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Journal of Cleaner Production 490 (2025) 144677

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Evaluating the environmental performances of thermal power plants: A study on EMAS registered Italian sites

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ARTICLE INFO

Handling Editor: Tomas B. Ramos

Keywords:
Energy production
Thermal power plants
Environmental impact
EMAS
Emissions
Water consumption

ABSTRACT

Transitioning to sustainable energy production is imperative to mitigate the environmental impacts associated with the reliance on non-renewable resources. However, thermal power generation still provides a significant share of electricity production, originating significant impacts that will need to be better understood and addressed along the transition period. This paper comprehensively analyzes the environmental performance of 73 Italian thermal power plants registered under the Eco-Management and Audit Scheme (EMAS) from 2014 to 2021. The key goals were to assess current performance levels, examine how plant characteristics influence performance, and analyze temporal trends. Using independently validated data, 12 key environmental performance indicators (energy production efficiency, emissions to air, water consumption, waste production, and electricity consumption) were analyzed. Natural gas (NG) plants consistently outperformed others. For instance, they achieved a higher net energy efficiency (46.7% median) compared to coal plants (32.1%), while emissions of NOx were significantly lower (122 g/MWh for NG vs. 447 g/MWh for others). From 2014 to 2021, NG plants exhibited performance improvements across all indicators (+18% overall), while coal plants' performance declined in 7 out of 12 indicators (−72% overall). Combined heat and power (CHP) plants also outperformed conventional plants, while plant size, age, and operational hours exhibited limited influence. This study highlights the need to promote the transition from coal to natural gas, even if anti-coal policies might have hindered coal plant performances. Also, CHP facilities should be encouraged when heat demand is high. Moreover, disclosing and mitigating emissions occurring under other than normal operating conditions should be prioritized to allow for fairer comparisons of plants' performances and to reduce environmental impacts.

1. Introduction

In 2022, fossil fuels provided 79% of global energy supply (IEA, 2023), and the power sector accounted for 27% of global greenhouse gas (GHG) emissions (European Commission, 2023). The European Green Deal (European Commission, 2019) plans to reduce GHG emissions by at least 55% by 2030. A shift towards renewable energy sources is urgently needed to achieve this ambitious goal. However, transitioning towards renewable energy will require time. Meanwhile, understanding and mitigating the environmental impacts of thermal power plants is crucial. Understanding the current environmental performance of thermal power plants allows targeted measures to improve them and limit their impacts during the transition period. Thermal power plants generate electricity by employing steam or gas turbines. The first accounts for 46% of EU-27 and 19% of Italian electricity production capacity, and the second for 5% and 6%, respectively (Eurostat, 2023a). Combined-cycle power plants employ both turbines (Arabi et al., 2016), accounting for 36% of EU-27 and 70% of Italian electricity production capacity (Eurostat, 2023a). Combined heat and power (CHP) plants maximize energy production efficiency by generating electricity and heat simultaneously. In Europe, natural gas (NG) accounts for most of the energy produced by fossil fuel combustion (51% in EU-27 and 88% in Italy in 2021), followed by coal and oil (Eurostat, 2023b).

The Best Available Techniques Reference (BREF) for large combustion plants (Lacomte et al., 2017) provides a comprehensive overview of the impacts associated with thermal power plants, such as water consumption and discharge, GHG and air emissions (SOx, NOx, particulate matter), and waste management. Thermal power generation has the highest environmental impacts (Stougie et al., 2018; Strezov and Cho, 2020; Vega-Coloma and Zaror, 2018), although specific plants may have better environmental performance than renewable sources under specific conditions (Cartelle Barros et al., 2020).

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https://doi.org/10.1016/j.jclepro.2025.144677
Received 25 July 2024; Received in revised form 6 December 2024; Accepted 3 January 2025
Available online 13 January 2025

Extensive research explored the environmental performance of thermal power plants, consistently indicating higher environmental impacts from coal and heavy oil plants than from diesel and NG ones (Strezov and Cho, 2020), with substantially higher air pollutants (Oberschelp et al., 2019; Zroichikov et al., 2015) and GHG (Chang et al., 2015; Song et al., 2018) emissions and higher water consumption levels (Chang et al., 2015). Coal quality (Kaldellis and Kapsali, 2014), specific air emission control technologies (Zroichikov et al., 2015), plant age and size (Kaldellis and Kapsali, 2014), combined cycle operations and CHP (Eguchi et al., 2021; Zroichikov et al., 2015) are also significant factors.

The literature also investigated specific impacts associated with thermal power plants: air pollutants and GHG (Guttikunda and Jawahar, 2014; Song et al., 2018), water consumption and footprint (Lee et al., 2018; Pan et al., 2018; X. Wu et al., 2019), electricity consumption (Mujanović et al., 2020), and power generation efficiency (Eguchi et al., 2021). Notably, Huang et al. (2017) identified power generation as China's predominant source of CO_2, NO_x, and SO_2 emissions.

Existing literature has paid limited attention to the temporal trends in the environmental performance of thermal power plants. Zroichikov et al. (2015) assessed the trends in the thermal power industry in Moscow from 1990 to 2010, highlighting significant reductions in air emissions attributed to increased NG use and improved emission control technologies. Similarly, Tong et al. (2018) evaluated the evolution of coal power plants in China from 2010 to 2015, revealing significant reductions in SO_2, NO_x, and dust emissions due to environmental legislation but increased CO_2 emissions. Kaldellis and Kapsali (2014) also identified significant reductions in SO_2 and NO_X emissions of Greek coal plants from 1995 to 2011 but increased CO_2 and dust emissions. Conversely, Huang et al. (2017) assessed the Chinese thermal power industry from 2008 to 2012, finding reductions only in SO_2 and dust emissions and increased NO_x, CO, and CO_2 emissions due to rising coal consumption. Finally, Zhang et al. (2018) found increased freshwater withdrawal for thermoelectric energy production in China from 2000 to 2015.

To the best of our knowledge, several knowledge gaps are present in existing literature:

- The European context is overlooked.
- The assessment of NG environmental performance is lacking compared to coal plants.
- Focus is limited to air emissions and water consumption.
- Lack of comprehensive analysis regarding the influence of thermal power plant characteristics on environmental performance.
- Limited exploration of temporal trends, especially post-2010.
- Life Cycle Assessment (LCA), a tool widely used to evaluate environmental impacts throughout a product's life cycle, is adopted in most studies. However, LCA is inherently limited by challenges such as the need for extensive data input, which is often incomplete or inconsistent, and the reliance on assumptions and modeling that introduce uncertainty in the results (Khandelwal et al., 2019; Zhang et al., 2021).

This study has three novelties. Firstly, it evaluates the current and long-term environmental performance of thermal power plants within the European context, adopting a novel holistic approach that considers overall environmental impacts. Secondly, it thoroughly assesses how the characteristics of thermal power plants influence environmental performance. Thirdly, it relies on publicly available, comprehensive, and independently validated data, enabling a robust and replicable analysis. This study analyses the environmental performance of Italian thermal power plants registered under the Eco-Management and Audit Scheme (EMAS) over an 8-year period (2014–2021). EMAS, a voluntary Environmental Management System (EMS) established by the European Union, helps organizations manage and reduce their environmental impacts. Registered organizations must disclose environmental performance data annually through an Environmental Statement (ES), subject to validation by an independent verifier. This study focuses on the European context because publicly available, comprehensive, and independently validated data in the form of ESs is uniquely available for EU companies. This study specifically targeted Italian plants as Italy contributes to 16% of the electricity generated by thermal power plants in the EU-27 (Eurostat, 2023c), and 146 of the 257 European EMAS-registered energy production sites are located in Italy.

