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Hourly electricity CO_2 intensity profiles based on the real operation of large-scale natural gas combined cycle cogeneration plants

Michel Noussan, Gabriele Fambri *, Viviana Negro, David Chiaramonti

Department of Energy, Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino, 10129, Italy

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ABSTRACT

The decarbonization of energy systems is a major challenge that requires complex cross-sectoral strategies that need to be supported by energy modeling. As many technologies rely on electricity, an accurate estimation of its CO_2 intensity is of utmost importance for the reliability of modeling results. When electricity is generated from fossil sources, its CO_2 intensity depends on several parameters. This research paper presents an hourly calculation of the CO_2 intensity of power generation from natural gas combined cycles, based on real data from several years of operation of three plants. As these plants are also operated in combined heat and power mode, two alternative allocation methods are compared. The results confirm the variability of CO_2 intensity based on the different operation strategies of the plants and the share of heat and electricity generated. The hourly analysis shows average values in the range of 230–250 g_{CO_2}/kWh in winter, rising to around 330–370 g_{CO_2}/kWh in summer. The real CO_2 intensity profiles presented in this paper can be integrated into energy planning models to improve their ability to estimate the potential benefits of different decarbonization solutions by including the effect of the operational profiles over the day and the year.

1. Introduction

The decarbonization of the energy system is an imperative for the European Union (EU), as it strives to achieve climate neutrality by 2050, in accordance with the Paris Agreement's objective of limiting global warming to less than 2 °C [1]. To reach this ambitious goal, it is crucial to leverage the most efficient technologies and methodologies available. In order to optimize the entire energy system and maximize efficiency, a holistic approach is necessary. Indeed, the traditional energy system operated under a vertical structure, where the different energy flows in final uses, such as heat and electricity, were addressed independently (single-sector energy systems). However, to fully exploit potential synergies among various sectors and enhance overall efficiency, it is essential to revise this paradigm and consider the system as a whole [2]. This approach is known as a multi-energy system (MES) [3]. Compared to single-sector energy solutions, MES systems introduce greater complexity in managing the energy system, but, on the other hand, they also offer opportunities to exploit synergies and improve overall efficiency [4,5]. For this reason, simulation models are needed that take into account the dynamics of the various interconnected energy sectors [6].

One of the more diffused solutions that align with MES principles is the combined heat and power (CHP) [7]. Using the CHP solution is one efficient option to lower primary energy consumption [8]. CHP in a MES contest enables the exploitation of coupling synergies between the power and thermal sectors, resulting in significant improvements in energy conversion efficiency, environmental impact and operation cost [9]. In terms of conversion efficiency, natural gas combined cycle (NGCC) plants running in CHP mode are currently among the best technologies available [10]. In full-electric mode, a modern NGCC plant can reach up to 60% efficiency [11], while in CHP mode, it can achieve up to 90% overall conversion efficiency [12].

For complex energy systems optimization, specific performance indicators for energy carriers are needed, especially the CO_2 intensity of electricity [13]. More and more technologies, in fact, are powered by electricity [14], and electricity penetration in final uses is growing [15]: from a greenhouse gas (GHG) minimization perspective, it therefore becomes important for both the planning and operation of these facilities to know the amount of CO_2 that is emitted upstream for the electricity production [16,17]. These parameters are crucial for assessing the GHG impact of electrification of different energy sectors: for example, to compare the use of heat pumps with fossil fuel combustion solutions [18], or electric vehicles with thermal vehicles [19]. In addition, time-dependent carbon intensity indicators are needed to optimize the operation of the technologies involved in the energy system: to prioritize the least carbon-intensive generation

* Corresponding author.
E-mail address: gabriele.fambri@polito.it (G. Fambri).

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Nomenclature

CHP	Combined heat and power
DH	District heating
EMS	Emission monitoring system
ENTSO-E	European Network of Transmission System Operators for Electricity
ETS	Emissions Trading System
EU	European Union
GHG	Greenhouse gas
ISPRA	Italian Institute for Environmental Protection and Research
MES	Multi-energy system
NGCC	Natural gas combined cycle

technologies and to operate electricity-consuming technologies during the least carbon-intensive time slots in the grid [20]. In a scenario with CHP systems, the definition of the carbon intensity of electricity is not so trivial due to the intersection of various energy sectors. Specifically, in the case of a CHP system, it is not obvious how to allocate the carbon contained in the fuel to the two outputs of the system: electricity and heat [21].

1.1. Literature review

With the growing interest in energy systems emissions, the study of the carbon intensity of the electricity grid is a topic that has been covered considerably in the scientific literature over the last two decades. In 2002, the impact of the production of electricity on emissions, considering the fuel mix used for generation was analyzed in [22]. The study examines the impact of disposing of old systems and commissioning new systems in the Belgium scenario. In 2014, in [23], the concept of long-term marginal emission was introduced. The change in the demand for electricity causes in the short term a variation in the generation plants operation; in the long term however, a permanent change in the demand leads to a readjustment of the entire energy system, consequently changing the electricity CO_2 intensity in a different way. In 2018 the carbon intensity data of the grid electricity in the EU countries were calculated, considering the impact of cross-border energy exchange on the carbon intensity values [19]. A new methodology for calculating emissions was proposed in 2022 [24]. This methodology takes into account not only the emissions generated during the operation but also the emissions caused by the construction and disposal of generating plants as well as the upstream emissions of the fuels consumed by power plants.

The quantification of GHG emissions resulting from electricity production is generally calculated as average annual CO_2 intensity values. However, the need to use higher-resolution temporal profiles of carbon intensity in order to analyze and optimize the operation of the energy system appears increasingly evident [25,26]. In [25], the emissions associated with the electricity consumption of a heat pump were analyzed by comparing the results obtained using a CO_2 intensity average annual value of the network and those obtained using an hourly profile. The study demonstrated that the difference between the two approaches increases as the penetration of variable renewable energy in the electricity system increases. The half-hourly carbon intensity profile was calculated for the specific case of New Zealand [26] whose penetration of renewable energy in the electricity system is approximately 80%. The analysis made it possible to highlight that due to the predominance of hydroelectric energy, the carbon intensity of the network is poorly correlated with energy demand. In [27] the hourly values of electricity CO_2 intensity in Switzerland were presented. The data refers to the years 2016 and 2017 and it includes also the effect of energy cross-border imports. In [28] a methodology to determine hourly carbon intensity was presented. The methodology was used to control the operation of heating, ventilation, and air conditioning systems in order to maximize GHG savings: the greater the temporal fluctuation of the CO_2 intensity of the network, the greater the environmental positive effect of this control strategy. In [29] the charging of electric vehicles has been optimized according to a half-hour profile of carbon intensity of the network and on the profiles of over-generation of renewables; this control methodology allows the emissions associated with the electric vehicles charging to be reduced by 30% in the case study analyzed.

