



Energy and Environmental Performance Analysis of Industrial Cogeneration and Trigereneration Plants: The Impact of Actual Global Efficiency

Marco Noro^{1*}, Fabio Minchio²

¹ Department of Management and Engineering, University of Padova, Vicenza 36100, Italy

² 3F Engineering, Creazzo 36051, Italy

Corresponding Author Email: marco.noro@unipd.it

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ABSTRACT

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The use of cogeneration and trigereneration systems in industry, also due to favourable price conditions until 2021, has seen significant development over the past decade. However, if we analyse the final performance of a significant sample of plants, distributed across different industrial sectors (chemical, pharmaceutical, tanning, and others) and in district heating, it emerges that the average global efficiency of the plants is very often far from the 75% target. If from an economic point of view the impact is variable depending on the prices of the energy vectors, in terms of primary energy savings and, above all, the actual reduction of greenhouse gas emissions compared to separate generation, in some cases the results are much lower than expected. The paper presents an analysis of a set of cogeneration and trigereneration plants and highlights the variability of main drivers (primary energy, greenhouse gas emissions, and economic profitability) in function of the global performance, underlining the critical issues that also lead to a reduction in the final global efficiency compared to expectations.

1. INTRODUCTION

The use of cogeneration in Italy has shown significant development in the last decade, in particular due to a favourable situation in natural gas (NG) prices, abruptly interrupted with the peaks recorded between 2021 and 2022.

According to TERNA statistics [1], in 2023 a total of 6657 cogeneration plant sections are active (of which 2390 are self-producers), out of a total of 8406 thermoelectric sections (2552 self-producers). In terms of efficient installed power, this means that electric power installed in cogeneration plants is 26815 MW out of a total of 63212 MW. If we consider the total production of electricity from thermoelectric plants (168.3 TWh, the largest part by producers, 145.9 TWh), 57.2% is produced by cogeneration thermoelectric plants. Approximately 50.87 TWh of thermal energy is also produced, 7 TWh of which is heat that is not usefully utilised and so is wasted. With particular reference to internal combustion engines (ICE), they produce 13.2% of the total electricity (3.29 TWh produced by only electricity production plants + 18.98 TWh produced by CHP plants out of a total of 168.3 TWh) and 27% of the heat. In the industrial sector, this is undoubtedly the most widely used solution.

According to Eurostat 2021 data [2], out of the approximately 62 TWh of heat produced in Italy for industrial and district heating (DH) or cooling (DHC) uses, approximately 58 TWh come from cogeneration (corresponding to approximately 6 billion cubic meters of natural gas avoided).

As is well known, the combined production of electricity

and heat (combined heat and power, CHP) and the combined production of electricity, heat and cooling (combined heat, cooling and power, CHCP) by means of the available technologies allow for significant primary energy savings compared to separate generation. For example, in the study of Li et al. [3], a 100 kW proton exchange membrane fuel cell was coupled with a high temperature heat pump steam and power cogeneration system for industrial application. The performance in terms of heat production by the fuel cell and the system power output and efficiency were investigated by varying the fuel cell operating temperature and humidity. As a review paper, in the study of Chakraborty et al. [4], various cogeneration schemes and their implementation challenges were discussed with examples of studies from various countries.

Focusing on the studies of CHP and CHCP in Italy, Cannistraro et al. [5] evaluated the technical and economic feasibility of the integration of a cogeneration and trigereneration system fuelled with natural gas in an existing dairy industry, located in the north of Italy. Also the Authors of the present paper focused their research in cogeneration systems in the past by a comparison from the energy, economic, and environmental point of view between the gas engine heat pump integrated with the condensing boilers plant of one of the Department buildings with traditional systems [6]. In another study [7], the Authors focused on the comparison of the cost of heat and power produced by the main district heating technologies based on NG with that of producing the same quantity of electrical energy by a reference gas turbine combined cycle. The latter was intended to be the most

efficient technology for pure electrical production. The comparison also included the cost of production of heat by modern local NG based heating technologies like condensing boilers, electrical, gas engines and absorption heat pumps. More recently, the Authors focused on cluster analysis to analyse energy consumption data to design cogeneration systems more efficiently [8, 9], and on the coupling of a high-temperature heat pump with a combined cooling, heat, and power system [10].

As is known, in trigeneration systems, thermally driven cooling chillers produce cooling energy by recovering (part of) the heat from the prime mover (e.g., an internal combustion engine) [11, 12]. The absorption chiller is the most widely diffused technology for the generation of cooling from recovered heat [13, 14].

If we consider a modern ICE with a rated electrical power of 1 MW, it is characterised by an electrical efficiency of approximately 42-43% and an overall thermal efficiency (heat recovery from exhaust, engine and lubricating oil cooling, and intercooler) of 43-45%, for a nominal total efficiency (electric + thermal) of approximately 85-88%.

However, if we analyse the real performance data of CHP and CHCP plants based on ICE installed in different industrial contexts or serving district heating networks, it can be verified that the average annual total efficiency is actually lower and in some cases significantly compared to the nominal values.

1.1 Limiting factors for industrial cogeneration optimization

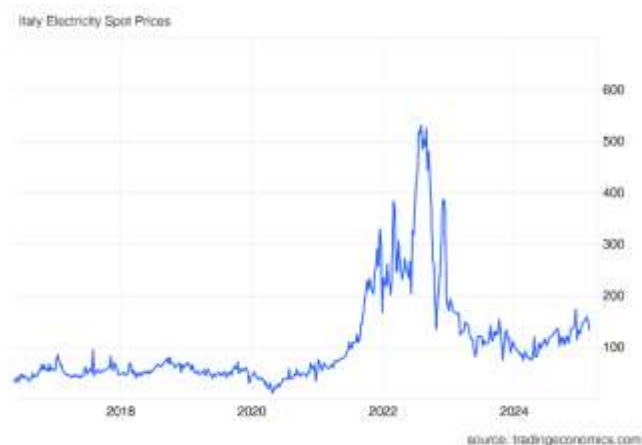
For those who deal with cogeneration from a strictly technical point of view, the objective has always been to guarantee a high plant operability (4000-5000 operating hours per year) and an overall first-principle efficiency of at least 75%. This is useful to achieve high primary energy savings and therefore economic profitability of investment with reference to EU Regulation 2015/2402 [15] and the Italian implementation of the EU cogeneration directive, the Ministerial Decree of 4 August 2011 [16]. As will be seen later, in reality, the achievement of these results does not correspond at all to the results obtained by many of the plants in operation. Therefore, it is interesting to analyse the very reasons that determine an energy performance that is often not in line with the parameters initially envisaged in the feasibility study and economic offer.

Clearly, the choices in the industrial sector are primarily of an economic nature: in the initial evaluation, priority is legitimately given to the simple pay-back, and only in more structured situations, to more significant financial mathematical parameters such as net present value or internal rate of return. In this sense, the impact of fuel prices is a critical factor, since, for the same investment, the impact of operating costs significantly modifies the results of technical and economic assessments. In Italy, electricity and natural gas costs are generally linearly correlated, as shown in Figure 1. However, in periods when NG prices are particularly low, the operation of CHP/CHCP systems can be assured even with a very high percentage of thermal energy dissipation. As a matter of fact, what should in principle be avoided from a technical and environmental point of view can instead have an interesting economic return. These conditions occurred especially between 2019 and 2020 (Figure 1) and determined a low overall performance efficiency of cogeneration plants.