Table 1
Selected KPIs (NEE = net electrical efficiency, NTFU = net total fuel utilization).

Key aspect	Indicators	Unit
Energy production efficiency	NEE, NTFU	%
Emissions to air	CO_2, CO, NO_x, SO_x, Dust	kg/MWh, g/MWh
Water consumption	Cooling water, process water	m^3/MWh
Waste production	Total waste, hazardous waste	kg/MWh
Electricity consumption	Grid electricity	MWh/MWh

Specifically, our study explored three key research questions. 1. What is the current environmental performance of Italian thermal power plants? 2. How do thermal power plant characteristics influence environmental performance? 3. How did the environmental performance of Italian thermal power plants evolve from 2014 to 2021?

2. Methodology

This study adopted a three-phase methodology (Castelluccio et al., 2022, 2024; Comoglio et al., 2022a, 2022b, 2023): inventory of EMAS registered Italian thermoelectric power plants; data collection and analysis from the ESs, focusing on plants technical features and environmental performance; sensitivity analysis to assess the robustness of the findings.

2.1. Inventory

The inventory was compiled by cross-referencing the National Register of EMAS-certified sites (ISPRA, 2024) and the European Commission's EMAS Register (European Commission, 2024). The ESs of sites under NACE code "E35.11" (i.e., production of electricity) were collected through the companies' websites or direct contact with the facility managers (Castelluccio et al., 2024) and thoroughly screened to exclude sites:

- Performing activities different from thermal power plant operation.
- Performing other activities along thermal power plant operation when only overall information was disclosed.
- With the last ES published before 2020 (i.e., outdated data).
- EMAS-registered after 2022 (i.e., EMS not yet consolidated).

2.2. Data analysis

2.2.1. Plant features

The initial phase of the ESs analysis focused on examining key characteristics of the plants: plant configuration, installed capacity, primary fuel, emission control technologies, operating hours, and energy production. Plants were categorized as CHP when heat accounted for more than 10% of the total energy output.

2.2.2. Identification of key environmental aspects and performance indicators

Through an extensive analysis of the scientific literature and BREF, energy production efficiency, emissions to air, water consumption, waste production, and electricity consumption were identified as key environmental and technical aspects. Twelve related key performance indicators (KPIs) were defined (Table 1). The KPIs describing the energy production efficiency were derived from the BREF and calculated through eqs. (1) and (2):

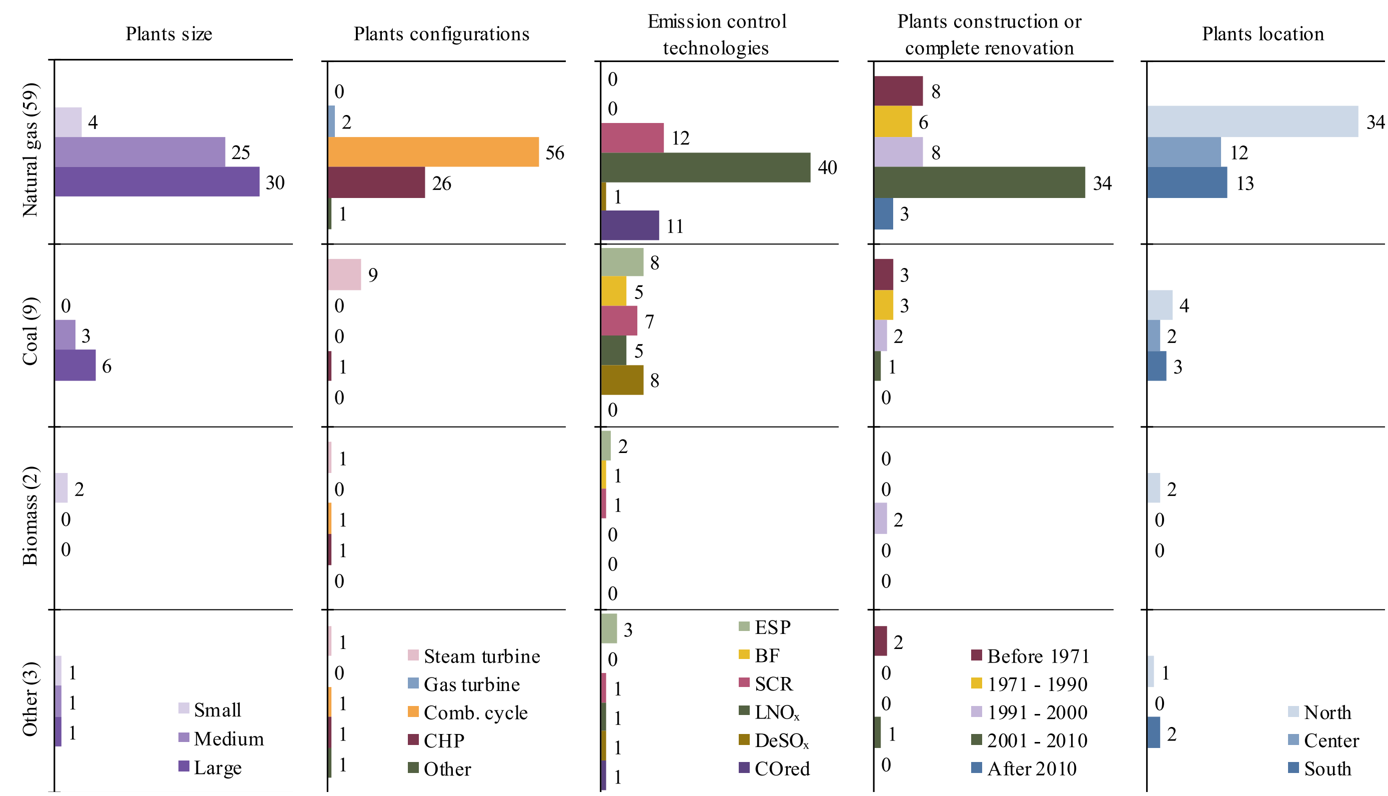

Fig. 1. Overview of the plants' characteristics based on primary fuel used (Plants' size: Small<100 MW_{tot}; 100 MW_{tot} ≤ Medium <500 MW_{tot}; Large≥500 MW_{tot}. Emission control technologies: ESP = electrostatic precipitator; BF = bag filter; SCR = selective catalytic reactor; LNO_x = low NO_x burner; $DeSO_x$ = SO_x removal; CO_{red} = CO reduction. Plant configurations: CHP = combined heat and power).

$$\text{Net Electrical Efficiency } (NEE) = \frac{El_{out}}{En_{fuel}} \tag{1}$$

$$\text{Net Total Fuel Utilization } (NTFU) = \frac{En_{out}}{En_{fuel}} \tag{2}$$

where El_{out} is the net electrical output, En_{out} the net energy output (i.e., electricity, heat, and mechanical energy), and En_{fuel} the fuel energy input.