However, as discussed in the previous section, the use of CHP plants makes the definition of the carbon intensity of the network more complex. It is clear that the determination of the real carbon intensity of electricity produced from CHP is of great importance considering for example that in Italy in 2022 the production of electricity from CHP plants was 105 TWh [30], which corresponds to approximately one third of the annual Italian electricity demand (i.e. 315 TWh in 2022 [31]). In [32], seven different CO_2 allocation methodologies for cogeneration plants were analyzed. The study calculated that the quantity of CO_2 allocated to thermal generation depends on the methodology used: the values can vary from 6% to 38% of the total emissions of the cogeneration plant. Different allocation methodologies were also compared in [21]. The study also evaluated the impact of the different allocation methodologies on a range of cogeneration technologies using real-world plants parameters. In [33] the CO_2 allocation of a cogeneration plant connected to district heating is calculated in order to correctly evaluate the performance of the plant from an economic and environmental point of view.

1.2. Scope

Despite the growing importance of cogeneration plants in electricity production, there is a lack of studies in the literature that provide a temporal profile of the carbon intensity produced by real CHP units. This kind of data is crucial for energy system modelers and policymakers to accurately assess the carbon emission impact in complex and interconnected energy systems. Based on the authors' knowledge, no energy system simulation software implements this type of calculation [34]. To fill this research gap, this paper focuses on analyzing the CO_2 intensity of electricity generated by three real NGCC plants operating in CHP mode. The study calculates the CO_2 allocation in the products of these plants using the two most recent allocation calculation methodologies published by the European Union. The obtained results are compared with the annual average CO_2 intensity values of the national electricity network. The authors utilize 14 years of operational data from the three plants to calculate the carbon intensity of electricity with a 1-hour discretization. Furthermore, the study provides the hourly discretized characteristic profiles of CO_2 intensity, derived from the processing of real operating data. These profiles are included as supplementary materials, serving as valuable resources for energy planning models. By incorporating these profiles, energy planning models can improve their ability to estimate the potential benefits of different decarbonization solutions, considering the operational profiles throughout the day and year.

2. Materials and methods

2.1. Input data

Our study is based on the analysis of three CHP generation units located in Turin, Italy. The plants are natural gas combined cycles connected to the district heating (DH) system of the city (see Fig. 1), which in 2021 supplied 2.04 TWh of heat to the 73 million cubic meters of connected buildings [35]. Almost all the heat supplied to the DH is

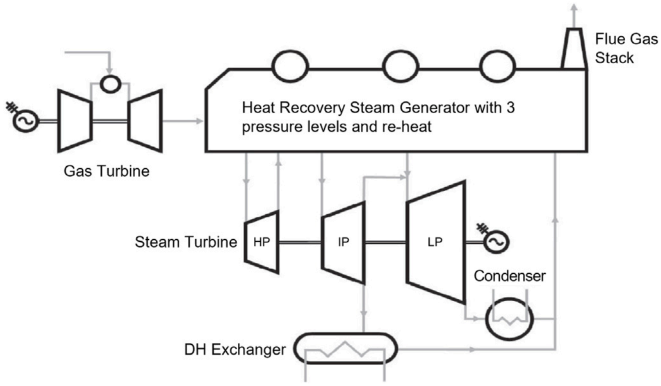

Fig. 1. Diagram of the three natural gas combined cycles power plants connected to the district heating in Turin.
Source: [36].

Table 1
Main characteristics of the three generation units analyzed.

		Moncalieri 2GT	Moncalieri 3GT	Torino Nord
Gas turbine gross nominal power	MW	270	260	270
Steam turbine gross nominal power	MW	141	138	119
District heating exchanger	MW	260	260	220
Nominal net power - full electric mode	MW	395	383	390
Overall efficiency - full electric mode	–	58%	57%	56%
Nominal net power - CHP mode	MW	340	322	340
Overall efficiency - CHP mode	–	90%	87%	87%

produced by these three CHP plants, also thanks to the availability of 15,000 m^3 of heat storage systems that are operated in peak hours.

The generation plants are located in two distinct sites. Two units are in Moncalieri, a municipality of 55,000 inhabitants in the southern outskirts of Turin (and will be called "2GT" and "3GT" in this paper), while the third is located in the Northern part of Turin (and it will be called Torino Nord or "TON" in this paper).

The main characteristics of the three plants are reported in Table 1. The three systems are quite similar, although with some small differences on nominal power and heat outputs and efficiency.

Hourly operational data are available from 2010 to 2023 (up to September 30th), and they are obtained from the Emission Monitoring System (EMS). The available data include the output power, both the total and the gas turbine output, the heat supplied to the DH system, the natural gas volumetric flow and other parameters (including flue gases volumetric flow and concentration of different pollutants).

The annual hours of operation of these plants varied from a year to another, due to a number of reasons including market electricity prices, maintenance, etc. It is important to note that the plants are owned and managed by the same company, which can thus choose the best combination based on different reasons. In the years considered in this analysis, the plants have had annual operational hours in a range from 3200 to 7500, with median values of around 5600 for 2GT, 6000 for 3GT and 7000 for TON. These figures correspond to median values of 1.5–2.0 TWh of annual gross electricity generation depending on the plant, and 0.6–0.8 TWh of annual heat supplied to the DH network.

An example of the daily variation of energy generation profiles is reported in Fig. 2. The chart shows the median hourly electricity and heat output of Torino Nord power plant in four months of 2022. These selected profiles allow to compare the different operational strategies over the year, based on the heat demand of the district heating network that is connected to the CHP plant.