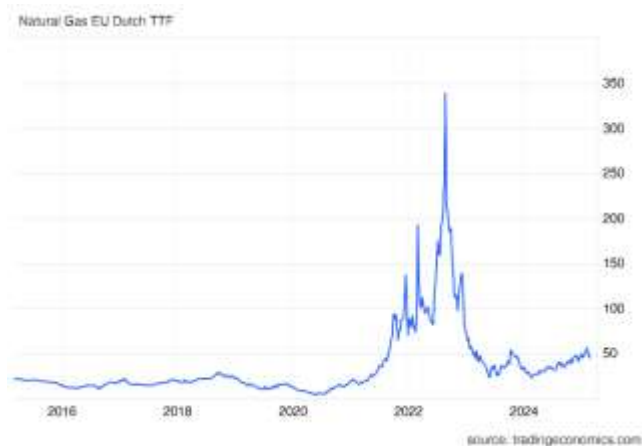
However, a very common reason for low energy

performance in real operating conditions is the presence of errors made in the initial assessment stage in determining thermal energy load. Especially in small power systems with an installed power lower than 200 kW, this can be due also to aggressive commercial actions coupled to the absence of a competent technician alongside the end customer, able to grasp the issue. In the design phase, the customer's focus is almost always or exclusively on self-production of electricity to avoid purchasing from the grid, unfortunately neglecting the thermal part. The result is a thermal efficiency that is often lower than the design value calculated when signing the contract. The reasons can be as follows:

- Objective difficulties in determining the thermal load profiles, whereas the electrical load curves are easier to build;



(a)



(b)

Figure 1. Italy electricity spot prices (EUR/MWh_e) (a) and Natural Gas EU Dutch TTF (EUR/MWh_p) (b) (updated to 5 March 2025)

- The difficulty in matching the thermal energy loads with the thermal levels that are made available by the cogeneration technology used. In particular, ICEs make available a significant part of the thermal energy recovered at temperatures on the order of 80-90°C. If there are no industrial thermal loads at this thermal level, part of the thermal energy produced by the cogenerator will be dissipated. In some cases, such uses are present only during the winter season. ICEs also make available thermal energy at higher temperature in form of pressurised water or water vapour by recovering heat from the exhaust (the consideration can also be extended to natural gas turbines): In this case, the minimum admissible

temperature of the outgoing exhaust is conditioned by the thermal level or by the steam pressure level of the user as can be highlighted by the pinch analysis. This causes energy losses at the chimney, as the exhaust still has a high residual enthalpy in cases where there is no thermal energy demand at a lower temperature that could be satisfied by introducing an additional economiser. Many industrial processes continuously use only steam at pressures above 6 bar, or diathermic oil at 300°C, significantly limiting the achievable thermal efficiency;

- The underestimation of the supplementary works necessary for the optimisation of the use of thermal energy on site. Often, the costs of creating the technical interface on the thermal side between existing plants and the cogenerator are not properly evaluated. This leads to budget overruns and a delay or postponement of works initially planned, necessary for a better use of thermal energy (for example, transformations of utilities from steam to hot water, new lines for space heating, etc.);

- Design errors, for example, in sizing the thermal storage or in the operation control logic of the auxiliary generators and the cogenerator. Other critical issues can be the correct correspondence between the temperature drops of the cooling circuit of the lubricating oil with that of the heated water (usually return water has to be maintained above 70°C to guarantee the correct viscosity of the lubricating oil). A similar issue can arise in coupling an alternative ICE and an absorption chiller due to the poor correspondence between the two temperature drops [17].

As a result, in many cases the combination of these factors determines a lower thermal efficiency than that calculated in the economic offers or in the feasibility analyses. This determines an overall efficiency lower than expected and also a reduction in the number of Energy Efficiency Certificates that the cogeneration unit could potentially have obtained.

1.2 Scope and novelty of the study

As the main purpose and novelty of this study, the real energy performance of twenty different cogeneration and

trigeneration plants that use internal combustion engines of different power ratings installed in industrial contexts and district heating networks is analysed. The objective is to evaluate the actual savings in (non-renewable) primary energy of this kind of plants and determine whether, considering the real operation that is often non-optimised, they allow a reduction in greenhouse gas emissions with respect to the separate production of electric, thermal, and cooling energy. Finally, the study verifies whether greenhouse gas emissions can be obtained in accordance with the requirements that will be imposed in the future.

2. METHODS

2.1 Cogeneration plants analysed

Twenty different cogeneration and trigeneration plants were analysed, all of which use ICE fuelled by NG. All the plants are subject to annual high efficiency cogeneration qualification (Cogenerazione ad Alto Rendimento in Italian, CAR), in compliance with the EU Regulation 2015/2402 [15] and the Ministerial Decree of 4 August 2011 [16].

As can be seen from Table 1, the nominal electrical power varies from a minimum of 50 kW to a maximum of 3.36 MW. The applications span across various industrial sectors (chemical, food, tanning in particular), and the performance data of cogeneration units used in district heating plants are also reported. Data are reported anonymously, in compliance with the confidentiality required, given that for the purposes of the analysis presented, highlighting the geographical location or the name of the owner of the plant does not add significance.

As reported in Table 1, there are also trigeneration plants (using single-effect LiBr-H₂O absorbers), one in particular (number 8) operates exclusively for the production of cooling energy. In some cogeneration plants used in DH systems, high-temperature heat pumps have also been included that use the second stage of the engine intercooler as a heat source.

Table 1. Rated data of the twenty CHP/CHCP plants (in italics the thermally driven cogeneration system)

#	Industrial Sector	Electric Power (MW _e)	Thermal power (Hot water) (MW _t)	Thermal Power (Vapour) (MW _t)	Cooling Power (Trigeneration) (MW _c)	HP Intercooler (MW _t)	Year First Operation
1	Chemical	2.679	1.430	1.05	0		2016
2	<i>Food</i>	<i>0.05</i>	<i>0.098</i>	<i>0</i>	<i>0</i>		<i>2015</i>
3	Food	0.801	0.555	0.448	0		2015
4	Tanning	0.2	0.341	0	0		2014
5	Tanning	0.399	0.22	0.22	0		2019
6	Electric components	3.201	3.384	0	1.36		2017
7	Chemical	2	0.615	1.395	0		2016
8	Processing of plastic materials	3.343	0	0	2.288		2016
9	Mechanical	1.501	0.191	0.56	0.72		2018
10	Surface treatments	0.854	0.447	0.53	0		2018
11	Chemical	0.772	0.19	0.402	0.315		2014
12	Agri-Food	3.3	2.216	0.948	0		2021
13	Hospital	0.851	0.489	0.515	0.285		2018
14	<i>Food</i>	<i>0.238</i>	<i>0.363</i>	<i>0</i>	<i>0</i>		<i>2021</i>
15	<i>Food</i>	<i>0.14</i>	<i>0.207</i>	<i>0</i>	<i>0</i>		<i>2021</i>
16	DH	2.83	2.996	0	0	0.252	2018
17	DH	0.851	0.947	0	0	0.131	2018
18	DH+Hospital	1.067	0.649	0.546	0		2019
19	DH+Hospital	1.5	0.89	0.613	0	0.201	2018
20	Paper mill	3.36	1.476	1.818	0	0	2018

Table 2. Operating hours, mean operating rate, energy production and consumption of the plants in the representative operation year