The dust KPI refers to a comprehensive measure of particulate matter (e.g., PM2.5, PM10) emissions as reported in the ESs. The dust metric is a general indicator representing the aggregate of PM emissions, ensuring consistency and comparability within the dataset, as most ESs disclose an integrated value rather than specific size-based fractions. The total waste KPI encompasses the total amount of waste generated by the plants, including but not limited to:

- Maintenance waste (e.g., used lubricants, machinery parts).
- Combustion waste (e.g., ash, slag from coal combustion).
- Exhaust treatment waste (e.g., residues from air pollution control systems).
- Wastewater treatment waste (e.g., sludge from water purification processes).
- Packaging waste (e.g., containers or materials used for raw material handling).
- Construction debris from plant upgrades.

These categories were aggregated to evaluate the overall waste management efficiency of the plants.

Apart from NEE and NTFU, all KPIs are normalized by the total net energy produced by the plant. Process water includes water used for all operations apart from cooling.

2.2.3. Assessment of environmental performance and plant characteristics influence

The average performance of the 12 KPIs was calculated over 2018–2020 (Supplementary Material C) and compared to the available Best Available Technologies Associated Emission Levels (BAT-AELs), serving as optimal performance benchmarks.

Z-score standardization was implemented when comparing indicators to minimize the effects of different orders of magnitude and variance. The Z-score was calculated for each KPI and each plant using eq. (3):

$$Z_i = \frac{\bar{x}_i - \mu_i}{\sigma_i} \tag{3}$$

where $\bar{x}_i$ is the average KPI value over the period, μ_i the average performance across the sample, and σ_i the standard deviation. Lower Z-scores typically indicate better performance across all indicators except for energy production efficiency.

The influence of the plants' characteristics on KPIs was evaluated, using the average KPI value over 2018–2020 for each plant, and compared with the BREF and relevant literature. The average Z-score of the five KPIs related to the aspect emissions to air was also calculated to evaluate the influence of plant characteristics on overall air emissions.

2.2.4. Trends assessment

The environmental performance trends were analyzed over 2014–2021 on a subset of plants (Supplementary Material D), as not all disclosed long-term performance data. The average performance was computed for all KPIs considering two sub-periods, i.e., 2014–2016 (t_{start}) and 2019–2021 (t_{end}), to minimize the impact of anomalies and specific events, providing a more robust representation of the underlying trends. The percentage change of t_{end} levels compared to t_{start} levels was calculated.

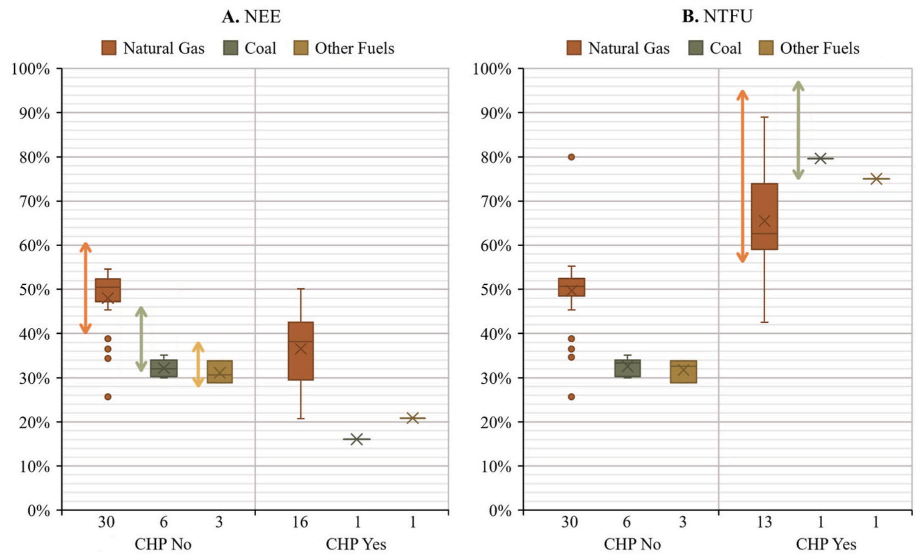

Fig. 2. Energy production efficiency Key Performance Indicators (KPIs) of the power plants (average values over the 2018–2020 period) by plant characteristics (fuel type and configuration). Panel A shows the Net Energy Efficiency (NEE), while Panel B presents the Net Total Fuel Utilization (NTFU). High KPI values = high performances. When applicable, the BAT-AEL range is marked by an arrow to the left of the corresponding box. The number of power plants in each group is shown on the x-axis. x = average, horizontal line = median, dots = outlier points. Non-CHP plants may have slightly higher NTFU than NEE due to minor heat production (<10% of total energy production).

The overall environmental performance trend (OPT) was obtained by averaging the performance change of all KPIs compared to 2014 levels, calculating OPT for each year separately for NG and coal plants according to eq. (4):

$$OPT_{\ t} = \frac{1}{n} \sum\nolimits_{i=1}^{n} \frac{x_{2014,i} - x_{t,i}}{x_{2014,i}} \tag{4}$$

where $x_{t,i}$ is a KPI value referring to a specific plant (i) and year (t), $x_{2014,i}$ the 2014 KPI value, and n the total number of KPI series. Positive values indicate improvements.

2.3. Sensitivity analysis

Multiple statistical tools were employed:

- The Mann-Whitney *U* test to identify statistically significant differences in the distributions of two independent variables. T
- The Chi-Square test for categorical data analysis to investigate potential significant differences between various groups or samples.
- The Spearman's rank correlation test to assess the strength and direction of a monotonic relationship between two variables.
- The Kendall's tau test to assess the significance of trends in the time series data.

A 5% significance level ($p < 0.05$) was adopted to determine the statistical significance of the observed results.

3. Results and discussion

3.1. Sample description

Out of 145 EMAS-registered Italian energy production sites registered in 2023, 86 included a thermal power plant (Castelluccio et al., 2024). The final sample of 73 installations (Fig. 1; Supplementary Material A and B) has an average installed capacity of 590 ± 490 MW_{tot} (43 GW_{tot} total), varying considerably from 6 MW_{tot} (plant 72, fed by biomass) to 2640 MW_{tot} (plant 61, using coal). The total heat and electricity production in 2019 (the year with the highest data availability) was 8.6 and 92.7 TWh (13.4 and 32.6% of Italian production) (Eurostat, 2023c). NG was the predominant fuel, providing over 85% of the total energy input in 59 plants. NG plants applied combined cycles (95% NG plants vs. 14% non-NG plants) and never used steam processes (vs. 86% non-NG). NG plants were more frequently operated as CHP (44% NG vs. 20% non-NG, difference not statistically significant).

Nine non-NG plants used coal as primary fuel, applying steam processes and displaying larger installed capacity compared to plants fed by other fuels (1012 ± 868 MW_{tot} vs. 534 ± 404 MW_{tot}, difference not statistically significant). Two plants predominantly used biomass, two relied on a combination of fuels, and one used oil. Excluding the oil plant, these plants employed steam or gas turbines, combustion engines, combined cycles, and had significantly smaller installed capacity than those using NG or coal (totaling 423 MW_{tot}, i.e., 1% of the sample installed capacity).

