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Research article

Environmental reporting in Italian thermal power plants: insights from a comprehensive analysis of EMAS environmental statements

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ABSTRACT

The global energy sector heavily relies on fossil fuels, significantly contributing to climate change. The ambitious European emissions' reduction targets require sustainable processes and alternatives. This study presents a comprehensive analysis of 73 Italian thermal power plants registered to the European Eco-Management and Audit Scheme (EMAS) aimed at assessing EMAS effectiveness in addressing and quantifying the environmental impacts of this relevant industrial sector. The analysis was based on EMAS environmental statements, publicly disclosing verified and certified data, with the secondary objective of evaluating if EMAS could be an efficient tool to improve the plants' environmental performances. An inventory of technical and environmental aspects, adopted indicators, and allocated budgets was based on 2023 data. A strong correlation was found between the significance of the environmental aspects and the number of adopted indicators. Gaps were observed in describing aspects like "biodiversity" and "local issues". Improvement objectives and budget allocation showed discrepancies and lacked correlation with the significance of the related environmental aspects. "Energy production" accounted for 68% of the total allocated budget; "environmental risks", "emissions to air", "electricity consumption", and "local issues" were also key focus areas. Insufficient information on emission control technologies and progress tracking of improvement objectives was detected. This study highlights the need for thermal power installations to improve the selection of appropriate indicators and to better relate allocated budget to improvement objectives when implementing EMAS. Such measures would facilitate the quantification of the effective environmental impacts of the energy production sector, supporting future research on this topic, allowing stakeholders a better comparison among plants, and driving industry-wide improvements.

1. Introduction

Globally, 44% of greenhouse gas (GHG) emissions from fossil fuel combustion are originated from power generation (IEA. Electricity Sector - Sectoral overview, 2022; IEA, 2021). The European Climate Foundation published in 2010 the Roadmap 2050 (ECF, 2010) to assess the feasibility of 80% reduction of GHG emissions by 2050. It presented key policy recommendations such as accelerating energy efficiency measures, discouraging investments in high-carbon generation, and promoting renewable energy sources and carbon capture and storage technologies. The Roadmap recognized 95% decarbonization of the power sector by 2050 as a crucial goal. In 2019, the European Green Deal (European Commission, 2019) planned for Europe to be the first climate-neutral continent by 2050 and to reduce GHG emissions by at least 55% by 2030. To meet these ambitious targets, shifting the focus toward renewable energy sources and decreasing the reliance on fossil fuels-based thermal power plants is imperative. Meanwhile, decreasing the environmental impacts of existing thermal power plants is crucial.

Thermal power plants implement different processes to extract energy from fuels. One approach involves combustion in a boiler to generate steam used to feed turbines for electricity production (Lacomte et al., 2017). Otherwise, gas turbines directly extract energy from combustion gases. These two processes are coupled in combined cycle plants, where the residual energy of exhaust gases from a gas turbine is fed to a steam turbine. Combined cycle plants offer enhanced power generation efficiency and reduced emissions (Kotowicz and Brzęczek, 2018; Ersayin and Ozgener, 2015). The energy output of thermal power plants can also be maximized by combined heat and power (CHP) plants, which simultaneously produce electricity and heat (Ahmed and Kumar, 2023). There are also power plants based on internal combustion engines, where the exhaust gases directly power reciprocating engines. Overall, the variety of available processes gives thermal power plants

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great flexibility, making them adaptable to various fuels and requirements of industrial and heating applications. In EU-27, electricity is generated by plants using steam turbines (45%), combined cycles (34%), internal combustion engines (9%), and gas turbines (7%) (Eurostat, 2023a). Italian plants use combined cycles (66%), steam turbines (19%), internal combustion engines (9%), and gas turbines (7%) (Eurostat, 2023a). Natural gas was the most used fuel in 2021 (51% in EU-27 and 88% in Italy), followed by coal and oil (Eurostat, 2023b).

According to the Best Available Techniques Reference Document (BREF) for Large Combustion Plants (Lacomte et al., 2017), the highest environmental impacts associated with thermal power plants are contribution to climate change and water consumption for cooling purposes, followed by air pollution (sulfur dioxide, nitrogen oxides, and particulate matter), soil contamination through ash disposal, and the discharge of cooling water. The scientific community focused on specific environmental impacts related to thermal power plants, such as particulate matter and pollutants emitted into air (Kaplan and Witt, 2019; Tang et al., 2020; Zhou et al., 2022), GHG emissions (Hardisty et al., 2012; Chang et al., 2015; Cano-Rodríguez et al., 2022), water consumption (Cano-Rodríguez et al., 2022; Pan et al., 2018; Zhang and Anadon, 2013), waste generation and management (Singh et al., 2016), soil contamination (Gedik and Imamoglu, 2011; Zou et al., 2021), impacts on biodiversity and river ecosystems (Raptis et al., 2016, 2017), and on human health (Sakulniyomporn et al., 2011). Life Cycle Assessment (LCA) has been widely employed in these studies (Akber et al., 2017; Turconi et al., 2013; Atılgan Türkmen et al., 2021), as well as the calculation of externalities (Bielecki et al., 2020; Jorli et al., 2018) and ecological efficiency (de Castro Villela and Silveira, 2007; Qaiser and Grigoriadis, 2020). Some studies compared the performance of different thermal power technologies (Silveira et al., 2007; Strezov and Cho, 2020), while others compared the environmental impacts of thermal power generation with renewable energy (Stougie et al., 2018), nuclear power (Vujić et al., 2012), and municipal solid waste incineration (Song et al., 2018). Literature also focused on the development of efficient and sustainable processes (Miao et al., 2022; Ram et al., 2018), such as high-efficiency thermal generators (Eslick et al., 2022; Tian et al., 2021), Carbon Capture and Storage technologies (Wang and Song, 2023; Youns et al., 2023), biochar and biomass co-firing (Huang et al., 2013), and operating under supercritical conditions (Han et al., 2019).