2.2. CO_2 intensity of electricity and heat

There is no univocal methodology for defining the CO_2 intensity of electricity and heat production in cogeneration, given the alternative options of allocation. Of all the existing methods for calculating the CO_2 allocation for combined heat and power plants, two specific allocation methods have been selected for this work. This choice was made in order to comply with European policies, as these two methods are proposed by the European Union (for other allocation methods, see [21,37]).

These methodologies define how to allocate the CO_2 generated by the cogeneration plant to the energy outputs. In the plants analyzed CO_2 is generated by the combustion of natural gas taken from the national gas network. The data collected reported the standard cubic meter consumed by the plants at every hour (V_{NG} [Sm_3]). CO_2 production was calculated as a function of natural gas consumption considering the lower heating value of natural gas (LHV_{NG} [kWh/Sm_3]) and its carbon intensity (c_{NG} [g_{CO2}/kWh]).

$$C_{tot} = V_{NG} \cdot LHV_{NG} \cdot c_{NG} \tag{1}$$

Due to the lack of specific data on the quality of natural gas a standard lower heating value of 9.766 kWh/Sm^3 has been assumed. This value is the average of the annual figures published by the Ministry of the Environment and Energy Security from 2014 to 2022 in support of the EU Emissions Trading System directive (EU ETS) [38]. With the same logic, and from the same source, a standard carbon intensity for natural gas of 201.6 g_{CO2}/kWh has been considered.

The first methodology proposed by the EU is called energy share allocation. This methodology is well established and its use has been recommended within the Renewable Energy – Recast to 2030 (RED II) (EU RED II) [39] in 2018. The methodology involves allocating the CO_2 generated during cogeneration proportionally to the energy quantity of the outputs. The total CO_2 emissions are allocated as:

$$C_{el} = C_{tot} \cdot \frac{E_{el}}{E_{el} + E_{th}} \tag{2}$$

$$C_{th} = C_{tot} \cdot \frac{E_{th}}{E_{el} + E_{th}} \tag{3}$$

where:

- C_{el} [g_{CO2}] is the carbon dioxide emissions flow allocated to the electricity output;
- C_{th} [g_{CO2}] is the carbon dioxide emissions flow allocated to the heat output;
- C_{tot} [g_{CO2}] is the total carbon dioxide emissions flow produced by the CHP plant;
- E_{el} [kWh] is the electricity energy production of the CHP plant;
- E_{th} [kWh] is the thermal energy production of the CHP plant.

The carbon intensity of the two products (and c_{el} [g_{CO2}/kWh] and c_{th} [g_{CO2}/kWh] for electricity and heat respectively) are defined as the ratio of the CO_2 allocated and the energy generated:

$$c_{el} = \frac{C_{el}}{E_{el}} \tag{4}$$

$$c_{th} = \frac{C_{th}}{E_{th}} \tag{5}$$

It can be seen that combining Eqs. (2) (4) and (3) (5) results that, for this methodology, the CO_2 intensity values for electricity and heat are equal.

$$c_{el} = c_{th} = \frac{C_{tot}}{E_{el} + E_{th}} \tag{6}$$

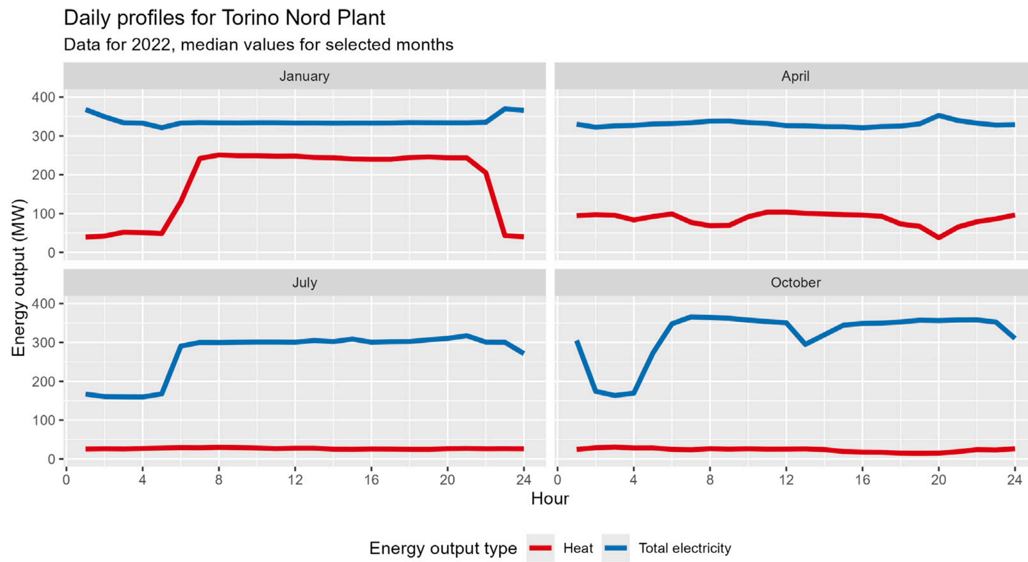

Fig. 2. Median daily profiles for hourly electricity and heat production. Torino Nord Plant, selected months, 2022 data.

The second method analyzed in this paper is called "alternative heat generation allocation". This methodology has been proposed in 2023 in the Commission Delegated Regulation (EU) 2023/1185 [40]. In this case, the emissions allocated to electricity are defined as the difference between the total emissions and the emissions allocated to the heat generated. The CO_2 emissions allocated to heat are assessed as if they were produced with the same fuel in a simple heating plant (i.e. without cogeneration) with an overall reference efficiency for heat production ($\eta_{th,ref}$). When considering natural gas, the reference efficiency is set to 85% by the Commission Delegated Regulation (EU) 2023/1185 [40]. Thus, emissions allocation to electricity and heat are defined as follows:

$$C_{el} = C_{tot} - C_{th} \tag{7}$$

$$C_{th} = c_{NG} \cdot \frac{E_{th}}{\eta_{th,ref}} \tag{8}$$

The CO_2 intensity of electricity and heat are therefore:

$$c_{el} = \frac{C_{tot} - C_{th}}{E_{el}} \tag{9}$$

$$c_{th} = \frac{c_{NG}}{\eta_{th,ref}} \tag{10}$$

When analyzing the two methods, it should be noted that in the "alternative heat generation allocation" method, the CO_2 intensity of the heat does not depend on the performance of the system, but only on the carbon intensity of the fuel that is used. Due to the definition of the two methods, the values of the CO_2 intensity coincide when the overall efficiency of the system (ratio between the total energy outputs, electricity and heat, and the energy input of the fuel) equals the reference efficiency for heat generation (i.e. 85%) or when the heat produced by the system is equal to zero, i.e. when the system operates in full-electric mode. For other working conditions with an overall efficiency of less than 85%, the "energy share allocation" method allocates less CO_2 to electricity than the "alternative heat generation allocation" method. For working conditions with an overall efficiency of more than 85%, the opposite is true.