Summarizing the configurations of the surveyed plants, 58 used combined cycle systems, 11 steam turbines, 2 gas turbines, and 2 combustion engines combined with gas or steam turbines. Compared to other plants, NG ones showed more efficient configurations, such as combined cycles and CHP. For coal plants, more complex configurations, such as integrated gasification combined cycle systems, can improve efficiency and reduce pollutants emissions (Yang et al., 2019). However, the scheduled shutdown of coal plants in Italy by 2025 (Ministry of Economic Development et al., 2019) can explain the absence of advanced plant configurations, which in Italy are primarily observed in refineries (Allevi and Collodi, 2017).

Considering age, plants using coal and oil were significantly older than others (Mann Whitney's *U* test, Mdn = 1984 vs. Mdn = 2003, U [$N_{oil\&coal}$ = 10 N_{other} = 61] = 132, $p = 0.004$), and none underwent significant renovation after 2003. 68 out of 73 plants were operating in 2019. Among the five inactive plants, three (plants 13, 18, 19) were small NG plants (<150 MW_{tot}), one (plant 25) a larger NG plant implementing a less efficient configuration (gas turbines), and the last (plant 44) a small coal plant (150 MW_{tot}). Plant 31, a medium-sized coal plant, was shut down after 2021. In 2019, the active plants operated 5477 ± 2273 h on average.

A moderate positive correlation was observed between the plants' installed capacity and average operating hours in 2018–2021, $r(26) = 0.45$, $p = 0.022$ (Spearman's test, r(26) refers to the correlation coefficient calculated for 26 data points). Larger plants usually benefit from

Table 2
Average mass of pollutants emitted to air divided by energy produced in 2019.

Pollutant	N. of plants	Unit of measurement	Average	Natural gas average	Coal average
CO_2	53	kg/MWh	489 ± 274	375 ± 93	928 ± 240
CO	51	g/MWh	119 ± 125	115 ± 126	127 ± 123
NO_x	54	g/MWh	209 ± 260	125 ± 49	414 ± 218
Dust	14	g/MWh	9.6 ± 10.8	0.8 ± 0.3	11.6 ± 10.0
SO_x	13	g/MWh	316.6 ± 225.0	3.1 ± 0.4	392.1 ± 198.9

improved fuel efficiency and economy of scale and can produce energy at lower cost (C. Wu et al., 2019; N. Zhang et al., 2014), which could incentivize longer operating hours.

Regarding air emissions treatment, NG plants did not implement ESPs, BFs, or DeSOx systems (except plant 70, which also used small amounts of biomass), while these technologies were employed by 93%, 43%, and 64% of non-NG plants, respectively. On the contrary, only NG plants adopted CO catalytic reduction (18% of plants) and were characterized by a significantly higher adoption rate of LNO_x burners (89% NG vs. 43% non-NG), $X^2(2, N = 59) = 13.2$, $p < 0.001$ (Chi-Square test). As expected, NG plants prioritized the reduction of CO and NO_x emissions, while others focused on mitigating dust and SO_x emissions.

3.2. Environmental performance

3.2.1. Energy production efficiency

In 2019, power plants achieved 41.1 ± 10.2% NEE (NG 44.0 ± 9.1%, coal 30.8 ± 5.8%) and 51.4 ± 14.8% NTFU (NG 54.2 ± 12.0%, coal 40.3 ± 20.2%) on average. Most NG plants exhibited optimal performances, with NEE and NTFU values within the BAT-AEL ranges (Fig. 2). Four out of five underperforming NG plants were non-CHP, with a capacity <250 MW_{tot}, and the least efficient employed an open-cycle gas turbine, which is less efficient compared to a combined cycle (Aminov et al., 2016; Kotowicz and Brzęczek, 2018). Conversely, the NEE and NTFU values of the coal plants were at the lower end of the respective BAT-AEL range (Fig. 2) or slightly below the lower BAT-AEL.

The most significant factors influencing NEE and NTFU were the fuel type and whether the plant operated as a conventional or CHP facility (Fig. 2). Considering the fuel used, NG plants exhibited higher NEE and NTFU values. Conventional NG plants demonstrated significantly higher NEE than those using other fuels (Mann Whitney's *U* test, Mdn = 46.7% vs. Mdn = 32.1%, $U[N_{NG} = 30, N_{non\text{-}NG} = 10] = 12$, $p < 0.001$). This was expected since NG is known for its higher efficiency (Gonzalez-Salazar et al., 2018).

CHP plants significantly outperformed conventional plants about NTFU (Mann Whitney's *U* test, Mdn = 68.7% vs. Mdn = 49.0%, $U[N_{CHP} = 15, N_{non\text{-}CHP} = 40] = 54$, $p < 0.001$) and underperformed in terms of NEE (Mann Whitney's *U* test, Mdn = 34.8% vs. Mdn = 48.4%, $U[N_{CHP} = 18, N_{non\text{-}CHP} = 40] = 167$, $p = 0.001$). While conventional plants typically reach slightly higher NEE by optimizing operational parameters to maximize electricity production (Jarre et al., 2016), combining electricity and heat production increases the fuel energy that CHP plants extract (Riley et al., 2020) and their NTFU.

The efficiency of NG plants was also positively correlated with their size, as observed in previous studies (Eguchi et al., 2021; C. Wu et al., 2019). NG conventional power plants smaller than 250 MW exhibited significantly lower NEE compared to larger plants (Mann Whitney's *U* test, Mdn = 34.5% vs. Mdn = 50.5%, $U[N_{<250}=4, N_{>250} = 26] = 0$, $p = 0.002$). However, these plants were also operated at lower rates compared to their larger counterparts (Mann Whitney's *U* test, Mdn = 869 h vs. Mdn = 6782 h, $U[N_{<250}=3, N_{>250} = 13] = 0$, $p = 0.004$), likely contributing to their lower efficiency. No significant correlation between NEE and size for conventional NG plants was found when plants below 250 MW were excluded from the sample.

NG CHP plants exhibited a strong positive linear correlation between size and NEE (Spearman's test, $r[14] = 0.76$, $p < 0.001$) but no correlation with NTFU. This result is related to larger power plants emphasizing electricity production, as evidenced by a strong positive linear correlation between size and % of energy produced as electricity (Spearman's test, $r[11] = 0.71$, $p = 0.006$). A substantial, although not statistically significant, difference in operation rates between NG CHP plants focusing on heat production (4222 ± 128 h) and electricity production (7188 ± 1205 h) was reported, likely related to the higher seasonality of heat demand compared to electricity (Król and Ocłoń, 2018).

