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Hourly carbon intensity of natural gas combined cycles compared to the current and future electricity mixes in Italy

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Abstract. The current solutions for power generation include a wide range of technologies, each providing specific advantages and limitations. In a decarbonization perspective, their carbon intensity will represent a crucial factor in determining their success towards a future low-carbon electricity mix. Today, natural gas combined cycles are among the most efficient plants, especially when operating in combined heat and power mode. This paper presents the analysis of the actual carbon intensity of a large-scale natural gas combined cycle, calculated on an hourly basis over several years of operational data, compared with the average hourly emissions of the Italian power grid both with the most recent electricity mix and the forecast to 2030 and 2040, based on the decarbonization targets that are currently in place. The results of this study highlight the very low carbon intensity of the electricity produced in CHP mode, with average monthly values as low as 242 g/kWh during the winter months, compared to around 350 g/kWh when operating in full-electric mode in summer. These values are lower than the current performance of the Italian electricity mix in winter, although the opposite is true in summer, confirming the importance of the cogeneration in decreasing the carbon intensity of the energy output. However, in a future low-carbon electricity system, fossil gas CHP units will have higher carbon emissions than the average mix. In order to achieve the decarbonisation objective it is necessary to take these considerations into account. The availability of a high-resolution estimate of the performance of power generation will support policy makers in developing strategies to deploy the most effective technologies to decarbonize the energy system.

1 Introduction

In the perspective of the Paris Agreement goal of keeping global warming well below 2°C, the European Union (EU) aims to achieve climate neutrality by 2050. A progressive decarbonization of the European energy system is thus necessary, and to reach this ambitious goal it is essential to exploit a combination of the most effective technologies and approaches available. Natural gas combined cycles (NGCC) are among the most efficient dispatchable power plants in Italy, especially when they are operated in combined heat and power (CHP) mode to supply heat to industrial users or district heating networks [1]. However, these systems are increasingly facing the competition with low-carbon alternatives such as solar and wind, which are providing emissions-free electricity, although they are not able to operate in CHP mode.

In a decarbonization perspective, a precise and reliable estimation of the carbon intensity of electricity is required to support optimization and decision models that compare alternative strategies and policies.

Nomenclature

CHP	combined heat and power
DD22	Documento di Descrizione degli Scenari 2022
DE	Distributed Energy
EMS	emission monitoring system
ENTSO-E	European Network of Transmission System Operators for Electricity
ENTSO-G	European Network of Transmission System Operators for Gas
EU	European Union
GA	Global Ambition
GHG	greenhouse gas
ISPRA	Italian Institute for Environmental Protection and Research
NGCC	natural gas combined cycle
RED	Renewable Energy Directive

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 [2, 3, 4, 5]. The calculation of greenhouse gas (GHG) emissions related to 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 [6, 7, 8].

However, the calculation of the electricity carbon intensity is generally limited to power plants that have electricity as the only energy output. Considering CHP units requires a more complex evaluation, given the need of additional information on the heat produced by a large number of plants, in addition to the choice of a methodology to properly allocate emissions to heat and electricity outputs [9]. However, CHP units represent a relevant share of the total power generation, and should be included in the evaluation. In Italy, in 2022, the production of electricity from CHP plants was 105 TWh [10], which corresponds to approximately one third of the annual Italian electricity demand (i.e. 315 TWh in 2022 [11]). Some scholars have discussed different allocation methods, highlighting the variability of the results [9, 12, 13].

A correct definition of carbon intensity of CHP units is essential, and should be integrated in the broader evaluation of the carbon intensity of the national electricity mix with detailed temporal resolution. The carbon emissions intensity of CHP plants depends on their operating efficiency and the amount of heat that can be successfully recovered, with significant variations throughout the day and throughout the year, also due to specific operational strategies and the interaction with other heat generation units.

This paper presents a detailed hourly analysis of the actual performance of real NGCC plants operated in CHP mode, by assessing their carbon intensity in comparison with that of the Italian electricity mix. The comparison is performed both for historical data and for future scenarios in accordance with the national decarbonization targets of the power generation sector.

2 Methods

2.1 NGCC generation plants

To carry out this study, the actual operating data of a large-scale NGCC power plant was collected. The selected plant is one of three cogeneration plants (with similar characteristics) feeding the district heating network in Turin (Northern Italy). The plant has a nominal electrical power (in full electric operation) of 390 MW. The main characteristics of the plant are summarized in Table 1. The plant operates in CHP mode to supply heat and electricity. During the summer season, the heat demand is greatly reduced and in some periods it operates in full power mode.