2.3. Comparison with the national power grid

A further aspect that we evaluate is the comparison of the calculated CO_2 intensity with the average power generation at the Italian level, to see how these plants compare with the other available technologies.

The estimation is based on electricity generation data by source in Italy, considering hourly time series from 2018 to 2022 (data available from the European Network of Transmission System Operators for Electricity (ENTSO-E) [41]). We calculate the CO_2 intensity of the electricity generation by using annual average intensity per source provided by the Italian Institute for Environmental Protection and Research (ISPRA). This is an approximation compared to the evaluation of this case study, as we assume a constant conversion efficiency for power plants, but no detailed data is available at an hourly basis on the actual fuel consumption, nor on heat production in CHP plants. Nevertheless, we believe that this calculation can help in providing a further representation of the context in which these power plants are operating.

3. Results

This section presents the main results of the calculation, and additional information is reported in the supplementary materials. The first subsection presents the results obtained with the allocation based on energy output, which is the main method that is commonly used in the field. The second subsection presents the results obtained with the allocation based on alternative heat generation, together with a comparison between the two methods.

3.1. CO_2 intensity - energy output allocation

The CO_2 intensity of the electricity generation has significant variations, based on the operation of each unit. Fig. 3 shows the operational diagram of the Torino Nord plant, comparing the heat and power output levels of the unit on a hourly basis calculated using the energy share method. The two histogram diagrams show the distribution of heat and power output levels over the time span considered in the analysis, and the color of the points represents the calculated CO_2 intensity. Similar charts for 2GT and 3GT are reported in the supplementary materials.

The diagram confirms that the plant has a wide range of operational conditions over the year, with different electricity and heat outputs. This is due to the heat demand of the district heating in winter, while in summer the operation logic of the plant is often driven by the electricity generation and the specific market conditions. The histogram distribution of the heat output clearly shows two local maximum values, one for the winter (with heat output larger than 200 MW) and one for the summer (with no or very limited heat output). The histogram distribution for the electricity output highlights a significant concentration

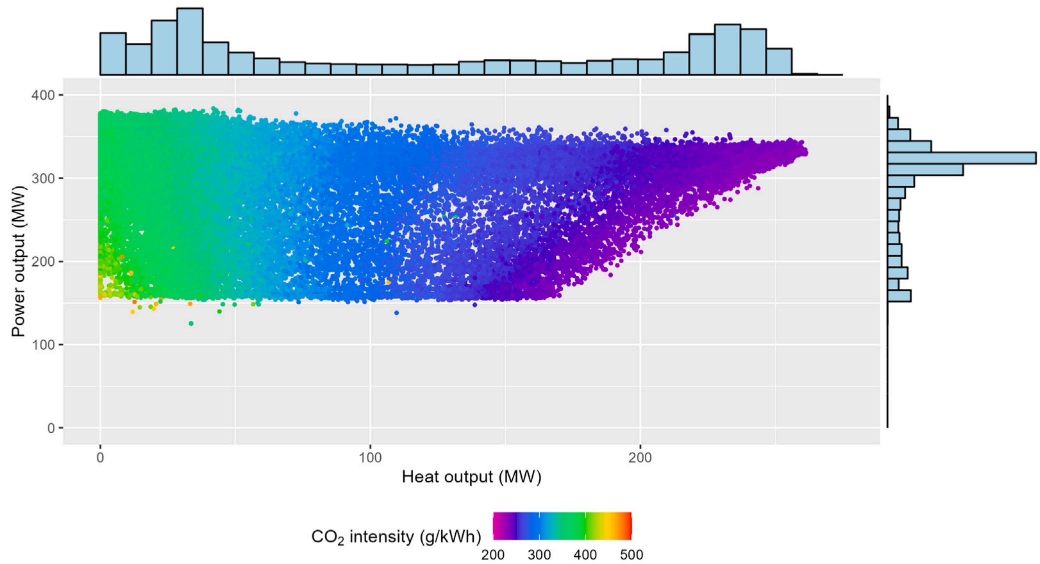

Fig. 3. Operational diagram of the Torino Nord generation unit, comparing the power output and heat output with the calculation of the CO_2 intensity (allocation based on the energy share). Calculation on hourly operational data, years 2014–2023. The histograms represent the distribution of the two variables that are plotted in the main chart.

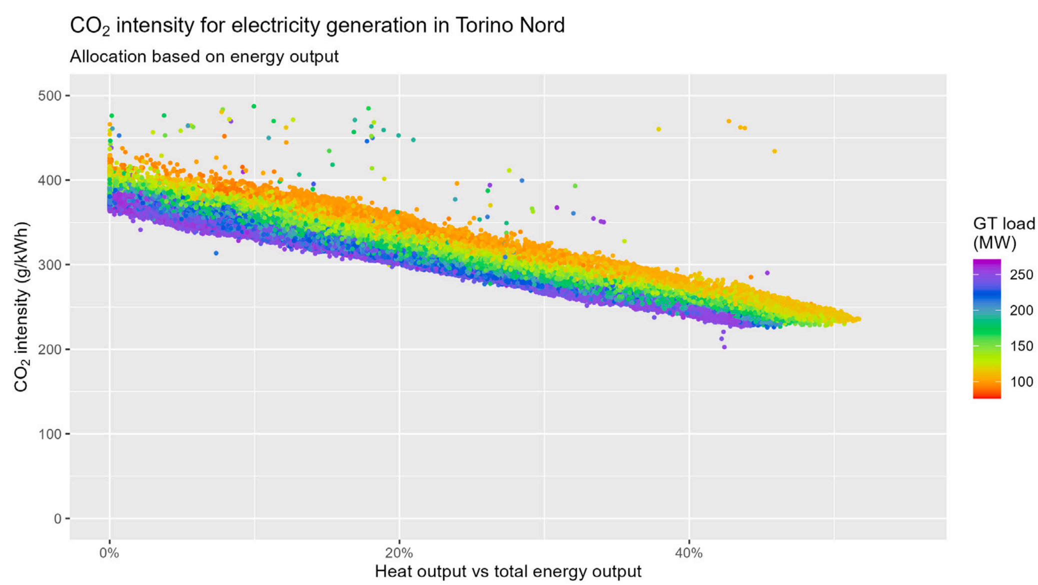

Fig. 4. CO_2 intensity of electricity and heat generation in the Torino Nord power plant, based on the energy share allocation. Calculation on hourly operational data, years 2014–2023.