#	Operating Hours	Mean Operating Rate	Electric Energy Produced (MWh _e)			Thermal Energy Produced (MWh _t)	Cooling Energy Produced (MWh _c)	NG Consumed (non-Renewable Primary Energy) (MWh _p)
			Total	To the Grid	Self-Consumed			
1	7948	98.1%	20887	0	13011	13011	0	48988
2	3721	98.5%	183	41	343	343	0	652
3	3793	94.5%	2871	209	2920	2920	0	7575
4	2054	95.1%	391	12	464	464	0	1182
5	4399	87.6%	1537	4	1161	1161	0	3798
6	6544	85.3%	17870	210	4303	4303	2102	44914
7	4727	84.5%	7993	4	5312	5312	0	20077
8	8407	99.3%	27916	0	0	0	15903	66115
9	4174	84.4%	5286	27	1812	1812	1269	13484
10	5314	88.5%	4016	5	1752	1752	0	9755
11	4806	83.5%	3098	108	2043	2043	1059	7976
12	7983	99.8%	26300	6803	13622	13622	0	62710
13	7783	99.8%	6610	3	4265	4265	796	17313
14	7550	49.9%	897	1	1875	1875	0	3103
15	1983	65.7%	182	0	328	328	0	590
16	7835	87.4%	19373	0	16678	16678	0	47994
17	6885	98.7%	5782	123	6593	6593	0	14963
18	7930	99.2%	8393	558	9814	9814	0	21677
19	6489	99.0%	9632	3727	9626	9626	0	23199
20	5884	99.3%	19623	2245	9652	9652	0	45080
Total			188841	14081	174760	105574	21130	461143

Among the twenty plants of the sample for this analysis, there are three small plants, indicated in Table 1 in italics (n. 2, 14, and 15), which are exclusively thermally driven, due to the lack of the heat dissipation circuit. All the other plants can operate with strategies chosen by the operator, as they are equipped with dissipation circuits.

2.2 Plant operation performance data

For each plant, the performance data for the last year of operation, or of a representative year if the last one was characterised by technical problems or significant failures, were considered. For all plants, the year reported is representative of all the other years of operation of the unit in which there were no anomalies or particular situations (for example, the period from the end of 2021 to 2022, when some plants were stopped due to the peak of natural gas prices).

Data relating to energy performance for a whole year are reported in Table 2.

The average annual number of operating hours is 5795, with a minimum of 1983 and a maximum of 8407. The average value of the mean operating rate is 89.9%. This high value highlights the very intensive use of cogeneration plants in the industrial sector to recover the economic investment as soon as possible. It should be noted that conversion of NG into (non-renewable) primary energy in Table 2 is carried out on the basis of the actual value of the lower heating value, communicated for each plant by the network operator with reference to the regulation and measurement NG cabin (cabina di Regolazione e Misura in Italian, REMI) to which the engine power point of delivery (Punto Di Riconsegna in Italian, PDR) is connected.

With regard to operating strategies, it can be observed that almost all industrial plants, excluding the three without a dissipation circuit (n. 2, 14 and 15), operate in electrical driven mode, with the aim of minimising the injection of electrical energy into the grid (Table 2). The plants connected to district

heating networks have high percentages of electrical energy injected into the grid, as in that case the primary objective is to produce thermal energy for the network, in the face of limited electrical loads present in the plant. This is the case of plant n. 19, whereas n. 16, 17, 18 are particular cases in which the electrical utility is a utility efficient system (Sistema Efficiente di Utenza in Italian, SEU). They are electrical systems connected to the public grid, characterised by the presence of at least one electricity production plant and a consumption unit (consisting of one or more real estate units) directly connected to each other, within which the transport of electricity is not configured as a transmission and/or distribution activity, but as an energy self-supply activity.

3. RESULTS AND DISCUSSION

3.1 Assessment in terms of energy efficiency

With regard to the electrical, thermal and total efficiency data, they have been determined in accordance with the CAR methodology (detailed in Ministerial Decree 4 August 2011, [16], Ministerial Guidelines [18] and GSE Guide [19]). In particular, the total efficiency value is a “first principle of thermodynamics” efficiency, that is it is the sum of electric and thermal efficiencies. In the context of the aforementioned CAR methodology, in the case of internal combustion engines, a total efficiency threshold value equal to 75% is decisive. The whole quantity of electrical energy produced by the plant is considered cogenerated only if this threshold is exceeded. This is essentially a target that identifies the achievement of a minimum level of optimization of the production and utilization of thermal and electrical energy. A lower value of the overall efficiency compared to this threshold does not directly determine the non-assignment of the CAR qualification: in that case the algorithm of the Ministerial Decree [20] provides for the creation of a virtual cogeneration

machine on which the Primary Energy Saving (*PES*) index is determined (see next section).

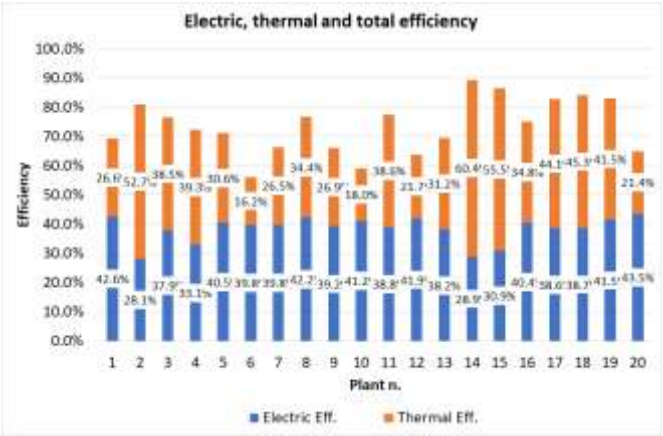


Figure 2. Electric, thermal and total efficiency of the plants

The value of 75% of the overall efficiency is that it would be desirable for an efficient cogeneration plant to reach. It can also be highlighted that this is a global efficiency value, significantly lower than the nominal performance of a typical ICE, which, as stated before, is generally higher than 85%. It would therefore be reasonable to expect that the cogeneration units would reach it. Instead, the analysis of the data reported in Figure 2 highlights that only half of the plants exceed an overall efficiency of 75%, and among these only six exceed an overall efficiency of 80%. It is interesting to note that, with the exception of a plant in the food industry of about 800 kW_e (n. 3) and a plant with an absorption chiller for the plastics industry (n. 8), all the others exceeding the threshold value essentially belong to two categories:

- Cogeneration plants with power up to 240 kW_e built without a dissipation circuit, therefore operating exclusively in thermal load driven mode (plants n. 2, 14 and 15 as cited in the previous section). Due to their intrinsic technical characteristics, this type of cogeneration units always operate with high overall efficiency, because in the absence of thermal demand, the engine operates in a partial mode or switches off;
- Cogeneration plants serving district heating networks and/or hospitals: in this case, the plant is operated on a thermal load base (that is always present) and is possibly turned off in the summer months.

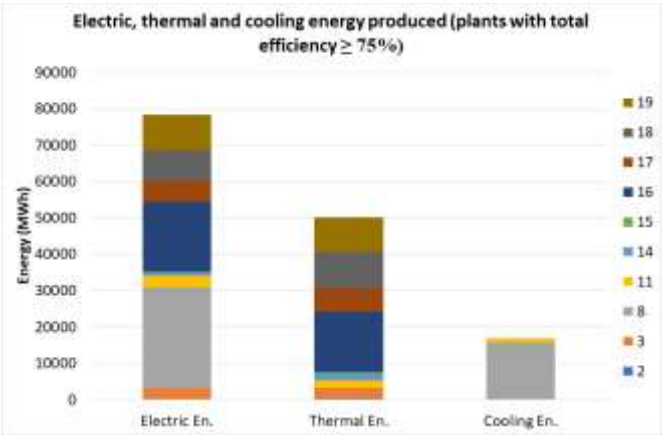


Figure 3. Electric, thermal and cooling energy produced by plants with total efficiency $\geq 75\%$

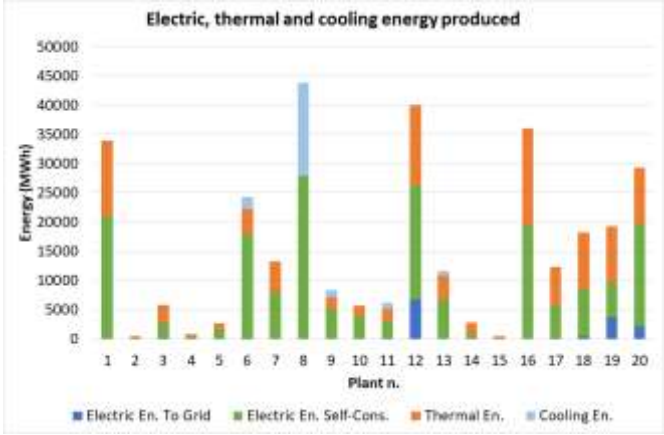


Figure 4. Electric (divided into self-consumed and to the grid), thermal and cooling energy produced by the plants

If we consider the total electrical energy produced by the group of twenty plants analysed, plants with overall efficiency greater than 75% produce just over 41% of the electrical energy (Figure 3, Figure 4, and Table 2).