The operating data of these plants are available on an hourly basis from the Emission Monitoring System (EMS). The main data available are the electrical and thermal power generated and the volumetric consumption of gas taken from the grid. Hourly data from 2018 to 2022 was used for this study. The hourly values made it possible to calculate the hourly carbon intensity of the electricity generated from 2018 to 2022 and consequently to compare the carbon intensity of the electricity from this plant with the values of the national grid. For the comparison between the intensity of the electricity generated by the plant and that of the future scenarios, it was assumed that the plant would be operated in the future scenarios as in 2019. The year 2019 was considered the most appropriate reference year, as it is

Table 1: Main characteristics of the NGCC plant.

Term	Unit	Value
Gas turbine gross nominal power	MW	270
Steam turbine gross nominal power	MW	120
Nominal net power - full electric mode	MW	390
Overall efficiency - full electric mode	-	56%
Nominal net power - CHP mode	MW	340
Overall efficiency - CHP mode	-	87%

the most recent year that was not affected by external effects that changed the normal operation of the power plant, such as the COVID19 pandemic (which affected the electricity and heat demand profiles) and Russia's invasion of Ukraine (which caused a significant increase in energy costs).

2.2 Cogeneration CO_2 intensity

In the case of cogeneration, it is not straightforward how to define the carbon intensity of the electricity generated. The CO_2 generated by the combustion of the fuel must in fact be allocated partly to the electrical energy produced and partly to the thermal energy produced. In the past, different methodologies have been proposed for the allocation of CO_2 in the case of cogeneration [14, 9]. One of the most common methodologies is the so-called energy share method, which was suggested by the European Union in 2018 as part of the recast of the Renewable Energy Directive (RED II) [15]. According to this methodology, the CO_2 of fuel used for cogeneration is allocated among electricity and heat productions in proportion to their energy content of the two outputs. Therefore, the CO_2 emissions allocated to the electricity output (C_{el} [g_{CO2}]) and the CO_2 intensity of the generated electricity (c_{el} [g_{CO2}/kWh]) are equal to:

$$C_{el} = C_{tot} \cdot \frac{E_{el}}{E_{el} + E_{th}} \tag{1}$$

$$c_{el} = \frac{C_{el}}{E_{el}} \tag{2}$$

where E_{el} [kWh] and E_{th} [kWh] are the electricity and heat productions respectively. C_{tot} [g_{CO2}] is the total CO_2 emissions coming from the fuel combustion in the CHP plant. The CO_2 associated with the fuel used depends on the properties of the fuel. The plant analyzed in this article uses natural gas from the national gas grid, whose carbon intensity value (c_{NG}) was assumed to be 201.6 g_{CO2}/kWh [16]. C_{tot} is calculated as:

$$C_{tot} = V_{NG} \cdot LHV_{NG} \cdot c_{NG} \tag{3}$$

where LHV_{NG} [kWh/Sm_3] is the the lower heating value of natural gas assumed equal to 9.766 kWh/Sm^3 [16].

2.3 Scenarios

The carbon intensity values of electricity generated from CHP were compared with those of the current and future national grid. The carbon intensity of the current grid was assessed using data from 2018 to 2022. The carbon intensity of the hourly grid was estimated using the actual electricity generation profiles by technology and source available from the European Network of Transmission System Operators for Electricity (ENTSO-E) [17] and the average carbon intensity value per source defined by the Italian Institute for Environmental Protection and Research (ISPRA) [18]. The grid carbon intensity of the future scenarios was based on the future scenarios defined by the Italian electricity and gas transmission system operators (Terna and SNAM respectively) and published in the report 'Documento di Descrizione degli Scenari 2022' (DDS22) [19]. The scenarios presented are a more detailed adaptation of the scenarios defined by the European National Transmission System Operators (ENTSO-E and ENTSO-G for the electricity and gas sector respectivly) for the Italian case [20]. 3 different scenarios were considered: 1 for 2030 and 2 scenarios for 2040. The scenario for 2030 is in line with the European targets to reduce CO_2 emissions by 55% compared to 1990 levels. The scenario envisages a complete phase-out of coal use and electricity generation from renewable sources equal to 65% of electricity demand. The use of electricity-powered technologies that replace fossil solutions (e.g. heat pumps, electric vehicles and electrolysers)