of operational hours near the full-load conditions, although the unit also operates at partial load for a considerable period of time (with a technical minimum of around 150 MW of power output).

As it will be further discussed in the next paragraphs, the distribution of CO_2 intensity figures show two maximum frequency levels. In the winter months, especially during the hours with maximum heat production, the CO_2 intensity of electricity is mostly in the range 230–250 g_{CO2}/kWh. On the other hand, during the summer months, in which heat generation is very limited, the decrease of the overall energy output leads to a CO_2 intensity in the range 330–370 g_{CO2}/kWh, and in some cases higher than 400 g_{CO2}/kWh.

The CO_2 intensity shows a very clear dependence on the heat output, which is even better represented by Fig. 4.

The chart highlights a clear linear trend, with an additional effect of the power plant load, which is represented by the colored scale showing the gas turbine load. The higher the heat supplied to the DH system, the lower the CO_2 intensity of the produced electricity. At the same time, the CO_2 intensity tends to increase with decreasing power plant load, due to a lower conversion efficiency compared to nominal conditions. Similar charts for the 2GT and 3GT units are available in the supplementary materials.

There are some outliers in the chart, showing a lower performance of the system in comparison with the main trend. These specific points may reflect a variable operation during the hour, or possibly some issues that have lead to an increased consumption of fuel compared to the expected behavior of the plant. Nevertheless, it is clear for the chart that these points only represent a very marginal share of the total, being a few dozen hours over many years of operation.

It is important to remark that when allocating emissions using the energy share methodology, the CO_2 intensity value is the same for both heat and electricity. Thus, the values represented in Fig. 4 are also valid for the estimation of the emissions associated to the heat supplied to the DH network. In both cases, this value is representing the emissions for the energy produced in the power plant, thus without accounting for the downstream losses of the power grid and the DH network.

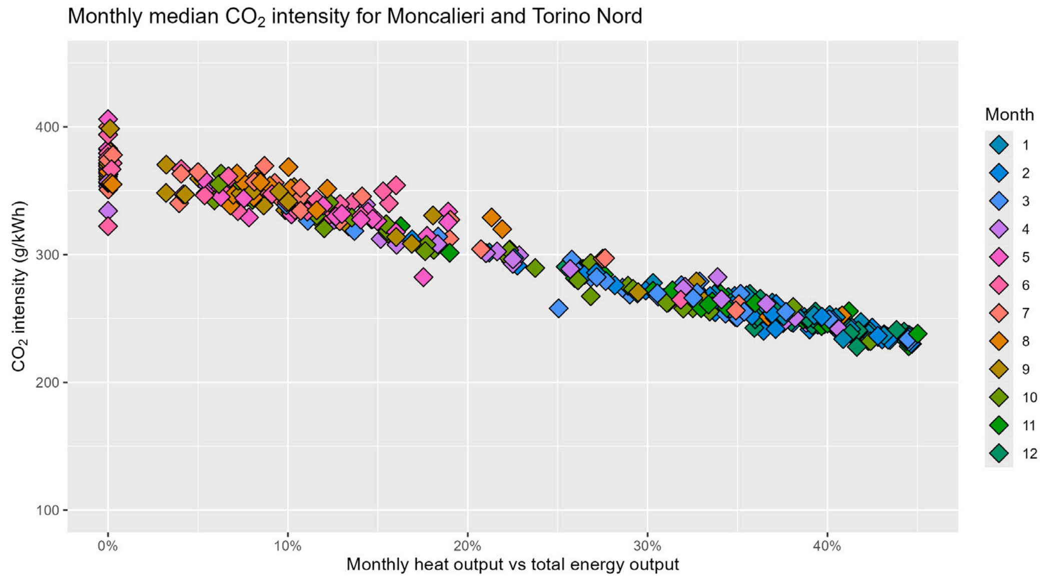

Fig. 5. Monthly CO_2 intensity of electricity generation in Moncalieri and Torino Nord power plants, based on the energy share allocation. Median values for each month based on hourly operational data, years 2010–2023.

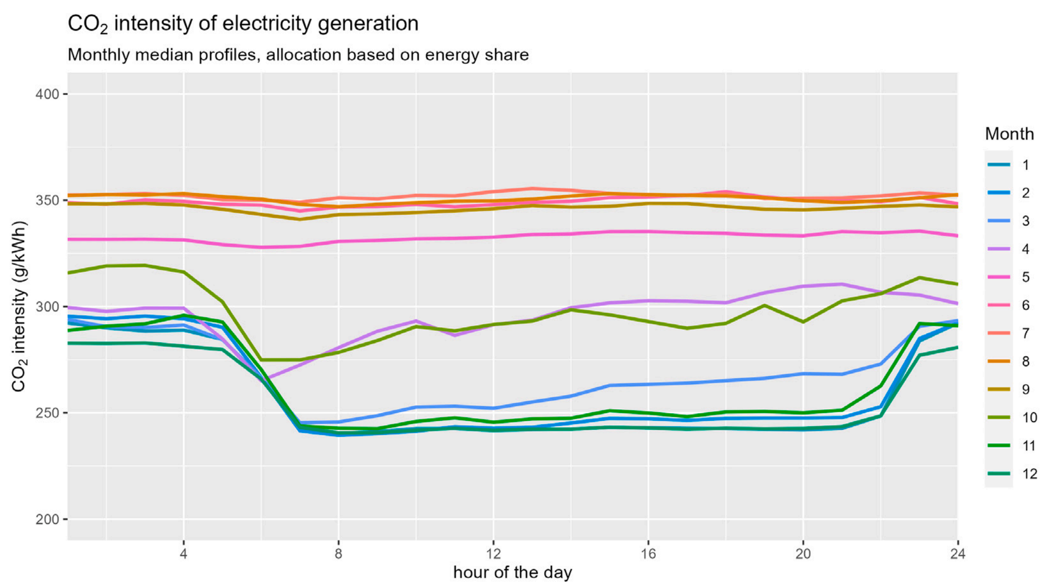

Fig. 6. Average daily patterns of CO_2 electricity intensity, based on the energy share allocation. Average values for each hour and month based on hourly operational data, years 2010–2023.