While electrical efficiency values do not involve any particular surprises and engines perform in line with the nominal characteristics indicated by the manufacturer, thermal efficiencies feature values that can be even much lower than the nominal ones (Figure 2). This can also be appreciated in Figure 5 that shows the electric and thermal efficiency as a function of the nominal electrical power of the system. ICEs with nominal electrical power of less than 400 kW_e typically have electrical efficiencies that are well below 40%. There is surely a certain variability in the efficiencies as a function of the brand of the ICE. Anyway, these are also the plants that typically present the highest thermal efficiency. Above approximately 400 kW_e, the electrical efficiency of units is greater than 38%, whereas thermal efficiency is lower than 45% (and, in most cases, lower than 40%). Choosing an ICE with higher electrical efficiency can be an optimal choice, especially in the presence of variable thermal demand, to improve the overall efficiency.

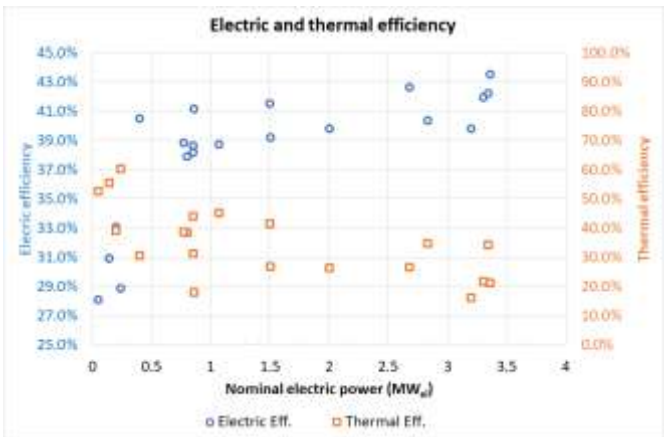


Figure 5. Electric and thermal efficiency as a function of the nominal electric power of the plants

3.2 Assessment in terms of primary energy

The main objective of a cogeneration plant is to achieve (non-renewable) primary energy savings compared to the separate generation of electric and thermal energy.

The assessment of primary energy savings can be carried out by calculating the *PES* (Primary Energy Saving index), that is, the (non-renewable) primary energy saved using CHP technology with respect to the separate production of the same quantities of useful energy. It is determined pursuant to the Delegated Regulation 2015/2402 [15], in addition to the Ministerial Decree of 4 August 2011 [16] and related operating guides. The methodology will also have to be updated, even if not substantially, with the implementation of Directive EED III 2023/1791 [21]. The *PES* is calculated by Eq. (1):

$$PES = \frac{\frac{E_{CHP}}{\eta_{ref,el}} + \frac{H_{CHP}}{\eta_{ref,t}} - F_{CHP}}{\frac{E_{CHP}}{\eta_{ref,el}} + \frac{H_{CHP}}{\eta_{ref,t}}} = 1 - \frac{1}{\frac{\eta_{CHP,el}}{\eta_{ref,el}} + \frac{\eta_{CHP,t}}{\eta_{ref,t}}} \quad (1)$$

where:

- E_{CHP} is the electric energy produced by the cogeneration unit;
- H_{CHP} is the useful thermal energy produced by the cogeneration unit;
- F_{CHP} is the energy of the fuel used by the cogeneration unit ((non-renewable) primary energy);
- $\eta_{ref,el}$ is the average conventional efficiency of the Italian electricity production park. For each plant, the value relative to first year of operation has been assumed (values that for NG are in the range 0.48-0.50 according to Annex I corrected to adapt to the average climatic conditions of each Member State (Annex III) and to take into account avoided grid losses (Annex IV) of Commission Delegated Regulation (EU) 2015/2402) [22];
- $\eta_{ref,t}$ is the average conventional efficiency of the Italian thermal production park, assumed to be 0.90 in the case of steam / hot water;
- $\eta_{CHP,el}$ and $\eta_{CHP,t}$ are, respectively, the electric and thermal efficiency of the CHP unit.

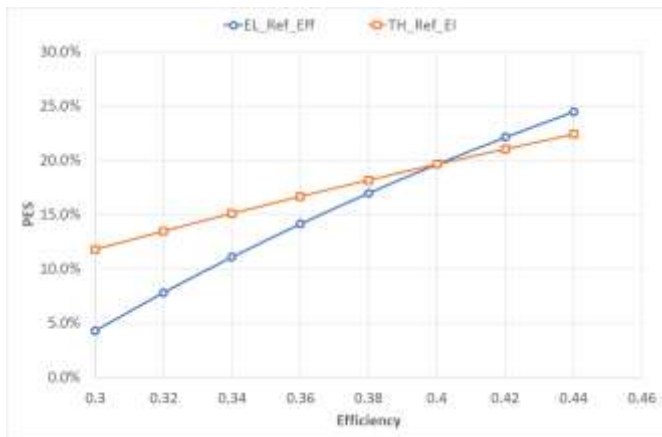


Figure 6. Trend of the *PES* varying the electric and thermal efficiency of the CHP unit ($\eta_{ref,el} = 0.50$; $\eta_{ref,t} = 0.9$)

To guarantee the CAR qualification, the *PES* index must be equal to at least 10% for cogeneration units with a generation capacity greater than 1 MW_e and greater than 0% for smaller cogeneration units. When considering ICE cogenerators like in this study, it is not difficult to satisfy these values. In fact, due to the calculation procedure, the *PES* greatly depends on

the electrical efficiency, which in the case of ICEs is in any case quite high (Figure 6). In fact, even in the presence of a significant percentage of heat dissipation, with overall efficiency lower than 75%, it is not difficult to obtain a *PES* greater than 10% due to the creation of a “virtual unit” in the calculation process. In this case, in Eq. (1) E_{CHP} does not correspond to the entire value of electric energy produced in the reference period by the cogeneration unit. Instead, it is determined as the lowest value between the total amount of electric energy produced and the quantity $H_{CHP} \cdot C_{eff}$ where C_{eff} is the ratio between the useful electrical and thermal energy produced by the ICE in the reference period.

In any case, with an overall efficiency lower than 75%, the cogeneration unit is penalised by a reduced number of Energy Efficiency Certificates (*CB*, Eq. (2)) obtained pursuant to the Ministerial Decree of 5 September 2011 [20]. These are calculated using the parameters *RISP* (that quantifies the (non-renewable) primary savings) and *K* (Eq. (3)):

$$CB = RISP \cdot 0.086 \cdot K \quad (2)$$

where:

$$RISP = \frac{E_{CHP}}{\eta_{ref,el}} + \frac{H_{CHP}}{\eta_{ref,t}} - F_{CHP} \quad (3)$$

and *K* is the harmonization coefficient set equal to:

$K = 1.4$ for power shares up to 1 MW_e;

$K = 1.3$ for power shares greater than 1 MW_e and up to 10 MW_e;

$K = 1.2$ for power shares greater than 10 MW_e and up to 80 MW_e;

$K = 1.1$ for power shares greater than 80 MW_e and up to 100 MW_e;

$K = 1$ for power shares greater than 100 MW_e.