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will increase the national demand for electricity. The two scenarios for 2040 are 2 possible evolutions of the 2030 scenario that make it possible to achieve the carbon neutrality targets in 2050. The first scenario, called 'Distributed Energy' (DE), foresees a higher penetration of renewable energy and greater electrification in all sectors (buildings, industry and transport), while the second possible scenario, called 'Global Ambition' (GA), relies more on the use of biomethane and green hydrogen. Both scenarios require a significant improvement in the efficiency of the end-use sector. The energy demand per sector for the different scenarios is shown in Table 2. Although higher efficiency is expected, increasing electrification leads to an increase in energy demand in all sectors. Compared to electricity consumption in 2019, the demand for electricity increases by around 15% in 2030. Compared to 2019, energy demand in 2040 increases by 30% in the DE scenario (with more electrification than in the GA scenario) and by 24% in the GA scenario.

Table 2: Electricity consumption by sector.

	Unit	2019	2030	2040 DE	2040 GA
Industry	TWh	129	136	150	145
Buildings	TWh	161	177	182	179
Transport	TWh	12	34	64	51
Network losses	TWh	18	20	22	21
Tot electricity consumption	TWh	320	366	418	396

Electricity generation will change considerably. In 2019, 43% of electricity generation was produced by burning natural gas and 10% by other non-renewable sources (including coal and petroleum products). RES covered about 35%: 15% from hydropower and the remaining 20% in almost equal parts from photovoltaic, wind and other RES (including biogas). The reduction in the carbon intensity of the grid will be achieved through a reduction in fossil fuels and an increase in renewables. Gas consumption will account for 20% of total consumption in 2030, falling to around 11-13% in 2040. The use of coal will be completely phased out and a small share of electricity from petroleum products will remain, accounting for about 1% of the total. Wind an PV energy generations will increase significantly and cover more than 45% of electricity demand in 2030 and around 60% in 2040. Other renewable energies, on the other hand, will remain more or less unchanged. At the same time, losses due to the curtailment of surplus generation from renewable energies and losses due to the use of storage facilities will also increase. Energy exchange with other countries will increase in absolute terms, but will remain between 12% and 14% in percentage terms. The data on electricity generation by source is summarized in table 3.

Table 3: Electricity generation by source.

	Unit	2019	2030	2040 DE	2040 GA
Gas	TWh	138	75	46	50
Other non-RES	TWh	31	5	3	3
PV	TWh	23	101	157	138
Wind	TWh	20	68	108	99
Hydro	TWh	46	51	51	51
Other RES	TWh	23	23	25	25
Import-Export	TWh	38	52	54	49
Curtailment	TWh	0	-5	-16	-11
Storage losses	TWh	-1	-4	-10	-8
Tot electricity generation	TWh	318	366	418	396

Note that the scenarios defined by Terna and SNAM also include a significant increase in biomethane production. According to the DM 15/09/2022 regulation [21], electricity production from biomethane cannot be subsidized. Moreover, biomethane will be an asset for the decarbonization of the transport sector [22] (whose decarbonization is more critical), so in this work it was assumed that there will be no electricity generation from biomethane. To assess the hourly carbon intensity, hourly production values from the different sources are needed. For the 2019 case, the real hourly generation profiles from ENTOS-E were used [17]. The electricity generation profiles required to calculate the carbon intensity of the grid for the years 2030 and 2040 were simulated using the EnergyPLAN tool [23]. EnergyPLAN is a well established simulation tool for the energy analysis of systems at a national and regional level [24, 25, 26]. The energy balance of the scenario is created on an hourly basis, taking into account the different energy sectors and infrastructures and their interconnections according to the smart energy system approach [27]. The tool takes the hourly profiles of energy demand and renewable generation as input. The current hourly electricity demand profile was downloaded from the Terna database [28]. For future scenarios, a change in the profile due to an increase in electric heating and electric transport was taken into account. The consumption profile for electric heating was assessed considering 2010 as the baseline climate profile, as proposed in the study carried out by Terna and the Polytechnic University of Bari [29]. The electricity demand profile for electric vehicles was taken from [30] and scaled according to the energy demand predicted in the DDS22 scenarios. The photovoltaic and wind power generation profiles were downloaded from renewable.ninja [31] considering again the 2010 as the reference climating year. The EnergyPLAN output contains hourly electricity generation profiles of all technologies involved in the scenario and the fuels used. On this basis, it was possible to produce an estimate of the carbon intensity profiles of the grid for the years 2030. Although this approach has its limitations, this method made it possible to estimate the variations in the different times of the year and day.