Furthermore, the energy production efficiency was correlated with

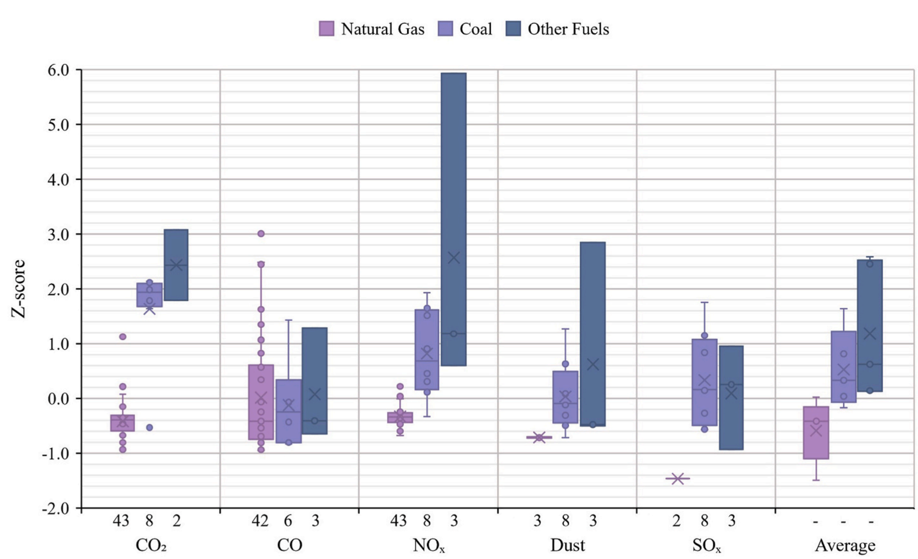

Fig. 3. Mass of pollutants emitted to air normalized per the net energy produced (average values over 2018–2020) by fuel type. Low values = better performances (low emissions). Number of power plants for each group on x-axis. X = average, horizontal line = median, dots = outlier points.

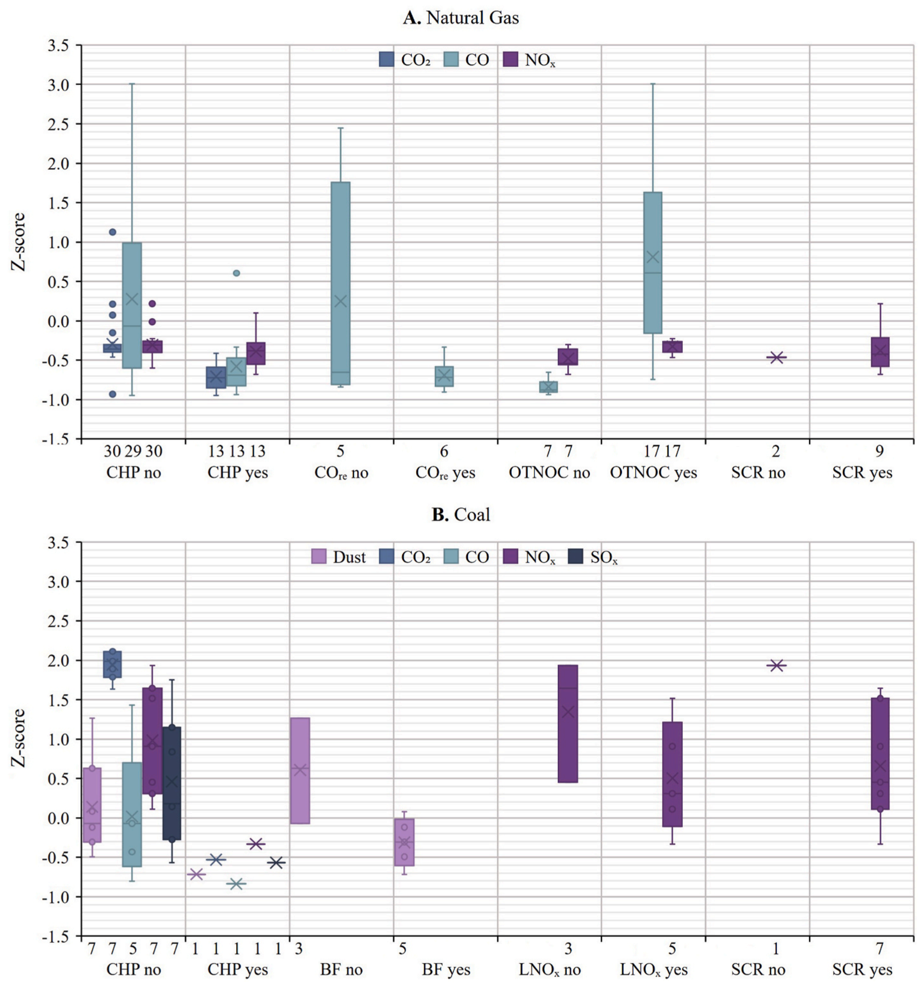

Fig. 4. Mass of pollutants emitted to air normalized per the net energy produced (average values over 2018–2020) by plant characteristics (configuration, emissions reduction technologies) divided into (A) Natural Gas and (B) Coal. Low values = better performances (low emissions). Number of power plants for each group on x-axis. x = average, horizontal line = median, dots = outlier points. CHP = combined heat and power; CO_{re} = technologies for reducing CO emissions; OTNOC = other-than-normal-operating-conditions emissions included in the total; SCR = selective catalytic reactor; BF = bag filter; LNO_x = low NO_x burner.

the energy conversion process and flue-gas treatments. However, these factors are often associated with the fuel type or are overrepresented in plants operating under conventional or CHP conditions. Although the flue-gas treatments (Liang et al., 2011) and especially the energy conversion processes (Kosowski and Piwowarski, 2020; Smith, 2017) play a role in determining energy production efficiency, they were not primary drivers in this context.

3.2.2. Emissions to air

NO_x exhaust gas concentrations were the only ones extensively reported in the ESs. In 2019, the average NO_x concentration was 35.6 ± 33.5 mg/Nm^3. NG plants exhibited significantly lower NO_x concentrations compared to other plants (Mann Whitney's *U* test, Mdn = 23.0 mg/Nm^3 vs. Mdn = 147.0 mg/Nm^3, U[N_{NG} = 29, $N_{non\text{-}NG}$ = 3] = 1, p = 0.007). Most plants complied with their BAT-AEL range, although five NG plants exceeded the higher limit (50 mg/Nm^3). However, among these five plants three were small (<150 MW_{tot}), and one had limited operating hours. Both plant size and operational rate are described as influencing factors for NO_x emissions in the BREF and literature (Blondeau and Mertens, 2019; Ma et al., 2016).

Our analysis primarily focused on the mass of pollutants emitted per unit of net energy produced (Table 2). The high standard variation emphasizes the substantial variability in emission levels among the sample.

Fuel type strongly influenced the emissions normalized by net energy production, with NG plants consistently outperforming others (Fig. 3). Significant differences were observed in the emissions of CO_2 (Mann Whitney's *U* test, Mdn = 382 kg/MWh vs. Mdn = 1036 kg/MWh, U[N_{NG} = 43, $N_{non\text{-}NG}$ = 10] = 31, p < 0.001), NO_x (Mann Whitney's *U* test, Mdn = 122 g/MWh vs. Mdn = 447 g/MWh, U[N_{NG} = 43, $N_{non\text{-}NG}$ = 11] = 22, p < 0.001), dust (Mann Whitney's *U* test, Mdn = 0.6 g/MWh vs. Mdn = 10.4 g/MWh, U[N_{NG} = 3, $N_{non\text{-}NG}$ = 11] = 1, p = 0.011), and SO_x (Mann Whitney's *U* test, Mdn = 3 g/MWh vs. Mdn = 355 g/MWh, U[N_{NG} = 2, $N_{non\text{-}NG}$ = 11] = 0, p = 0.026).