A similar analysis can be performed with a different time resolution, by considering monthly values (Fig. 5). In this case the linear relationship between the heat share on the total energy output and the CO_2 intensity appears even more clearly.

Summer months are generally associated with a lower heat share and a higher CO_2 intensity, and the opposite is true for winter months. However, there are some exceptions. During some summer months the units may need to shut down for maintenance, and in some cases a single unit in operation may supply the heat required by the DH system, as some users require the heat also during the summer (e.g. hospitals). For this reason, some points on the right in the chart are showing summer months.

Finally, the daily operation pattern, which follows the DH management logic, has an important impact on the variation of the CO_2 intensity. The median daily profiles reported in Fig. 6. The difference between summer and winter months is clearly noticeable on the chart. While the summer months have on average quite a constant pattern, in winter an important variation is noticeable in the morning and late evening. This is due to the schedule of the heating systems of residential buildings, which are generally shut down at night. This is due to the fact that most of the buildings in Turin are large apartment buildings with centralized heating that has strict schedules. As a result, the heat demand over the night remains quite limited, although a part of the heat could be produced via CHP and stored for the morning peak, thanks to the availability of heat storage systems.

The profiles in Fig. 6 report the median values for the three plants. The median values have been chosen as representative of the typical behavior for the performance of the system in each month, to avoid choosing a random working day that could have been affected by outdoor temperature anomalies. The values of the CO_2 intensity profiles obtained from the analysis are provided in the supplementary materials (together with the median heat and power output). These profiles offer a detailed representation of the temporal variations in CO_2 intensity resulting from the operation of the analyzed CHP plants.

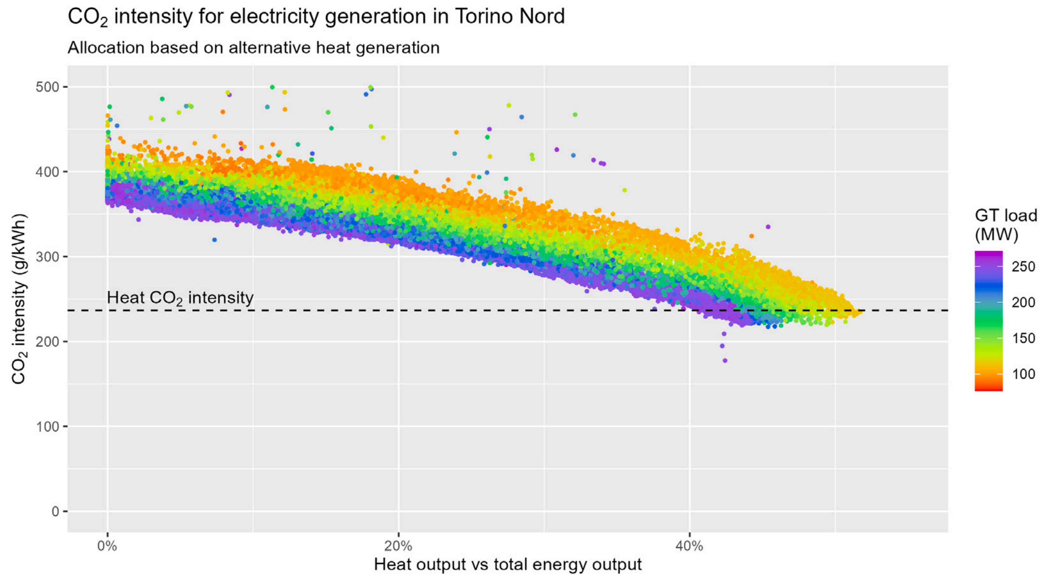

Fig. 7. CO_2 intensity of electricity and heat generation in the Torino Nord power plant, based on the alternative heat generation allocation. Calculation on hourly operational data, years 2014–2023.

Energy system modelers can utilize these profiles as valuable resources for further analysis and optimization of energy systems. The availability of these profiles enables a better understanding of the actual carbon emission impact of CHP plants. By incorporating the hourly discretized CO_2 intensity profiles into energy planning models, researchers can improve their assessments of the potential benefits of different decarbonization solutions by considering the hourly and seasonal operational characteristics.

3.2. CO_2 intensity - alternative heat generation allocation

The CO_2 intensity shown in the previous charts was calculated using the energy share allocation, which is the most common approach. As described in the methodology section, there is another option included in the EU regulations that is based on allocating part of the emissions to heat generation, assuming that the same heat would have been generated with an alternative technology with 85% of conversion efficiency. Using this allocation method, the chart corresponding to Fig. 4 is shown in Fig. 7. An additional visual comparison of these two charts in a single picture is presented in the supplementary material.

As explained in Section 2.2, the two methods have some differences. In full-electric mode, the two methods define the same carbon intensity value for the electricity generated. In CHP mode with maximum heat recovery, the overall efficiency of the plant is close to the value of 85%, so that also in this case the two methods provide very similar results (as explained in Section 2.2). In intermediate conditions, the overall efficiency is lower than 85%, which is why under these conditions the CO_2 intensity value of the "alternative heat generation allocation" method is similar but slightly higher than that of the "energy share allocation" method. In this case the relationship between the two quantities represented in the x and y axes, i.e. the heat share on total energy output and the CO_2 intensity of electricity, is no longer linear, although the difference remains limited. This method assumes a constant CO_2 intensity of heat, which in this case is around 236 g_{CO2}/kWh, and the resulting CO_2 intensity of electricity is almost always higher, with the exception of some points of operation when heat output is maximized. Thus, compared with the previous method, in this case the CO_2 intensity of heat is mostly lower, and the opposite is true for electricity CO_2 intensity (since total allocated emissions are the same). Again, similar charts for 2GT and 3GT units are available in the supplementary materials, and although the numerical results are slightly different, the qualitative considerations remain the same.