It is in the Authors' opinion that a better evaluation of the actual primary energy savings of cogeneration is obtained if the entire quantities of the electric, thermal and cooling energy produced by the CHP plant are considered regardless of the creation of the virtual unit. In this study, a new primary energy saving index (*PES_{new}*) is calculated with the following yields for separate generation (Eq. (4)):

$$PES_{new} = \frac{\frac{E + \frac{C}{EER}}{\eta_{ref,el}} + \frac{H}{\eta_{ref,t}} - F}{\frac{E + \frac{C}{EER}}{\eta_{ref,el}} + \frac{H}{\eta_{ref,t}}} \quad (4)$$

- Reference thermal energy generation efficiency ($\eta_{ref,t}$), fixed at 90%;

- Conversion factor of electric energy into primary energy equal to 1.9 as defined by the EED III Directive (article 31, paragraph 3) [21], corresponding to a reference electric efficiency $\eta_{ref,el} = 52.632\%$;

- Average seasonal reference value for the Energy Efficiency Ratio (*EER*) of the electric chiller for the production of cooling energy fixed at 3.5. In the case of plants in the plastics sector, where free-cooling is also used, the value is considered equal to $EER = 5$;

- *E* is the gross electric energy produced [MWh_e];

- *C* is the cooling energy produced by the absorption chiller in the case of trigeneration systems (zero in other cases)

[MWh_c];

- H is the useful thermal energy produced [MWh_t];
- F is the (non-renewable) primary energy of NG entering the system [MWh_p].

The results are shown in Figure 7. As can be observed, the PES values are well above the 10% threshold (minimum value approximately 13% for the lower power cogenerator) because the algorithm depends much more on the electric efficiency than on the global efficiency. As a matter of fact, even systems with very low global efficiency, with the virtual cogeneration unit, reach sufficiently high PES thanks to the good electrical efficiency of the medium-large sized motors they use.

The new index here proposed (PES_{new}), which does not consider the virtual cogeneration unit in the calculation procedure, features very different results.

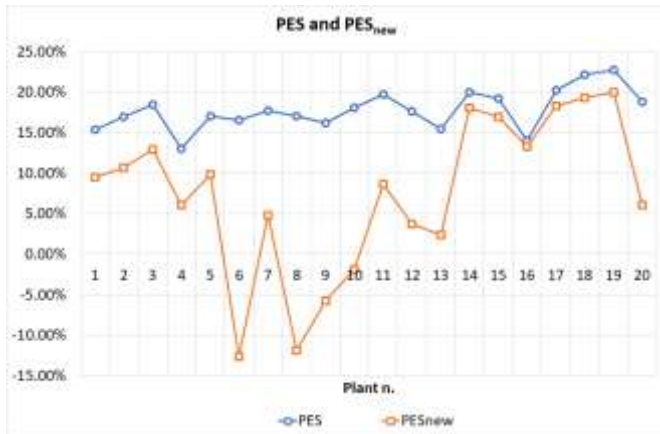


Figure 7. PES and PES_{new} for the plants considered in the study

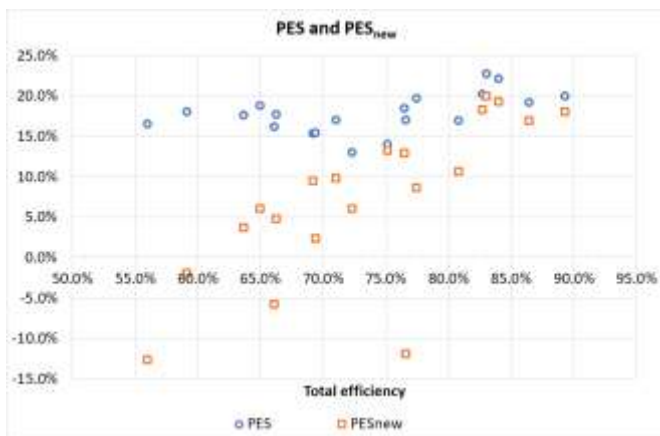


Figure 8. PES and PES_{new} as a function of the total efficiency of the plants

In fact, there is generally a positive primary energy saving, with maximum values around 20%, in particular for district heating systems (n. 17, 18, 19). For such plants, PES and PES_{new} assume quite similar values (Figure 7). The only systems in which there is no primary energy savings are those in which the production of cooling energy by trigeneration is predominant (n. 6, 8, 9). In fact, for these plants PES_{new} is negative even if PES is greater than 15%, despite the fact that the average annual EER chosen for the separate production of cooling energy is not particularly high. It is important to highlight that trigeneration, in contexts such as the plastics sector, replaces or integrates press oil circuit cooling systems,

where it is very often possible to guarantee almost complete coverage of the annual cooling demand through adiabatic free-cooling [23]. Although from an economic point of view this type of choice may be valid (because there is self-production of electricity), from an energy point of view it is hardly justifiable. In this case, the difference between PES and PES_{new} is related to the criterion with which the production of cooling energy is accounted for: according to the CAR methodology, the thermal energy supplied to the generator of the absorption chiller is considered, whereas, according to the PES_{new} calculation, the cooling energy produced is considered. As a matter of fact, the lower the EER of the absorption chiller, the greater the contribution in terms of useful heat, and the higher the PES . Instead, the calculation of the PES_{new} refers to the cooling energy produced and a reference EER .

As a main conclusion, obtaining a high overall efficiency and, in the case of trigeneration with single-effect absorption chiller, having a non-preponderant use of cooling energy are mandatory conditions to guarantee actual primary energy savings with cogeneration (Figure 8).

3.3 Assessment in terms of greenhouse gas emissions

3.3.1 Specific emissions

The future of cogeneration technology in Europe is highly conditioned by decarbonisation objectives and compliance with the DNSH (Do Not Significant Harm) principles [24].

The main issue is the use of natural gas as fuel, which determines a non-negligible impact in terms of greenhouse gas emissions. The European Directive EED III 2023/1791 [21] in Annex III reports the evolution of the criteria for obtaining the CAR qualification:

- The primary energy savings must be equal to at least 10% compared to the reference values for the separate production of electricity and heat; only for small cogeneration (nominal electric power less than 1 MW_e) and micro-cogeneration (nominal electric power less than 50 kW_e) units it will be sufficient to achieve a primary energy saving greater than zero;
- In case of construction or retrofitting of cogeneration units after the transposition of Annex III of the EED III Directive, direct CO₂ emissions from fossil fuel-fired cogeneration production must be less than 270 gCO₂/kWh of energy produced by combined generation (including heating/cooling, electricity and mechanical energy);
- Cogeneration units in operation before 10 October 2023 may derogate from this requirement until 1 January 2034, provided that they have a progressive emission reduction plan to comply with the threshold of less than 270 gCO₂/kWh by 1 January 2034 and that they have notified this plan to the relevant operators and competent authorities.