3 Results

The results of this study allows a comparison between the CO_2 intensity allocated to the electricity output of the NGCC unit analyzed with the average hourly electricity mix of the Italian network. This evaluation has been done both on an historical trend of five years and on future scenarios related to the current national decarbonization targets, as explained in the previous sections.

3.1 Historical trend

The CO_2 intensity of the electricity produced by the CHP plant shows significant variations over the hours of the day and the months of the year, due to the variable operation conditions related to the heat supply to the district heating and the power plant load. The median profiles of the CO_2 intensity are reported in Figure 1.

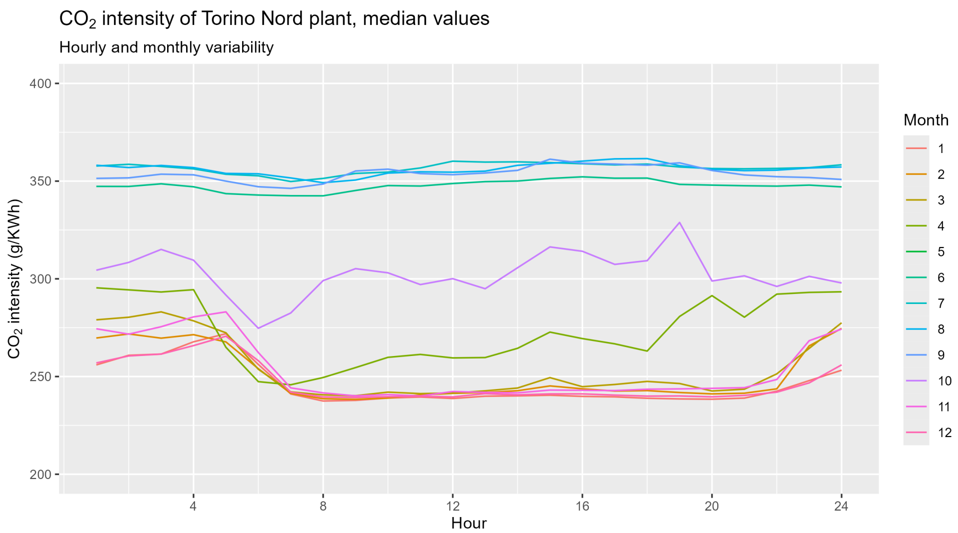

Figure 1: Median values of the CO_2 intensity of Torino Nord plant, detailed by month and hour.

The plot shows the two distinct groups of months in which the power plant is operating in full-electric mode (with a rather constant CO_2 intensity around 350 g/kWh) or in CHP mode (with variable daily profiles following the heat demand of the system). The chart also shows the behaviour of the system in mid-seasons, with the months of April and October where heating systems are in partial operation. The month of May is not reported in the chart, as the power plant always undergo planned maintenance and it is shut down for the entire month.

The median value of the CO_2 intensity of the plant is 291 g/kWh, while the monthly median values range from 242 g/kWh in January to 357 g/kWh in July. This indicator also show a variability from a year to another. Considering the years 2018-2022, annual median values varied from a minimum of 258 g/kWh in 2021 to a maximum of 325 g/kWh in 2022. This variability can be related to a number of reasons, including the different heat demand over the years, and the natural gas and electricity prices leading to different operation logics during the summer.

This chart highlights the importance of properly incorporating this variability in larger energy systems modelling, to account for a precise description of the performance of these CHP plants. At the same time, it is important to note that these units are actually coupled to both the electricity grid and the district heating network, and thus their operation logics should be defined based on the needs of both systems, and not only on their economic (or environmental) parameters on the electricity market.

A similar analysis is performed on the Italian hourly electricity mix, as explained in the previous sections. The monthly variability of the CO_2 intensity is reported in Figure 2, where median hourly profiles for each month are compared (considering the years from 2018 to 2022).