In this framework, several knowledge gaps still need to be addressed about how companies managing thermal power plants quantify and plan to improve their environmental performance, as existing literature focused on specific aspects and/or implemented assessment tools providing results that are not directly comparable. This information is essential for evaluating the effectiveness of the actions taken by plant operators in their pursuit of sustainability improvement. Therefore, the general objective of this study was to quantitatively assess up-to-date environmental reporting practices in the sector and to evaluate the effectiveness of the Environmental Improvement Programs implemented by these organizations. The analysis was based on the Environmental Statements (ESs) of 73 Italian thermal power plants registered under the Eco-Management and Audit Scheme (EMAS) in 2023. This study focused specifically on Italian thermal power plants due to their significance at the European level. Italy accounts for over 15% of EU-27 electricity production through fuel combustion (Eurostat, 2023c), and 148 out of 241 European EMAS-registered energy production sites in Europe are located in Italy. EMAS is a voluntary Environmental Management System (EMS) developed by the European Union for organizations to manage their environmental impacts effectively and promote sustainability practices aimed at improving the environmental performances of the organizations. EMAS and ISO 14001 are the reference schemes for EMS implementation at European and global levels. Unlike ISO 14001, EMAS requires periodic assessments by the National Competent Authority, which includes a check by the Environment Agency to ensure effective legal compliance with all applicable environmental requirements. Crucially for the scope of this study, EMAS also strongly emphasizes public acceptance and stakeholder engagement. In fact, EMAS-registered organizations are required to make their environmental performance publicly available through an ES, which is validated by an independent verifier. Compared to existing literature, the novelty of this study relies on the assessment of environmental reporting practices and performances of thermal power production at full scale, through the definition of quantitative performance indicators based on technical and environmental aspects and accounting improvement actions.

The methodology applied is based on multiple levels: firstly, it analyzes how thermal power plant managers quantitatively assess the environmental performance of their facilities and describe their mitigation strategies through improvement objectives; secondly, it provides a comprehensive analysis of the ESs (based on public and validated data) of 73 thermal power plants, offering a detailed analysis of their content and reporting practices. Specifically, this study aims to address the following scientific questions: (i) what are the environmental and technical aspects (and applied indicators) that thermal power companies consider most significant?; (ii) what improvement objectives (and allocated budget) do they set?; (ii) what are the limitations and gaps in the reporting practices adopted in the ESs of Italian thermal power plants?

2. Methodology

This study employed a three-phase methodology: (i) identification of the Italian thermal power plants registered to EMAS in 2023; (ii) categorization and analysis of the technical features and key environmental and technical aspects reported in the EMAS ESs; (iii) sensitivity analysis of the consistency and robustness of the approach.

2.1. Inventory

The inventory of the Italian thermal power plants registered to EMAS in 2023 was compiled by cross-referencing the National Register of EMAS-certified sites (ISPRA. List of organizations registered to EMAS, 2023) and the European Commission EMAS Register (European Commission, 2023). Then, the ESs of the sites categorized under the NACE code "E35.11" (i.e., electricity production) were collected through the companies' websites or directly contacting the plant operators. The ESs of the pre-selected sites were further screened to exclude non-relevant sites (e.g., including other activities and disclosing general information), ESs published before 2020, and organizations registered with EMAS during 2022, as their EMS was not fully established. Finally, 73 sites that successfully fulfilled all criteria were selected.

2.2. Data analysis

2.2.1. Plant characteristics and production data

The analysis of the ESs explored the key technical features of power plants (e.g., primary fuel, installed capacity, plant configuration, operating hours, emission control technologies) and energy production metrics. The collected net electricity and heat production data referred to 2020.

2.2.2. Reporting key environmental and technical aspects

A comprehensive analysis of 14 key environmental and technical aspects (emissions to air, fuels/water/raw materials and chemicals/electricity consumption, electricity/heat production, waste production, releases to water, local issues, environmental risks and emergencies, transportation issues, biodiversity, and process management) was performed on the ESs through the following steps:

- identification of the number of ESs mentioning each key aspect and considering it significant (i.e., related to a potential impact on the environment);

- identification of the metrics and indicators used to quantify the environmental impacts associated with the key selected aspects;
- collection of the data related to the objectives set by plant operators to enhance environmental performance within the period 2017–2026, including specific actions and metrics and related allocated budgets.