As a matter of fact, the determination of the direct emission factor of equivalent greenhouse gases is a key factor for new CHP/CHCP plants. Even existing plants will have to prepare to meet the targets imposed. It is therefore interesting to understand whether, by using national average equivalent greenhouse gases emission factors, the cogeneration plants are already able to guarantee the value of 0.27 tCO_{2eq}/MWh, or are able to ensure a reduction of emissions compared to the separate generation scenario. In the actual absence of national implementation, what is indicated in the EED III Directive is interpreted by the Authors as follows (Eq. (5)):

$$EmCO2_{CHP} = \frac{F \cdot EmCO2_{NG}}{E + H + C} \quad (5)$$

where, in addition to the variables previously defined:

- $EmCO2_{CHP}$ is the average equivalent CO_2 specific emissions of the cogeneration plant expressed in t_{CO2eq}/MWh ;
- $EmCO2_{NG}$ is the average equivalent CO_2 specific emissions relating to the combustion of natural gas, determined on the basis of the 2023 national standard parameters published by the Ministry of the Environment and Energy Security and equal to $2.004 t_{CO2eq}/1000 Sm^3$ with Lower Heating Value (LHV) equal to $8.469 MCal/Sm^3$ [25]. The factor is therefore equal to $0.20345 t_{CO2eq}/MWh_p$.

The values of the twenty plants analysed are shown in Figure 9. It can be observed that there are approximately ten plants already able to satisfy the requirement imposed in terms of greenhouse gas emissions (i.e., specific emissions are below the black line). It is interesting to note the existing correlation between specific emissions and total plant efficiency (Figure 10): An overall efficiency greater than 75% allows the achievement of the emission factor required by the EED III.

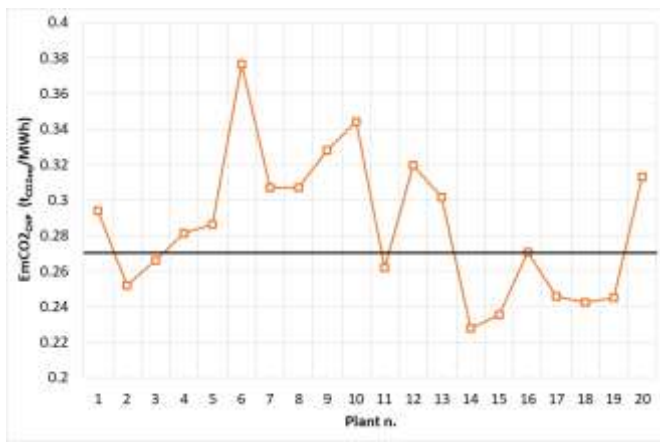


Figure 9. Equivalent CO_2 specific emissions for the plants

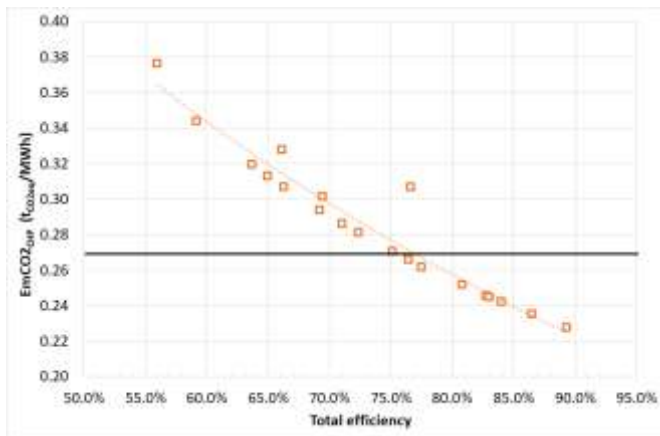


Figure 10. Equivalent CO_2 specific emissions in function of the total efficiency of the plants

3.3.2 Emissions saving with overall average factors

In addition to the specific emission factor, it is interesting to understand whether the operation of the CHP/CHCP plants considering the actual greenhouse gas emission factors may allow for an effective savings in greenhouse gas emissions with respect to separate generation. In this sense, the choice of the equivalent CO_2 emission factor for the electric energy withdrawn from the grid is critical. If we consider the overall average values, we can find different references:

- At the national (Italian) level, the two values of the emission factor referring to the year 2023 are a) $0.2363 t_{CO2eq}/MWh_e$ (based on electricity consumption) or b) $0.4591 t_{CO2eq}/MWh_e$ (based on gross thermoelectric production by fossil fuels) [2];
- At the European level, the average value published by the European Environment Agency, equal for 2022 to $0.288 t_{CO2eq}/MWh_e$ [26].

The European average value is not very different from the national one based on electricity consumption; therefore, the national values will be used in the analysis. As a matter of fact, the two values indicated (a: on final electricity consumption and b: on thermoelectric production from fossil fuels only) represent, respectively, the average situation and, in terms of marginal emission factor, the most favourable situation for a cogeneration plant. In fact, it can be assumed that the electricity not produced by the cogenerator can be withdrawn from the grid by: a) considering the average emission factor relating to electricity consumption or b) considering the emission factor associated with electricity produced by gas turbine thermoelectric plants, i.e. systems that can be quickly activated and connected to the network (marginal emission factor).

Figure 11 reports the emissions of the CHP/CHCP plants and those of the separate production considering the two emission factors. It can be seen that, if we consider the average greenhouse gas emission factor based on consumption, no plant allows for a reduction in emissions (black squares in Figure 11). Instead, considering the emission factor of thermoelectric production, all plants have savings that in most cases are around or greater than 20% (green circles in Figure 11). If the actual significant share of renewable electricity in electricity consumption is taken into account, cogeneration is a technology that is not effective in decarbonisation, not even with very high global yields. On the contrary, when a comparison is made with thermoelectric production from fossil fuels without heat recovery, a benefit is always found.

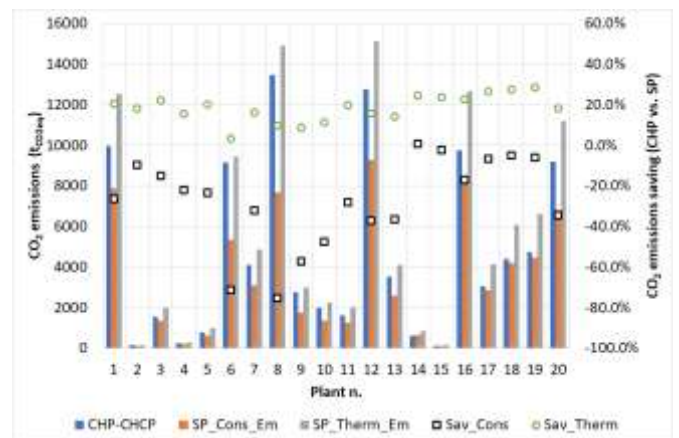


Figure 11. Equivalent CO_2 emissions for plants with respect to separate production with the two emission factors

It should be noted that in the hypothesis of electricity imported from the grid with a guarantee of origin from a renewable source according to the principles of the carbon footprint, a zero emission factor for greenhouse gas emissions is considered. As matter of fact, in these cases it would be more advantageous to withdraw electric energy entirely from the grid instead of operating the CHP plant.

3.3.3 Emissions savings with hourly average factors

In a future perspective in which the issue of greenhouse gas emissions will assume increasing importance, the choice of the emission factor to be used in the comparative analysis and for the operation of plants represents a fundamental step.

In this regard, the use of hourly emission factors and marginal emission factors in place of national or European average values has already been proposed in the literature. The study by Alikhani et al. [27] analysed how to determine marginal emission factors on electricity production. Furthermore, the same study highlighted that, at least until recent years, the prices of natural gas and of emission quotas in the Emission Trading System are still the main drivers that modify the choices of operation of plants. The study observed how the increase of penetration of renewables will increase the weight of the latter in determining the marginal emission factors.

The work of Peters et al. [28] addressed the issue of the impact of marginal emission factors in the analyses of different technologies, in this case with reference to photovoltaics. A first consideration is related to the use of hourly data rather than annual average values; in general, the analysis showed that the use of emission factors on the average generation mix with an hourly step, especially for non-programmable technologies, can lead to a lower quantification of the benefit in terms of decarbonisation, highlighting how the use of annual average values overestimates the latter. Instead, if the marginal hourly emission factors are used, the considerations are reversed.