The results regarding dust and SO_x emissions were predictable, as the combustion of NG generates negligible emissions of these contaminants (de Gouw et al., 2014). Similarly, the findings regarding CO_2 emissions correspond to the lower carbon intensity of NG compared to other fossil fuels (X. Zhang et al., 2014). Regarding NO_x emissions, our results are in accordance with BAT-AEL ranges for concentration levels and with the literature (Burney, 2020; de Gouw et al., 2014), which reports considerably lower levels for NG plants compared to others. In contrast, our data did not show a significant impact of the fuel used on CO emissions (Fig. 3). The CO emissions BAT-AEL ranges for NG plants are slightly lower than those of other plants. However, CO emissions from NG power plants increase drastically at lower loads compared to those of other plants (Gonzalez-Salazar et al., 2018).

Fig. 4 presents the influence of various plant characteristics on air emissions. The analysis was divided by fuel type to account for the significant difference in performance and the limited number of plants

Table 3
Average cooling and process water volume consumed, mass of total and hazardous waste produced, and electricity consumed normalized per the net energy produced in 2019.

Indicator	N. of plants	Unit of measurement	Average	Natural gas average	Coal average
Cooling water	24	m^3/MWh	184 ± 154	108 ± 75	355 ± 178
Process water	38	m^3/MWh	0.314 ± 0.402	0.208 ± 0.255	0.731 ± 0.661
Total waste	52	kg/MWh	10.5 ± 25.4	0.4 ± 0.6	57.0 ± 35.9
Hazardous waste	52	kg/MWh	0.25 ± 0.93	0.05 ± 0.08	0.90 ± 2.07
Electricity from grid	24	%	0.9 ± 1.4	0.9 ± 1.5	1.6

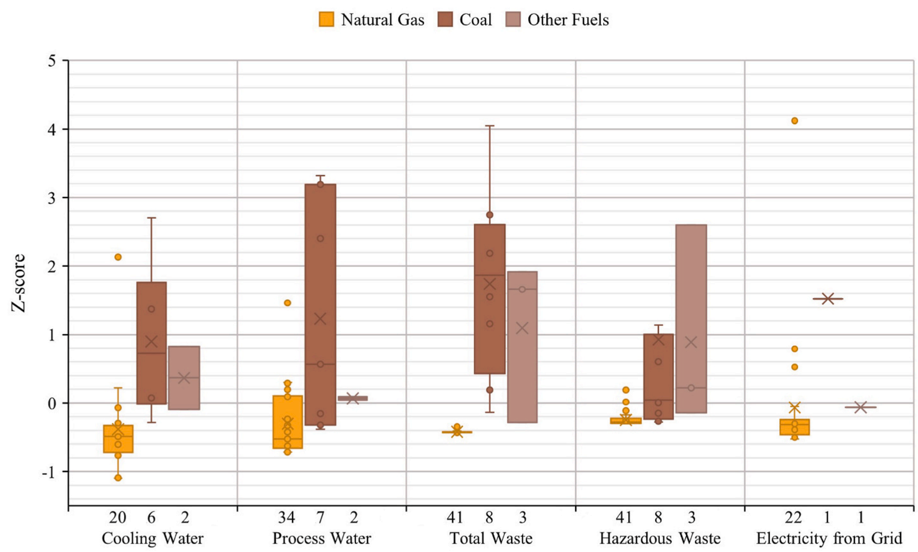

Fig. 5. Volume of cooling and process water consumed, mass of total and hazardous waste produced, and electricity consumed normalized per net energy produced (average values over 2018–2020) by fuel type. Low values = better performances. Number of power plants for each group on x-axis. x = average, horizontal line = median, dots = outlier points.

not using NG. NG CHP plants outperformed conventional NG plants in terms of CO emissions (Mann Whitney's *U* test, Mdn = 29 g/MWh vs. Mdn = 221 g/MWh, $U[N_{CHP} = 22, N_{non\text{-}CHP} = 32] = 84$, $p = 0.017$). NG CHP plants also showed lower CO2 and NOx emissions, although no statistically significant difference was observed for CO_2 and NO_x emissions. Notably, the only CHP coal plant reported considerably lower emissions compared to the other coal plants, confirming that the higher efficiency of CHP plants can lead to lower emissions (Guo et al., 2017; Wang and Song, 2023; Wang et al., 2016).

Evaluating the impact of emissions control technologies, NG plants (Fig. 4 Panel A) implementing SCR exhibited significantly lower NO_x emissions (Mann Whitney's *U* test, Mdn = 36 g/MWh vs. Mdn = 394 g/MWh, $U[N_{SCR} = 12, N_{non\text{-}SCR} = 6] = 114$, $p = 0.010$), confirming the scientific literature (Liu et al., 2018; Van Caneghem et al., 2016). As expected (Kurata et al., 2019; Romero and Wang, 2019), coal plants (Fig. 4 Panel B) with bag filters exhibited considerably lower dust emissions, 7.3 ± 5.1 g/MWh vs. 22.7 ± 10.9 g/MWh, and coal plants implementing LNO_x burners showed lower NO_x emissions, 599 ± 739 g/MWh vs. 754 ± 890 g/MWh, but the small number of plants did not allow statistical significance.

NG plants implementing CO emissions reduction techniques showed lower emissions compared to their counterparts (36 ± 26 g/MWh vs. 163 ± 197 kg/MWh, difference not statistically significant), and studies assessing the impact of CO emission control technologies are lacking. NG plants reporting other than normal operating conditions (OTNOC) exhibited significantly higher CO emissions (Mann Whitney's *U* test, Mdn = 212 g/MWh vs. Mdn = 12 g/MWh, $U[N_{Trans} = 17, N_{non\text{-}Trans} = 7] = 29$, $p < 0.001$) as supported by literature (Nsanzineza et al., 2017; Obaid et al., 2017) and BREF. Conversely, OTNOC reporting did not influence NO_x emissions.

Surprisingly, plant size, age, and operational hours exerted limited influence on emissions despite being often identified as primary performance drivers in BREF and literature (Xu et al., 2017). Notably, operational hours negatively correlated with CO_2 emissions (Spearman's test, $r[20] = -0.45$, $p = 0.035$), but the result was sensitive to outliers. Specifically, a plant with low operational hours and high CO_2 emissions significantly influenced the observed relationship. When this data point was excluded, the correlation disappeared, indicating the relationship was likely driven by this outlier rather than a general trend.

3.2.3. *Water consumption, waste production, and electricity consumption*

Table 3 presents the average values of water and electricity consumption and waste production for 2019, with high standard variations highlighting a considerable variability among the sample.