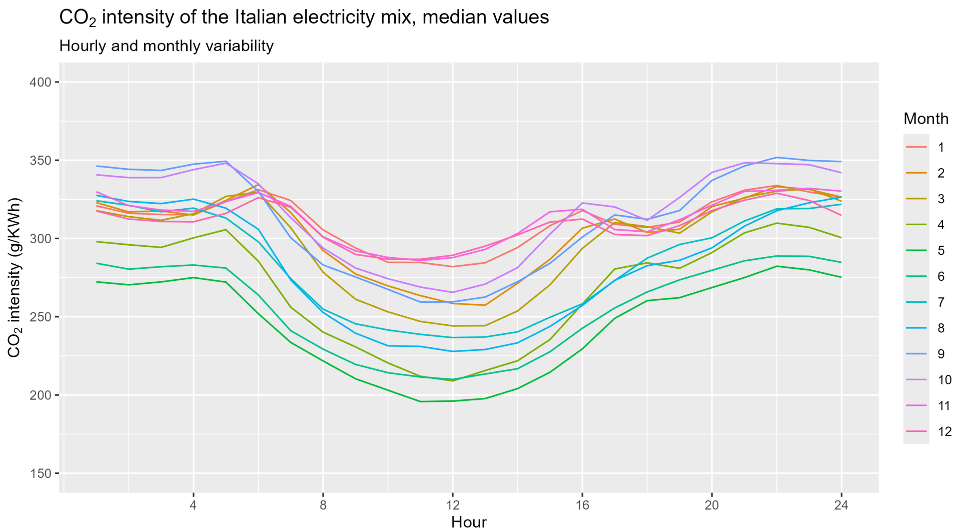

Figure 2: Median values of the CO_2 intensity of the Italian electricity mix, detailed by month and hour.

The different levels of the CO_2 intensity are related to the share of renewable sources, mostly hydropower, solar and wind. The contribution of solar is evident from the similar variations during daylight hours, although at different scales due to the seasonality. Monthly median values of the CO_2 intensity of the Italian electricity mix in the years 2018-2022 range from 247 g/kWh in May to 312 g/kWh in September. Annual median values range from a minimum of 272 g/kWh in 2020 to a maximum of 320 g/kWh in 2018, due to different electricity generation mixes over the year, which are in turn related to variable renewable generation and different fossil mixes, especially given the important variability of natural gas prices in the last years.

The variability of the CO_2 intensity represented above for both the CHP plant and the average electricity mix can be compared, to see when the plant performs better or worse than the average power plant. This comparison can be represented both in terms of monthly variability (in Figure 3) or as the probability density of the distribution over each of the five years considered in the analysis (in Figure 4).

In both charts the absolute difference is computed as CHP emissions vs electricity mix emissions. Thus, positive values represent conditions in which the CHP has emitted more than the average electricity mix per unit of electricity produced, while negative values represent conditions in which the CHP has performed better than the electricity mix in terms of CO_2 emissions. These charts incorporate the combined effect of the variability of the CHP emission intensity already discussed above and the variability of the CO_2 intensity of the electricity mix, that is widely addressed in the literature [6, 8].

Figure 3 clearly highlights the monthly variability of this comparison. During the winter months, the lower CO_2 intensity of the CHP discussed above lead to negative net differences against the average electricity mix, with median monthly values as low as -59 g/kWh in January (although with significant variations from a year to another, as clearly showed in the chart). Conversely, during the summer the