Visualization of hourly data and marginal emission factors is possible in real time from applications such as electricityMap, available at <https://app.electricitymaps.com/map> [29].

Thanks to the data obtained from the application, the average hourly greenhouse gas emission factors for electricity production were determined monthly, divided by working days, Saturdays and Sundays, as well as by holidays (Table 3). Note that these are average data and not marginal emission factors (not available at the time of writing). The months with the highest emission factors are January, February, and March, with a maximum peak of 0.440 tCO_{2eq}/MWh_e; the impact of photovoltaic production in the central hours of the day is clearly appreciable. It can also be observed that greenhouse gas emission factors on days other than working days are generally lower. Figure 12 shows the maximum, minimum, and average hourly values for the whole year 2023.

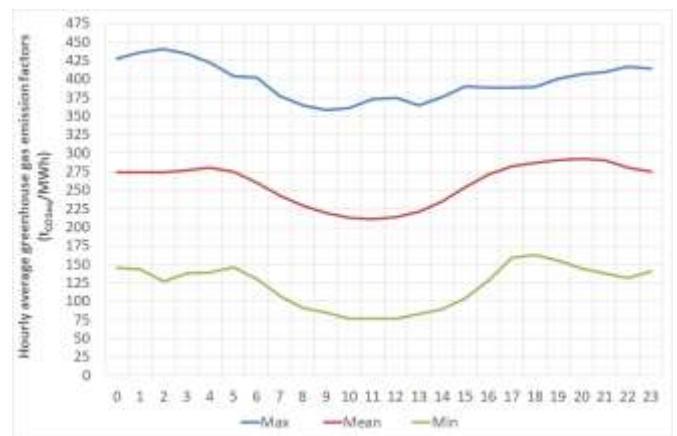


Figure 12. Greenhouse gas emission factor for electricity production per hour, maximum, minimum, and average annual values – Italy year 2023 (elaborated from Electricity Maps data, 2023)

Table 3. Hourly average greenhouse gas emission factors for electricity production in Italy– year 2023 - (elaborated from Electricity Maps data, 2023)

Month/	WORKING DAY [tCO _{2eq} /MWh _e]																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
January	349.	353.	354.	354.	355.	350.	349.	330.	317.	310.	308.	310.	311.	315.	326.	333.	334.	336.	340.	346.	343.	345.	345.	342.
February	374.	377.	375.	372.	372.	368.	354.	331.	317.	311.	303.	302.	301.	309.	324.	340.	351.	350.	351.	360.	364.	369.	373.	372.
March	343.	343.	340.	340.	344.	342.	320.	294.	278.	265.	255.	249.	248.	259.	273.	295.	321.	330.	333.	339.	343.	344.	340.	335.
April	261.	259.	260.	266.	275.	268.	246.	226.	213.	199.	187.	182.	186.	191.	201.	223.	251.	267.	270.	274.	280.	279.	268.	263.
May	225.	226.	231.	237.	244.	233.	213.	205.	197.	184.	168.	172.	180.	185.	199.	217.	235.	248.	259.	259.	261.	254.	235.	230.
June	281.	281.	280.	290.	292.	276.	252.	241.	228.	219.	213.	215.	220.	222.	232.	251.	272.	289.	304.	307.	321.	318.	296.	286.
July	291.	284.	286.	292.	295.	282.	260.	248.	239.	233.	229.	227.	232.	234.	243.	255.	272.	294.	303.	305.	315.	311.	293.	291.
August	269.	267.	264.	269.	275.	263.	240.	217.	201.	191.	188.	186.	187.	192.	204.	228.	253.	277.	286.	288.	294.	291.	280.	275.
September	273.	272.	273.	282.	299.	299.	279.	259.	246.	236.	223.	220.	225.	235.	252.	274.	301.	312.	313.	313.	310.	300.	271.	264.
October	254.	253.	254.	262.	274.	279.	267.	254.	243.	231.	222.	218.	226.	237.	253.	275.	285.	288.	288.	288.	283.	276.	261.	253.
November	215.	217.	218.	219.	221.	240.	246.	236.	225.	217.	212.	209.	213.	224.	241.	253.	256.	257.	257.	256.	247.	234.	226.	210.
December	244.	246.	245.	247.	255.	268.	279.	271.	262.	254.	251.	252.	254.	266.	277.	284.	279.	280.	281.	282.	275.	267.	257.	244.