Fuel type emerged again as the predominant factor influencing environmental performance, with NG plants consistently outperforming other plants (Fig. 5). A significant difference was observed in cooling (Mann Whitney's *U* test, Mdn = 118 m^3/MWh vs. Mdn = 298 m^3/MWh, $U[N_{NG} = 6, N_{non\text{-}NG} = 8] = 13$, $p < 0.001$) and process water consumption (Mann Whitney's *U* test, Mdn = 0.096 m^3/MWh vs. Mdn = 0.409 m^3/MWh, $U[N_{NG} = 29, N_{non\text{-}NG} = 9] = 47$, $p = 0.004$), total (Mann Whitney's *U* test, Mdn = 0.2 kg/MWh vs. Mdn = 55.1 kg/MWh, $U[N_{NG} = 41, N_{non\text{-}NG} = 11] = 0$, $p < 0.001$) and hazardous waste production (Mann Whitney's *U* test, Mdn = 0.02 kg/MWh vs. Mdn = 0.39 kg/MWh, $U[N_{NG} = 41, N_{non\text{-}NG} = 11] = 45$, $p < 0.001$). Moreover, NG plants consumed less electricity (1.2 ± 2.4% vs. 3.2 ± 2.8%, difference not statistically significant).

NG power plants were expected to outperform their counterparts, primarily due to their higher energy production efficiency. Moreover, NG plants often operate in combined cycle mode, typically requiring less

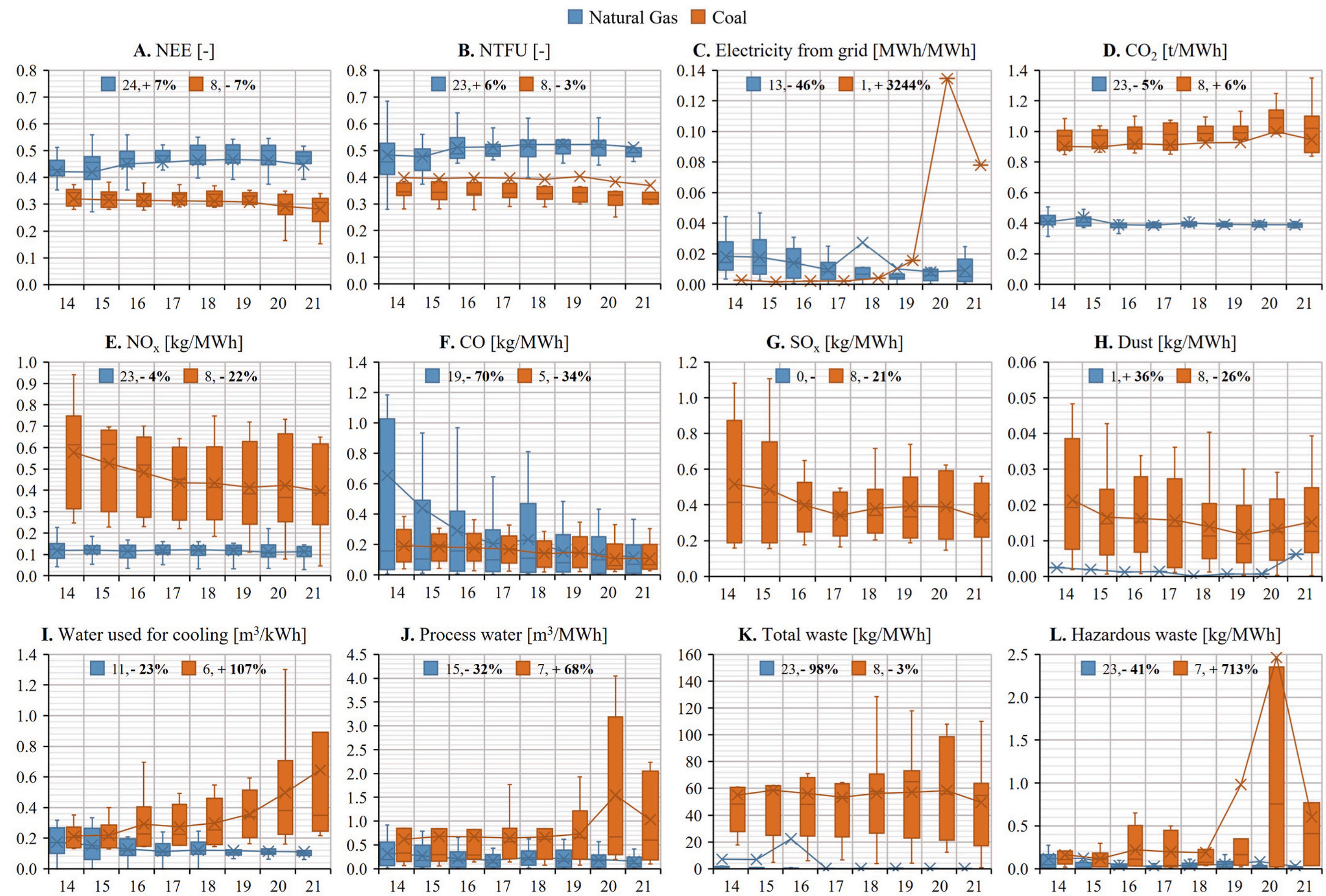

Fig. 6. Temporal trends in the 12 KPIs for natural gas and coal power plants over 2014–2021. For each KPI, the legend displays sample numerosity and percentage performance variation between 2014-2016 and 2019–2021. x = average, horizontal line = median.

cooling water (Lim-Wavde et al., 2018) and less process water for steam cycle integrations. Accordingly, combined cycle plants used significantly less cooling (Mann Whitney's *U* test, Mdn = 119 m^3/MWh vs. Mdn = 370 m^3/MWh, $U[N_{comb} = 17, N_{others} = 7] = 11$, $p = 0.001$) and process water (Mann Whitney's *U* test, Mdn = 0.137 m^3/MWh vs. Mdn = 0.381 m^3/MWh, $U[N_{comb} = 29, N_{others} = 9] = 62$, $p = 0.020$). Plants using coal or other fuels may also require more process water for additional activities, such as wet desulfurization and bottom ash handling (Chen et al., 2020; Nihalani and Mishra, 2020; Yao et al., 2021).

In terms of waste generation, NG combustion produces fewer ashes and slags compared to other fuel sources, which can be hazardous (Asquer et al., 2019; Di Bella et al., 2018; Zierold et al., 2022), and plants using solid fuels often necessitate more frequent maintenance (Barma et al., 2017; Sun et al., 2023). Accordingly, coal-fired plants generated significantly more maintenance and construction waste than NG plants (Mann Whitney's *U* test, Mdn = 0.05 kg/MWh vs. Mdn = 2.00 kg/MWh, $U[N_{NG} = 15, N_{coal} = 6] = 9$, $p = 0.003$). While no literature studies quantify waste from maintenance and construction in thermal power plants, 36 of 73 ESs identified these activities as the primary waste generators. Lastly, NG plants usually consume less electricity due to easier fuel and waste management and fewer emission control technologies implemented (Xiong et al., 2020; Zhang, 2019).

3.2.4. Trends

Fig. 6 illustrates the trends in the 12 KPIs from 2014 to 2021. NG plants exhibited positive trends (performance improvement) across all indicators except for dust emission (reported by only one plant). Significantly improving monotonic trends were observed for CO emissions (Kendall's tau = −0.929, p = 0.002; −70% from 2014 to 2016 levels (t_{start}) to 2019–2021 levels (t_{end})), cooling (Kendall's tau = −0.857, p = 0.004; −23% from t_{start} to t_{end}), and process water consumption (Kendall's tau = −0.714, p = 0.019; −32% from t_{start} to t_{end}). Additional improvements were observed for electricity consumed from the grid (−46% from t_{start} to t_{end}), total (−98% from t_{start} to t_{end}) and hazardous waste production (−41% from t_{start} to t_{end}), although statistically significant monotonic trends were not found.