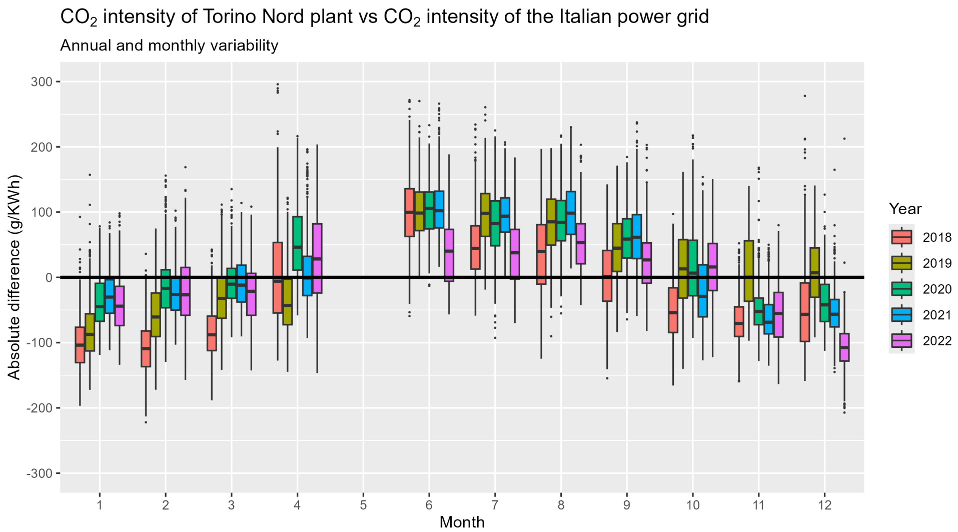

Figure 3: CO_2 intensity of Torino Nord plant vs Italian power grid, detailed by month and year.

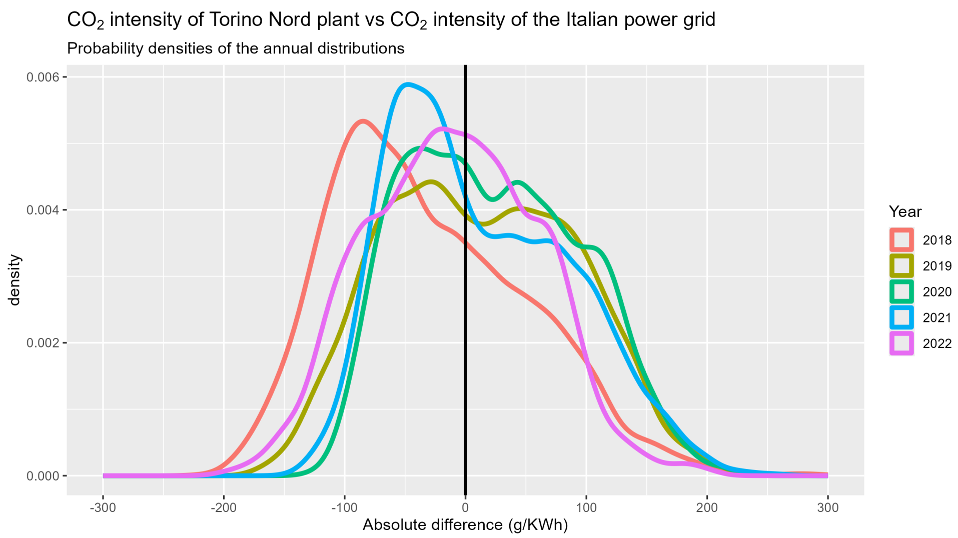

Figure 4: Probability density of the comparison of the CO_2 intensity of Torino Nord plant against the CO_2 intensity of the Italian power grid, detailed by year.

CO_2 emission intensity of the CHP plant is mostly higher than the average electricity mix, with a median difference in June that reaches 94 g/kWh. This result is the combined effect of a higher emission of the plants that are not producing a significant amount of heat and the lower carbon intensity of the national electricity mix thanks to the higher productivity of solar plants (and possibly hydro power plants) compared to the winter months.

Figure 4 highlights the monthly distribution of the same difference, whose median values range from -43 g/kWh in 2018 to 18 g/kWh in 2020. Thus, taking into account the variability over the year, the performance of this plant is generally comparable with the average electricity mix that is currently produced by Italian power plants.

3.2 Future scenarios

A similar analysis can be performed in the framework of the expected future scenarios, to assess how the current CHP units would compare with the expected future electricity mix of the Italian power generation system.Based on the scenarios presented in the previous sections, the CO_2 intensity of the Italian average electricity mix is expected to significantly decrease compared to the current situation. The median hourly profiles for the last five years are compared with the future scenarios for 2030 and 2040 in Figure 5. Results clearly show the very significant decrease of the GHG emissions of the Italian electricity generation system, mostly due to the very strong increase of RES power plants that are expected to begin operation. These challenging CO_2 intensity levels will also require a set of flexibility measures to balance the variability of some sources, especially solar and wind energy.