The distribution of the relative differences between the indicators calculated with the two allocation methods are represented in Fig. 8. Overall, considering all the operational hours of the three plants, the CO_2 intensity calculated with the alternative heat generation allocation is higher in 85% of the time. Nevertheless, the difference remains limited: the average difference is 3.8% and the median difference is 3.2%. As explained in Section 2.2, the two methods lead to similar results for plants that operate with an overall efficiency of 85%. And this is the case for large plants as the one analyzed in this study. This result shows that the two methods are compatible for this type of installation. This is consistent with the fact that both methodologies reflect approaches approved by the same body, i.e. the European Commission.

3.3. Comparison with electricity from the national grid

Fig. 9 clearly shows that the three units tend to have higher emission intensities than the average of the national grid during the summer months, while the opposite is true for winter months. This result is a combined effect of the seasonality of emission intensity for both the natural gas CHP plants and the average generation in Italy. In fact, the seasonality trends show opposite behaviors. Natural gas CHP plants have lower emission intensities in winter, thanks to the heat supply to district heating systems, while power generation in Italy has lower CO_2 intensity in summer thanks to a better productivity from renewables (especially hydro and solar). The chart also shows that 2022 figures are different from the other years, due to an important change in the Italian generation mix, caused by an increase of coal and a decrease of hydro. It is also worth noting that 2022 has been a peculiar year for the electricity market, with very high natural gas prices in Europe caused by the war in Ukraine, that have impacted the electricity generation mix.

4. Discussion

The results of this analysis show the significant variability of the CO_2 intensity of electricity in NGCC CHP plants. The main aspects affecting the value of this indicator are the share of heat produced, the power plant operational load and the allocation method. As a result, the hourly distribution of the results show a significant variability both over the months of the year and the hour of the day (see Fig. 6).

This variability could be incorporated in energy models of the electricity system, which are often considering average figures for the

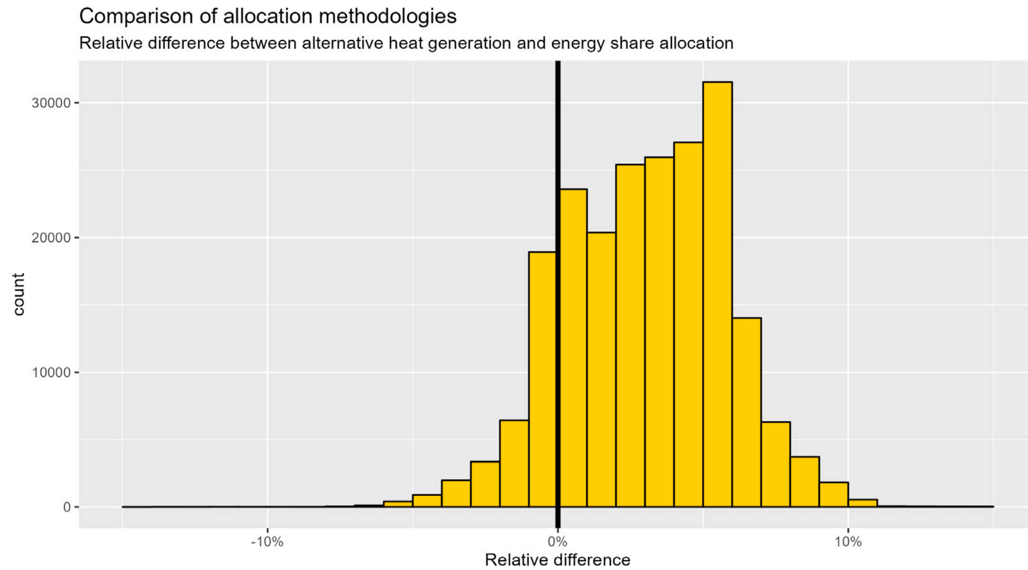

Fig. 8. Effect of the allocation method on the electricity intensity: relative difference between the indicator calculated with the alternative heat generation allocation vs the energy share allocation.

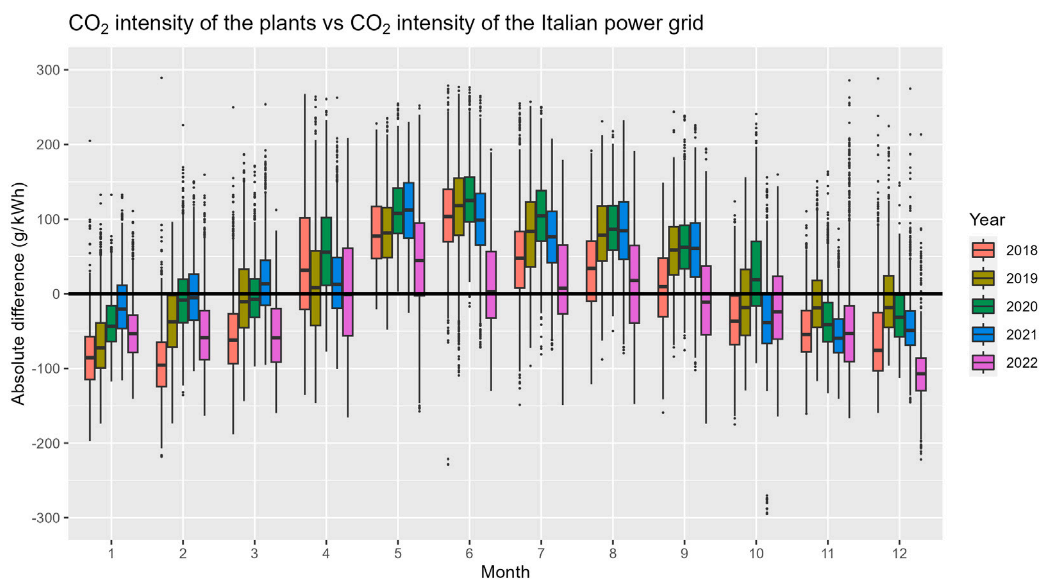

Fig. 9. Comparison of the emission intensity calculated for the three plants with the hourly average emission intensity of the Italian power grid. Boxplots showing the distribution of the absolute difference of the values.