Conversely, coal plants experienced a decline in performance for 7 of the 12 indicators. Significantly deteriorating trends were identified for NEE (Kendall's tau = −1.000, p < 0.001; −7% from t_{start} to t_{end}), CO_2 emissions (Kendall's tau.786, p = 0.009; +6% from t_{start} to t_{end}), cooling water (Kendall's tau = 0.929, p = 0.002; +107% from t_{start} to t_{end}), and energy consumed from the grid (Kendall's tau = 0.714, p = 0.019; +3204% from t_{start} to t_{end}). These performance declines are noteworthy, especially considering that NG plants generally outperformed coal plants at t_{start}. Apart from their limited size (600 MW_{tot} median capacity) and the potential influence of coal quality (Huang et al., 2000, 2013), coal plants aging infrastructure (1982 median construction year) and their scheduled shutdown in Italy by 2025 (preventing efficiency improvement investments, e.g. (Chatterjee et al., 2021; Chen and Wu, 2015; Mandi et al., 2010)) are the most plausible explanation. The energy output of coal plants also significantly decreased in the analyzed period (Kendall's tau = −0.857, p = 0.004; −62% from t_{start} to t_{end}), likely contributing to efficiency reduction. In contrast, significant decreasing (i.e. environmental improvement) monotonic trends were found for most air emission levels of coal plants, including dust

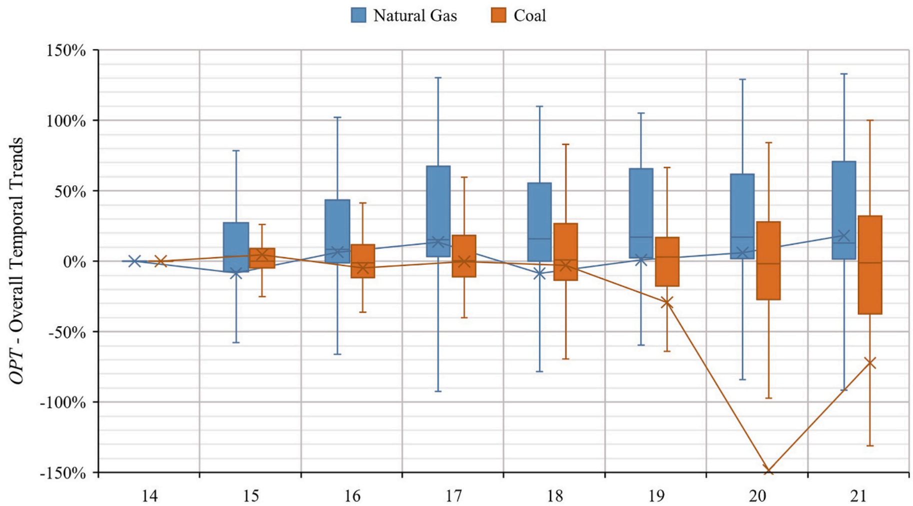

Fig. 7. Overall performance trends (***OPT***) for natural gas and coal power plants in 2014–2021. Positive values = performance improvements. x = average, horizontal line = median.

(Kendall's tau = −0.714, p = 0.019; −26% from t_{start} to t_{end}), NO_x (Kendall's tau = −0.929, p = 0.002; −22% from t_{start} to t_{end}), SO_x (Kendall's tau = −0.643, p = 0.035; −21% from t_{start} to t_{end}), and CO emissions (Kendall's tau = −0.857, p = 0.004; −34% from t_{start} to t_{end}) (Fig. 6).

Fig. 7 shows the overall performance trend *OPT*. Notably, a substantial divergence between NG and coal plants becomes apparent after 2018. In 2021, the overall performance of NG and coal plants improved by 18% and declined by 72%, respectively, compared to 2014 levels.

4. Conclusions

Current gaps in thermal power plants research include a bias towards studying coal over NG plants, limited consideration of environmental impacts beyond air emissions and water consumption, insufficient analysis of how plant characteristics influence environmental performance, and limited exploration of temporal trends post-2010. This study comprehensively analyzed the environmental performance of 73 Italian EMAS-registered thermal power plants, introducing three main contributions: evaluating current and long-term environmental performance in the European context, assessing the influence of plant characteristics on environmental performance, and using publicly available, certified, and independently validated environmental data.

The type of fuel used emerged as the main driver influencing the environmental performance of thermal power plants. NG plants consistently outperformed others in energy production efficiency, air emissions, water consumption, waste production, and electricity consumption. CHP plants also exhibited superior performance compared to conventional plants in terms of energy production efficiency and CO emissions. Plant size, age, and operational hours exhibited limited influence on environmental performance, challenging the conventional perception of their primary role. Plants that reported OTNOC emissions had significantly higher CO emission levels, highlighting their substantial impact on environmental performance.

Natural gas plants showcased improvements across all performance indicators. Conversely, coal plants suffered declines in 7 out of 12 KPIs. This deterioration is likely linked to the scheduled shutdown of coal plants in Italy by 2025.

The findings from this study provide valuable insights and significant implications. Policymakers should: promote the transition from coal to NG in recognition of its superior environmental performance; be aware that adopting policies against coal may lead to a further decline in coal plants' performance due to limited investments; encourage the development of CHP facilities when heat demand is sufficient. Industry practitioners should disclose and mitigate emissions occurring under OTNOC. Reporting OTNOC emissions enhances transparency and facilitates a fairer comparison of environmental performances across organizations. Concurrently, developing and implementing mitigation strategies could lead to significant environmental improvements, particularly in reducing CO emissions.

About the study's limitations, the sample shows limited variability in terms of fuels as it predominantly comprises NG-based plants. This may affect the generalizability of findings to plants relying on other fuels. Second, the reliance on EMAS environmental statements means the analysis is dependent on the accuracy and completeness of the disclosed data. While EMAS data are validated and independently certified, the lack of detailed reporting for OTNOC emissions represents a potential gap. Lastly, the geographical focus on Italy may limit the extrapolation of findings to other contexts where regulatory frameworks, plant configurations, or fuel availability differ significantly. Future research should address these limitations by expanding the geographical scope and fuel variety, integrating data sources beyond EMAS, and conducting dedicated analyses of OTNOC scenarios and their mitigation strategies. Finally, researchers should broaden the scope of this study to include social and economic impacts associated with thermal power plants, exploring the effects on local communities, job creation, and economic activity.

CRediT authorship contribution statement

Stefano Castelluccio: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Ilaria Orlandella:** Investigation, Formal analysis, Data curation. **Silvia Fiore:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Claudio Comoglio:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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.

Acknowledgements

The research received no specific funding. Authors' contributions: Stefano Castelluccio: conceptualization, methodology, formal analysis, investigation, data curation, visualization, writing - original draft; Ilaria

Orlandella: formal analysis, investigation, data curation; Claudio Comoglio: conceptualization, methodology, supervision, writing-review&editing; Silvia Fiore: conceptualization, methodology, supervision, writing-review&editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.144677.

Data availability

Data is provided in the Supplementary Materials.

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