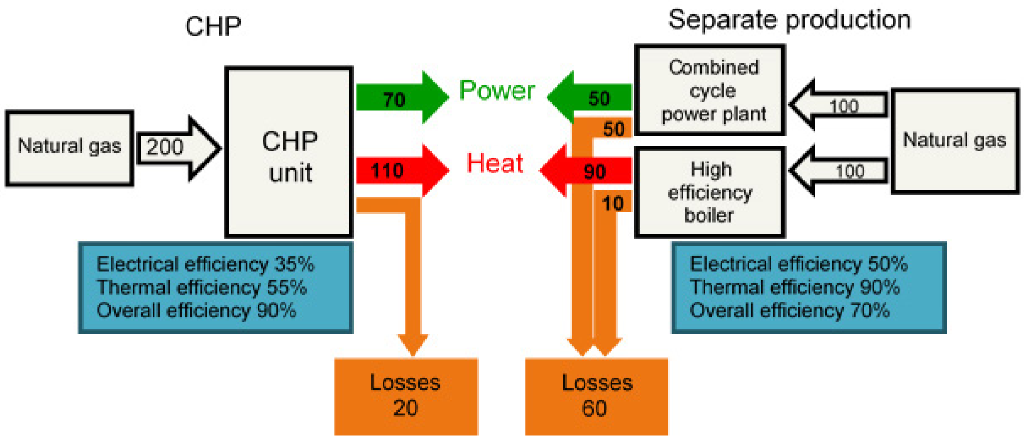

Figure 2: *Comparison between CHP and separate production of power and heat*

Furthermore, the development of cogeneration is also an opportunity to decentralize the power production. This reduces losses during energy transmission, especially during heat transmission [16]. In this way, transportation and distribution costs, as well as energy costs, are reduced. The technological innovation relating to the development of cogeneration also creates job opportunities.

Moreover, a local production ensured by cogeneration enables to guarantee energy security independently from the public grid, and energy autonomy consequently. Besides, this production supports the public grid especially during the peak periods by limiting the power demand of autoproducers and by providing the power excess to the grid.

Trigeneration offers the same benefits when a cooling need is added, but in a more significant way than cogeneration, thanks to the extension of the useful operating period of the plant all year long, which reduces the payback period. When a co/trigeneration plant is combined with a storage unit, the thermal losses decrease even more and the benefits mentioned above are amplified. However, the payback period assessment should take into account the cost of the absorption cooling system.

Thus, cogeneration and trigeneration are an effective way to fight global warming and to comply with the commitments made during the Kyoto Protocol and more recently during the COP 21 event.

Applications of cogeneration and trigeneration

Cogeneration

CHP can be applied to a lot of sectors which have a strong heat demand [15, 16]. We can classify different applications according to their electric output expressed in MWe [16, 18]:

- **Industrial cogeneration** (large-scale cogeneration >12 MWe and medium-scale cogeneration 1-12 MWe [19]): paper, chemicals, metal, combined food and petroleum refining industries usually represent more than two thirds of the total electric and steam capacities at existing industrial cogeneration facilities [15]. Indeed, these plants generally have high process-related thermal requirements that are not subject to daily or seasonal weather-related fluctuations.
- **Commercial, residential and institutional cogeneration** (small-scale cogeneration 215-1,000 kWe [19] and medium-scale cogeneration): the use of cogeneration in commercial buildings or residential complexes increases steadily because of technological innovations and related cost reductions. Cogeneration is effective for buildings requiring important quantities of heat and power such as universities, hospitals, airports, sports arenas, offices or governmental buildings.
- **Micro-cogeneration** (< 36 kWe [19]) and **mini-cogeneration** (36-215 kWe [19]): the development of small-sized cogeneration units, which can be set up in smaller buildings or even in individual houses, has grown steadily in the recent years. These installations can be easily integrated and may replace the boilers used previously. Micro-cogeneration and mini-cogeneration, due to their power level, are at the centre of technological development today, especially in Japan.