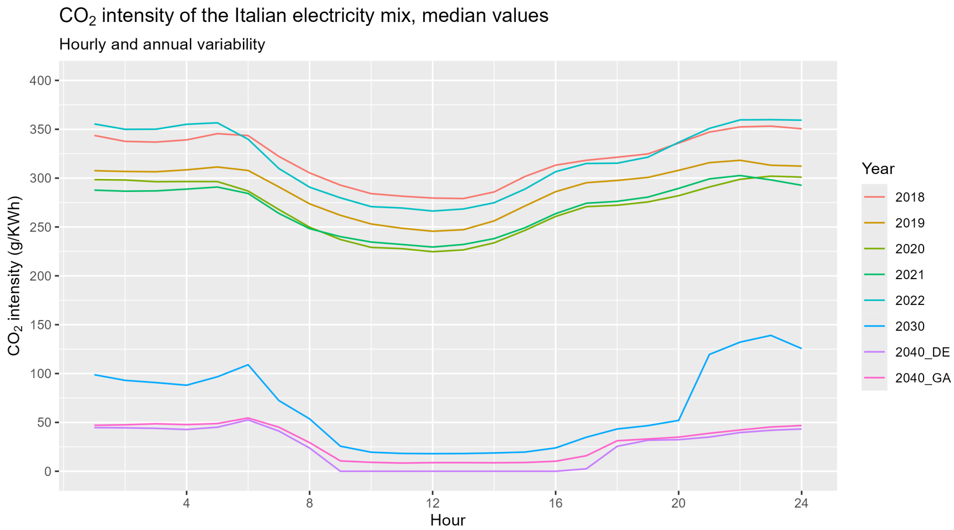

Figure 5: Median values of the CO_2 intensity of the Italian electricity mix, detailed by year and hour.

In this new context, the comparison of the performance of the CHP unit (considering 2019 as reference year) fares much worse than in the current situation. Figure 6 and figure 7 clearly demonstrate that the CHP units running on natural gas have almost always higher emissions compared to the average emissions of the Italian electricity mix. The absolute values remain slightly lower in winter, with median differences as low as 141 g/kWh in January for the 2030 scenario, compared to a value of 332 g/kWh for July of the same year.

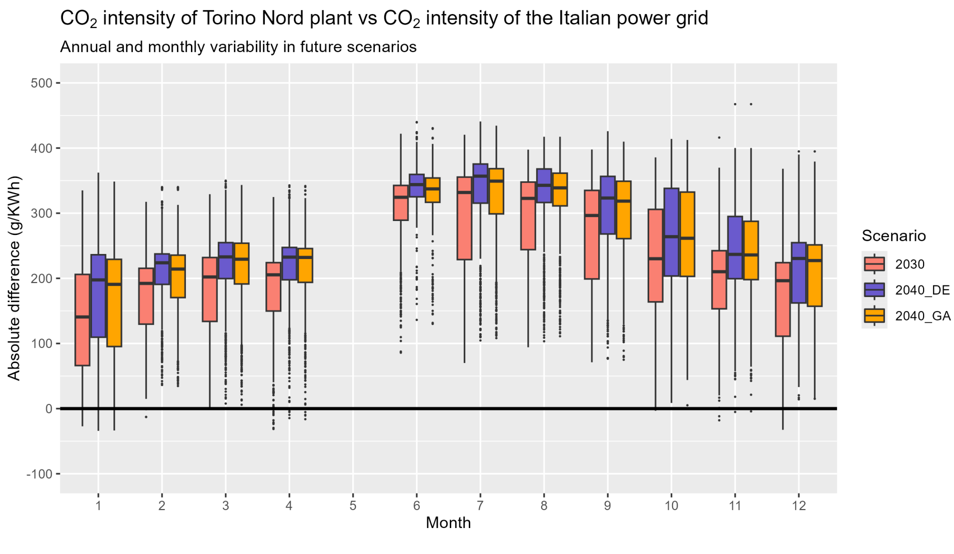

Figure 6: CO_2 intensity of Torino Nord plant vs Italian power grid in future scenarios.