SATURDAY [tCO _{2eq} /MWh _e]																								
Month /Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
January	335.8	338.2	337.1	335.7	332.9	328.7	322.8	308.0	296.2	285.0	278.4	279.7	287.2	295.8	311.1	326.4	321.9	315.9	319.4	329.0	334.5	338.6	352.5	351.6
February	336.5	337.9	341.2	346.2	346.0	338.4	322.0	304.2	287.1	274.7	265.5	263.4	260.5	263.4	280.1	304.1	318.3	313.1	313.4	321.0	326.6	328.9	336.4	324.9
March	329.5	328.8	323.9	319.8	315.1	310.9	286.5	250.2	222.7	208.6	204.1	207.6	209.5	217.4	231.5	257.3	308.1	323.0	320.4	326.9	340.4	348.2	352.9	348.9
April	237.8	231.8	228.1	229.1	233.6	219.2	195.0	175.9	151.3	135.8	130.2	129.8	130.2	133.2	148.3	179.2	216.1	236.3	243.9	248.5	254.2	257.2	244.7	239.7
May	198.2	190.4	193.5	202.5	194.2	184.0	169.7	155.6	140.3	121.4	130.7	121.8	122.7	132.7	144.2	163.8	188.5	214.4	218.8	216.9	216.9	218.9	198.4	195.3
June	214.4	218.1	220.2	205.6	201.1	177.3	165.1	153.3	135.7	127.1	125.9	119.4	120.3	120.1	133.1	152.2	191.0	212.4	227.5	223.4	230.2	240.1	221.1	207.9
July	256.6	266.8	263.1	263.9	262.6	237.9	214.1	201.7	187.2	167.6	164.8	161.5	161.3	159.2	176.4	187.8	227.4	243.3	264.0	265.1	269.0	274.1	257.8	243.3
August	258.9	255.5	253.2	248.4	244.2	226.6	201.8	177.9	163.7	151.9	150.1	146.7	145.7	146.9	162.5	185.7	216.5	242.4	257.8	261.0	257.2	261.6	245.5	240.7
September	205.8	205.3	204.6	208.4	210.0	204.1	191.5	174.9	159.1	143.4	138.2	133.3	134.4	145.1	157.6	186.7	272.2	284.4	284.9	283.7	284.8	279.5	255.1	247.2
October	215.6	213.6	216.5	223.6	226.5	224.8	210.9	190.1	170.4	152.2	142.1	139.7	138.4	145.1	171.6	211.7	233.3	237.2	241.6	242.1	237.0	230.1	210.5	203.5
November	173.9	174.6	173.9	172.8	175.6	177.7	168.1	153.3	137.3	124.1	122.7	124.1	125.1	137.9	159.8	180.8	189.8	195.4	199.3	197.6	196.5	195.6	202.2	195.8
December	226.5	216.1	213.2	211.6	218.0	225.4	225.8	221.0	212.2	203.7	195.5	196.6	200.3	214.1	233.5	250.0	250.6	250.6	249.8	252.5	249.2	254.5	245.1	239.3
SUNDAY [tCO _{2eq} /MWh _e]																								
Month /Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
January	361.0	370.3	372.9	372.4	373.1	338.4	347.3	322.9	299.8	290.7	286.3	284.3	284.2	286.9	301.7	314.8	311.7	309.0	306.9	312.2	318.6	327.2	337.9	336.7
February	324.1	326.9	326.4	322.4	326.4	321.7	312.3	283.2	257.4	245.5	236.1	237.2	232.7	230.9	242.6	271.9	297.5	298.7	302.4	311.3	323.7	333.4	345.7	354.7
March	346.7	354.6	354.6	352.6	351.0	341.8	311.1	272.9	248.2	228.3	217.6	216.6	219.7	228.5	246.9	277.6	310.7	315.7	318.2	322.5	332.6	337.9	340.2	334.4
April	239.6	237.2	238.4	242.3	239.4	224.9	196.2	175.3	158.1	152.4	147.8	143.8	148.5	155.9	169.8	185.2	222.6	243.2	243.0	244.1	246.1	238.5	226.7	221.1
May	190.2	184.0	176.2	191.6	186.4	173.8	144.1	127.8	124.1	117.3	114.3	112.3	119.4	120.4	134.6	147.8	166.4	206.1	220.5	224.9	225.7	216.6	201.0	191.5
June	226.1	224.1	207.2	215.6	210.2	171.7	152.7	134.8	124.4	116.6	118.0	115.2	119.4	123.2	135.0	158.4	184.1	210.9	222.4	234.7	236.7	245.4	234.8	224.0
July	240.0	261.9	251.6	251.7	238.6	213.9	186.0	169.0	153.7	148.4	146.6	142.6	146.8	148.9	159.0	189.9	219.9	244.3	260.0	270.8	273.0	272.6	275.6	274.1
August	240.2	236.0	233.3	232.8	228.5	208.1	157.8	144.2	134.3	130.6	127.4	109.8	117.1	135.7	177.1	208.9	234.7	246.4	249.5	255.2	254.3	236.2	230.1	230.6
September	245.9	243.7	247.5	247.1	247.7	237.9	206.2	175.2	156.6	148.9	147.9	142.9	145.8	149.2	162.7	202.9	249.7	263.7	268.3	264.9	268.7	265.2	247.3	237.7
October	205.8	202.8	203.8	205.7	209.7	201.8	182.4	158.4	143.4	136.9	135.5	129.1	128.1	135.1	155.5	197.5	224.8	228.5	230.5	235.5	237.0	231.9	228.6	224.2
November	209.4	209.7	208.9	209.1	210.5	210.3	182.9	164.2	154.3	152.4	150.4	150.4	158.4	174.4	189.1	194.2	195.4	201.7	204.1	208.1	214.3	218.2	222.6	222.6
December	232.0	236.1	233.9	230.9	233.4	228.2	215.1	200.4	189.9	190.3	194.8	188.0	198.0	223.1	242.8	245.1	245.1	242.4	242.2	244.4	248.7	249.0	247.4	243.3
HOLIDAY [tCO _{2eq} /MWh _e]																								
Month /Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
January	371.4	376.1	377.7	372.4	373.1	369.2	362.4	345.9	319.4	311.0	304.6	307.4	315.1	325.2	340.1	358.5	353.9	351.0	350.4	352.5	360.1	366.3	363.7	368.2
May	219.7	219.6	218.5	226.3	247.9	260.1	250.6	249.2	238.0	238.0	228.6	219.6	229.3	236.9	244.8	247.5	253.3	267.7	269.8	278.0	280.7	258.0	250.7	240.8
June	227.4	205.3	241.2	216.6	210.9	192.9	177.1	174.9	142.8	131.6	128.2	125.9	131.8	142.0	140.9	178.9	214.2	243.9	249.2	232.0	258.2	267.0	259.1	262.2
August	271.9	266.2	261.9	281.6	292.3	267.6	232.6	208.5	183.2	169.4	164.4	163.1	161.1	165.4	178.1	223.1	258.5	280.8	282.6	288.2	300.0	302.6	303.0	295.4
December	268.6	268.5	270.8	274.8	281.5	300.9	305.7	290.6	277.3	272.4	269.8	265.4	272.8	291.4	304.4	311.2	307.1	309.3	313.1	314.7	309.4	306.7	296.0	283.3

As demonstrated in the previous Section 3.3.2, the greener the values in Table 3, the harder it will be for cogeneration to allow for lower greenhouse gas emissions relative to the grid.

Only plants with higher overall efficiency, particularly at night and in the first months of the year, can allow a reduction in greenhouse gas emissions from the cogeneration plant.

4. CONCLUSIONS

The use of cogeneration has always represented a technical solution that aims to reduce primary energy consumption compared to the separate generation of electrical and thermal energy.

The results of the analysis of the operation of twenty different cogeneration and trigeneration plants operating in the industrial sector or serving district heating networks were presented. The analysis highlighted that, although all plants have a *PES* that guarantees the CAR qualification, the overall efficiency values are lower than the reference threshold of 75% in at least half of the plants. This happens above all in trigeneration plants in which the absorption chiller is mainly used, and when the thermal energy produced is not fully useful.

With regard to greenhouse gas emissions, the situation is more critical: If we consider the emission factor of electricity based on final consumption, no plant allows a reduction in the carbon footprint. However, a more in-depth analysis must be developed in relation to the hourly values of the emission factors and the marginal emission factors. Furthermore, with respect to the objectives imposed by Directive 2023/1791, only plants with an overall efficiency of at least 75% can reach the required level of 0.270 tCO_{2eq}/MWh_e.

Considering the scenario we are facing and the contents of Directive 2023/1791, beyond the formal constraints, in the evaluation of future cogeneration development scenarios, it is necessary to take into account the following:

- The quota of renewable electricity production will progressively increase with a significant portion of non-programmable renewables that will change the price structure, especially during the day, and also the hourly emission factor;
- The use of gaseous fuels, in part by renewables (biogas, biomethane, or green hydrogen), could contribute to lowering the cogeneration emission factors in the near future;
- At this moment, electricity from the grid with a guarantee of renewable origin determines a zero greenhouse gas emission factor, greatly favouring separate generation when adopted. However, this hypothesis could be modified over the next few years, since it allows too easily to maintain zero emissions with negligible investments and discourages investments in terms of self-production or energy optimisation.

In conclusion, on the one hand, it becomes increasingly disadvantageous in terms of primary energy to produce non-renewable electricity from natural gas. On the other hand, an evolution of the natural gas market and a use of at least a percentage of renewable gas or green hydrogen are necessary to operate. All this in scenarios differentiated in terms of the electricity market area and with associated different emission factors on an hourly basis. In any case, it will be essential that cogeneration plants are optimised from the point of view of the use of thermal energy, to achieve the highest overall efficiency.

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NOMENCLATURE

CAR	cogenerazione ad alto rendimento (high efficiency cogeneration)
CHP	combined heat and power
CHCP	combined heat, cooling and power
DH	district heating
DHC	district heating and cooling
DNSH	do no significant harm
EED	energy efficiency directive
EU	European union
GSE	gestore dei servizi energetici (energy services manager)
ICE	internal combustion engine
LHV	lower heating value
NG	natural gas

SEU sistemi efficienti di utenza (utility efficient system)

Symbols

C cooling energy, MWh
CB certificati Bianchi (white certificates)
E electric energy, MWh
EER energy efficiency ratio
EmCO2 CO₂ emissions, t_{CO2eq} MWh⁻¹
F NG (non-renewable) primary energy, MWh
H thermal energy, MWh
K harmonization coefficient
PES primary energy saving
RISP energy saving index to calculate *CB*, MWh

Greek symbols

η efficiency

Subscripts

c cooling
CHP combined heat and power
e, el electric
new new
NG natural gas
p primary
ref reference
t thermal