CO_2 intensity of thermoelectric power plants. The availability of precise data for a large number of plants remain an important barrier: while data on electricity output are often widely available, information about the heat output and the hourly fuel consumption are much harder to be collected. However, a first step could be to apply average daily profiles to the CHP plants in operation in the system, considering different profiles for each month to incorporate the seasonality effect of heat demand. Such a choice could improve the modeling of the electricity generation, with a better estimation of the actual CO_2 emissions. This approach would improve the accuracy of the analyses that aim at estimating the effect of a significant penetration of new electricity services that may alter the hourly demand profile over the grid, such as electric vehicles or heat pumps.

As discussed in [21,37] there are different CO_2 allocation methodologies for cogeneration plants that can lead to significantly different results. In this paper, we considered the two most recent methodologies recommended by the EU. In the analyzed cases, the effect of the allocation method appears limited, although the "alternative heat generation" method leads to slightly higher figures for the case study of this work. As explained in the methodology, this happens when the overall efficiency of the CHP unit is similar to the reference thermal efficiency for alternative heat generation (85% in this case). This is generally happening also for other CHP technologies running on natural gas, although with different levels of electric and thermal efficiency. Although there is still no unambiguous methodology for defining CO_2 allocation for cogeneration, the small difference between the two methodologies shows that at least within the EU, the current rules for defining allocation are becoming more uniform.

Furthermore, different allocation methods are proposed across sectors and applications, leading sometimes to the risk of incoherently accounting CO_2 emissions. Some current regulations, such as district heating rules for primary energy consumption estimation, require the use of other allocation methods (that are not discussed in this work, such as the power bonus method [21]), leading to consistency problems. Thus, we believe that the choice of a unified allocation method for different energy sectors is necessary to ensure consistency. Similar problems arise also in other applications, such as the life cycle assessment (LCA) methodology. Also in this case the literature highlights that various methods are used in LCA studies, such as economic allocation, mass allocation, energy allocation or zero-burden allocation strategies [42]. The literature reports divergent recommendations, although economic allocation is mainly preferred. Thus, allocation remains a key methodological issue also in LCA, since allocation rules in ISO standards are commonly subject to interpretation [43].

While we have focused this work on the CO_2 intensity of the electricity generation, suggesting it as a potential indicator to evaluate the performance of the plant, we believe it is important to point out that the operation of the plant is indeed dependent on several aspects. During the winter, the heat demand of the district heating is usually the main driver, although with a precise hourly schedule over the day that is related to the heating systems of the residential buildings (which are shut down at night). In this case, heat supply to the DH can only be done via CHP or integration boilers, and since they also run on natural gas, it is often more profitable to operate CHP instead. This option could become less profitable in case of very low electricity prices on the market, but as renewable generation in Italy is mostly from solar, electricity prices in winter are never reaching low levels. On the other hand, the operation schedule in summer is mostly related to electricity prices in the day-ahead market, due to the effect of an important share of power generation from solar and other renewables. Moreover, each unit also needs to be shut down for maintenance for some weeks, and this is generally happening during the summer.

This analysis includes some assumptions and limitations, that could be further addressed in dedicated future research works. In particular, when comparing the CO_2 intensity of the case study against the evolution of the average intensity of the power grid, the latter figure has been estimated by considering average values for thermoelectric power plants. This choice has been made due to the lack of detailed data about the number and types of CHP plants and their hourly operation (which is also the reason for which we have proposed our analysis on this case study).

Finally, this analysis is considering the electricity and heat production by the power plants, without accounting for any of the energy losses due to the supply of energy to the final users. Both power grids and DH networks are affected by distribution losses, due to a number of reasons. As a result, the figures of CO_2 intensity for the energy supplied to the final users should also incorporate these additional losses, that need to be evaluated considering specific parameters that depend on the case under evaluation (e.g. electricity voltage, distance from the power grid, DH temperature, auxiliary consumption for pumping, etc.).

5. Conclusions

This analysis presents an estimation of the CO_2 intensity of electricity generated in high-efficiency NGCC plants operating in CHP mode. The results show the important contribution of heat generation in improving the conversion efficiency and lowering the specific emission intensity of the output electricity. The hourly analysis allows to shed light on the variability of this indicator, which varies from an average level in the range 230–250 g_{CO2}/kWh in winter to values of around 330–370 g_{CO2}/kWh in summer (and in some cases higher than 400 g_{CO2}/kWh). Annual average values are in the range 270–304 g_{CO2}/kWh, due to the variable operation conditions of the three units across the years.

The results and patterns discussed in this paper can enhance energy modeling and planning tools, as they allow for a more reliable estimation of the actual emissions associated to different electricity mixes and generation profiles. This is of particular importance considering the increasing improvement of temporal and geographical resolution of the energy modeling tools. The availability of carbon intensity profiles, included as supplementary materials, ensures transparency and accessibility for further research and analysis. Conversely, considering only annual constant emission intensities for CHP plants can lead to underestimation or overestimation of the performance of electricity-powered technologies, such as heat pumps and electric vehicles, when compared to traditional technologies. Incorporating the hourly profiles addresses this limitation and enables more accurate evaluations of the environmental impact of different energy solutions.

In this perspective, future research works should widen the focus of analysis compared to this case study, as considering different plants may result in a more robust and reliable dataset for the accounting of emissions from power plants. The possibility of considering the variable performance of CHP plants over time and their effect on emissions intensity is an important aspect to be integrated in optimization models that need to compare alternative technologies as well as future scenarios. Heat and power generation are often considered as separate sectors, although an increasing body of literature is highlighting the importance and advantages of an integrated and coherent analysis of multiple sectors to obtain effective solutions for climate change mitigation.

CRediT authorship contribution statement

Michel Noussan: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Gabriele Fambri:** Writing – original draft, Investigation, Formal analysis. **Viviana Negro:** Writing – review & editing, Validation, Investigation. **David Chiaramonti:** Validation, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.energy.2024.133424.

Data availability

Data will be made available on request.

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