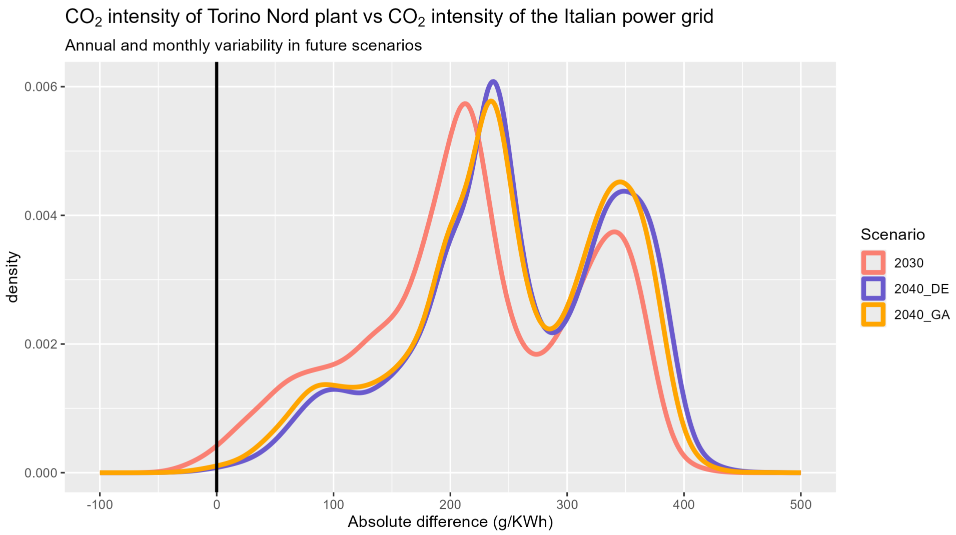

Figure 7: Probability density of the comparison of the CO_2 intensity of Torino Nord plant against the CO_2 intensity of the Italian power grid in future scenarios.

Figures for 2040 increase in both cases, with median monthly differences in a range from 191 g/kWh in January (GA scenario) to 357 g/kWh in July (DE scenario, where the average electricity mix has zero emissions).

4 Conclusions

This paper presented the hourly carbon intensity analysis of electricity generated by cogeneration. The plant analyzed is a large-scale natural gas combined cycle plant connected to the district heating network in Turin. The hourly carbon intensity profile of this plant was compared with the carbon intensity of the current and future national electricity system. The main conclusions can be summarized in the following points:

- The carbon intensity of electricity from cogeneration varies depending on the mode of operation of the plant. When the plant is operated in cogeneration mode, part of the CO_2 produced is allocated to the heat carrier, which reduces the carbon intensity of the electricity produced. For this reason, the lowest values for carbon intensity are found in winter, when heat demand is higher: the average carbon intensity in January (month when heat production is maximized) is 242 g/kWh, while in July it was 357 g/kWh (the overall average of the plant was 291 g/kWh).
- In contrast, the values for the carbon intensity of the electricity grid show an opposite trend. In summer, the carbon intensity of the electricity is lower due to the higher contribution of renewable energies. On an annual average, the carbon intensity of electricity produced from combined heat and power is similar to that of the national grid. The months in which the difference between the two carbon intensity values is greatest are January and June. In January, the carbon intensity of cogenerated electricity is 43 g/kWh lower than that of the grid, while in June it is 94 g/kWh higher.
- In the future scenarios, as in the current scenario, the carbon intensity of the electricity grid is lower in the summer months than in the winter months, which is due to the higher production of renewable energy. The high penetration of renewables in the energy mix significantly lowers the carbon intensity value of the national grid, which is practically always lower than the electricity generated by cogeneration. In the 2030 scenario, electricity from cogeneration has a higher carbon intensity value than electricity from the grid in more than 98% of the time. This difference increases in 2040 due to the increasing penetration of renewables.

Combined heat and power technologies have always been considered the most efficient methods of generating heat and electricity. In an energy transition that includes more and more renewables, this paradigm could change. It is clear that from a carbon neutrality perspective, it is more convenient to generate electricity from renewable sources and heat energy either directly from renewable sources (e.g. solar thermal) or from systems such as heat pumps powered by electricity from renewable sources. These scientific findings must be taken into account when planning the energy transition in the coming years. Large infrastructures, such as the district heating network in Turin, are based on combined heat and power technology. Numerous studies have shown the feasibility of low-temperature district heating networks that could be powered by renewable heat generation and/or heat pumps. However, these technologies must operate at lower temperatures. It would be interesting to invest in retrofitting these infrastructures to make them suitable for operation at lower temperatures. Finally, it should be noted that this article assumes that these plants will not fueled by biomethane. This assumption is in line with current policy and the idea of leaving this important resource to more critical sectors. Of course, the considerations made in this article would change if the use of biomethane were considered. The use of bioenergy could be the only solution to maintain the current operation of this infrastructure even in a carbon neutrality scenario.

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