Furthermore, CHP connected to a district heating network can provide the heat excess to multiple customers in villages, city centres, industrial zones, towns and other built environments with a high demand for heat. This connection provides particularly significant CO_2 emission savings.

CCP (Combined Cold and Power) has few applications, and when the cooling demand is high, in most cases, a CCHP plant that focuses on cooling production is set up instead. Besides, if a heat need emerges, a CCHP unit will meet it more easily.

Trigeneration

Trigeneration is useful when a cooling need is added to the power and heat demand. It increases the energy efficiency of industries using refrigeration systems like food industries [10], especially for the food and drinks storage. In these industrial processes, the cooling demand is often more constant than the heat demand. Moreover, trigeneration has benefits for every building using air conditioning, which may consume a lot of energy during summer. Therefore, such an installation can be cost-effective for all sizes of buildings. Several independent studies highlight the trigeneration preference for data centres [20] and for applications such as airports [21], hospitals [4, 22], supermarkets [23], and even domestic usage [24]. The connection of a CCHP plant to a district heat and cooling network is, just like cogeneration, an interesting application for distributing heat and cooling and at the same time, reducing greenhouse gas emissions, in particular when replacing conventional vapour-compression chillers [9].

Cogeneration and trigeneration around the world

The cogeneration and trigeneration development in the world is relatively low (around 10% of the global power production is ensured by cogeneration plants), and it tends to stall since 2005. For instance, in the EU, the power production ensured by cogeneration has been stagnant between 360 and 393 TWh per year from 2005 to 2013 (382.02 TWh in 2013) and represents between 11% and 12% of the overall power production in EU. Heat production oscillates between 800 and 850 TWh per year in EU [6].

However, the distribution is heterogeneous. Some countries have invested significantly in these technologies and their power production is largely ensured by cogeneration, e.g. Finland (34.1%, i.e. 24.32 TWh in 2013 [6, 25]), Denmark (50.6%, i.e. 17.58 TWh in 2013 [6, 26]), Slovakia (77%, i.e. 22.20 TWh in 2013 [6]) or Russia (around 30% in 2008), which has inherited many cogeneration plants built in the Soviet Union [17]. The United States (10% of the power production is provided by more than 3,300 cogeneration plants, i.e. a power of 85 GWe in 2008 [27]), Germany (12.4%, i.e. 78.67 TWh in 2013 [6]), or Italy (22%, i.e. 63 TWh in 2012 [28]) have invested in cogeneration as well, but because of their high-energy consumption, the power production is also ensured by conventional plants [17]. The results in these countries follow a strong political will to engage in favour of cogeneration.

The development of these techniques depends on the political choices and the energy orientation adopted by governments. As a result, countries that have turned to nuclear power generation such as France [29] (where less than 5% of electricity is produced by cogeneration [6]) or South Korea (4.6% or 23.90 TWh in 2011 [30]), or countries preferring hydraulic power such as Brazil (less than 3% in 2008 [17]), have a lower potential for cogeneration or trigeneration than countries that are still using more conventional energies (coal, natural gas ...) like Germany [17].

The climatic and historical context also affects the choices made by governments. The strong development of CHP in Russia is a consequence of the existence of a huge district heating network and of the cold climate that prevails there [17]. The recent Fukushima nuclear disaster in Japan can affect the energy policy and can encourage the development of cogeneration, which is still developing very slowly at industrial level (less than 4% of power production is ensured by cogeneration [31]). The development of co/trigeneration could extend itself worldwide with the awareness of global warming and the benefits of these technologies. Emerging countries such as China, India or South Africa could experience a rapid increase in power production from cogeneration. According to the IEA (International Energy Agency), thanks to incentive policies, China could move from 13% in 2008 to 28% in 2013 and India from 5% (i.e. 10 GW [32]) to 26% [17]. South Africa could rise from almost nil to more than 15% [17].

Hurdles and challenges

Although cogeneration and trigeneration offer many advantages, whatever their current development in the different countries, there are some obstacles to their development.

First of all, the investment costs for new cogeneration plants are high and can discourage the different players involved in the process. These costs are even higher for CCP or trigeneration plants due to the high price of absorption or adsorption systems [9]. This significant cost of refrigeration systems suitable for CCP and CCHP is a major hurdle for their development. Moreover, initial, outdated CHP systems have to be replaced in some countries, which is rather expensive.

Furthermore, cogeneration and trigeneration have to compete with the current decrease in fuel and power prices, which extends the payback period [33]. Technical advances in traditional sectors like insulation and the development of renewable energies (hydraulic, solar, wind, etc.) reduce the appeal of co/trigeneration.

Thus, long-term visibility of price fluctuations in electricity and raw materials is necessary in order to properly assess the profitability of a co/trigeneration system and its payback period. Indeed, unpredictable price changes can discourage investors. The economic context can also impact the development of co/trigeneration: the recent economic downturn has had negative consequences on the development of these technologies.

Furthermore, from an ecological point of view, cogeneration and trigeneration plants compete with renewable energies, because they still release CO_2 and pollutants. The replacement of fossil fuels by renewable resources such as biomass, biogas or biofuels is developing and it is a major step forward in favour of these technologies [11, 34].

Finally, in order to encourage investors, the public grid should purchase the excess electricity produced by cogeneration and trigeneration systems at preferential and sustainable prices. Regulation of trade should be clear and precise in this regard. There is also a need to ensure a reliable and affordable supply of fossil fuel because these production systems still depend on this supply despite their decentralization.

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[15] Energy savings due to co/trigeneration plants can be expressed with an index which represents the relative saving of primary energy compared to separate production of heat, cold and power. This index is provided in the following formula:

$$I = \frac{P' - P}{P'} = 1 - \frac{1}{\frac{\alpha_E}{\eta_E} + \frac{COP}{COP_c}\frac{\alpha_Q}{\eta_E}\lambda + (1 - \lambda)\frac{\alpha_Q}{\eta_Q}}$$

where:

- P et P': quantity of primary energy consumed by co/trigeneration plant and respectively by separate production in order to meet heat needs (Q), power needs (E) and cooling needs (Pf)
- COP: coefficient of performance of the ab/adsorption refrigeration unit
- COPc: coefficient of performance of the compression refrigeration unit
- αQ et αE: thermal and electrical efficiency of the cogeneration unit
- ηQ et ηE: thermal efficiency (respectively electrical efficiency) of the boiler (respectively power plant)
- λ: share of heat produced by cogeneration converted into cooling; when this parameter is nil, there is no cooling production and this is a CHP plant. When it is equal to one, all of the heat is converted into cooling.

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Recommendations

To help develop cogeneration and trigeneration, governments have to take a stand, e.g., by empowering a specific department to encourage research and development with a focused financial support. They could also set up a specific policy on taxes applied to the energy produced from co/trigeneration and regulate the market of electricity and fuel for more stability on the long run. The potential stakeholders should be more systematically informed about the benefits of cogeneration and trigeneration, to promote these technologies as widely as possible.

Supporting research in this sector is very important in order to further improve the efficiency of these technologies and to reduce their cost, especially for absorption or adsorption cooling systems. Furthermore, the general trend of replacing fossil fuels by renewable energies would make cogeneration and trigeneration even more effective and attractive compared to the alternatives considered.

The development of CCP and CCHP systems has to be speeded up to meet the increasing need of cooling while protecting the environment. These technologies provide an opportunity to produce cooling and power (which remains a strong need around the world) in an ecological way.

The development of new forms of cogeneration and polygeneration offers worthwhile prospects to help fight against the global warming phenomenon and phase-down the exploitation of fuel.

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