2.3. Sensitivity analysis

The Spearman's rank correlation test was used to evaluate the strength and direction of the monotonic relationship between two variables (e.g., the extent of changes in one variable corresponding to changes in another). The Mann-Whitney *U* test was applied to compare two independent groups or samples and determine the presence of a significant difference between their distributions. Additionally, the Chi-Square test was used to investigate potential significant differences between various groups or samples when analyzing categorical data. A 5% ($p < 0.05$) significance level was considered to assess the statistical significance of the observed findings.

3. Results and discussion

3.1. Sample description

In 2023, out of 145 energy production sites registered to EMAS in Italy, 86 included a thermal power plant. 13 sites were excluded (see section 2.1), resulting in a final sample of 73 installations included in the inventory. The main features of each plant are described in Supplementary Material (A and B). In 2020, they collectively generated 90.6 TWh of electricity and 8.5 TWh of heat, accounting for 32.3% and 14.3% of the total gross Italian energy production, respectively. These figures align with the findings of a study (ISPRA, 2022) conducted by the Italian Protection Agency (*Istituto Superiore* per *la Protezione e la Ricerca Ambientale, ISPRA*) on the effectiveness of EMAS in the energy production sector, which revealed that 31% of power plants authorized by the national Integrated Environmental Authorization according to EC Integrated Pollution Prevention and Control (IPPC) regulations were registered with EMAS. EMAS adoption in the Italian energy production sector exceeds other sectors in Italy and Europe (Castelluccio et al., 2022; European Commission et al., 2018). Still, it falls significantly below the 73% adoption rate observed in the Italian waste incineration sector (Comoglio et al., 2022a). This substantial difference could be attributed to the considerable public resistance encountered by waste incineration and supports the hypothesis that fostering public acceptance has a significant role in influencing EMAS adoption.

The inventoried thermal power plants are predominantly located in northern Italy (41 plants), while 14 and 18 plants are in the central and southern regions, respectively. This distribution can be ascribed to a higher level of industrial activity and greater population density in northern Italy (Benassi and Naccarato, 2019; Sechi et al., 2022). The plants varied greatly in installed capacity, ranging from 6 MW_{tot} to 2640 MW_{tot} (average 590 ± 490 MW_{tot}).

Methane was the predominant fuel in 59 out of 73 plants, usually applying combined cycles and cogeneration. Coal was the primary fuel source in nine plants (all operating steam processes), two plants primarily relied on biomass, one plant utilized oil, and two plants used a combination of different fuels. Interestingly, none of the analyzed ESs reported information on the fuel characteristics. Especially for plants that do not use methane, parameters such as ash, sulfur, and mercury content of the fuel substantially influence the environmental impacts (Baba et al., 2008; Munawer, 2018). Therefore, including fuel characteristics in the ESs would allow for a better comparison and benchmarking of the environmental performances of different plants, enhancing transparency and accountability.

In 2022, five plants were reported inactive, while the remaining 68 were operating. Among the inactive installations, three are relatively small CHP plants (ranging in capacity from 125 MW_{tot} to 138 MW_{tot}) fed by methane, constructed between 1995 and 2000, and operated by the same company. The ESs of these three plants ascribed their inactivity to overcapacity and limited electricity demand. Another inactive plant, built in 1992, also used methane but implemented gas turbines, produced only electricity, and had a significantly larger capacity (860 MW_{tot}). The reason for its inactivity was not mentioned in the ES. The fifth inactive plant (150 MW_{tot}) was built in 2000 and generated electricity through coal-based steam turbines. Although its ES did not specify the reason, it indicated that the decommissioning process was initiated due to the permanent cessation of activity.

The employed emission control technologies were mentioned in 32 ESs, reporting 13 plants equipped with electrostatic precipitators (ESPs) and 6 with bag filters (BFs) to reduce dust emissions. 21 plants also employed selective catalytic reduction (SCR) for NO_x removal, 10 used desulfurization ($DeSO_x$), and 12 implemented CO catalytic reduction. Eleven plants reported automatic systems to regulate combustion parameters, and 46 implemented low NO_x burners. Remarkably, we found a significant disparity in the reporting of implemented emission control technologies, with only 31% of methane-fired plants providing such information compared to the full disclosure by other plants, $X^2(2, N = 73) = 26.8$, $p < 0.001$ (Chi-Square test). While methane emits considerably fewer contaminants than coal or oil, the lack of reporting emission control technologies in such sites raises concerns. Including a comprehensive description of the emission control technologies implemented in the EMAS ESs is crucial for several reasons:

1. it would enhance transparency in reporting to the stakeholders while promoting accountability and encouraging continuous improvement;
2. it would facilitate a more accurate assessment and comparison of the environmental performance of different plants;
3. the disclosure of detailed information on emission control strategies would allow researchers and stakeholders to evaluate the implementation of best practices and gain valuable insights into the approaches used by plant operators.

3.2. Key environmental aspects and related performance indicators

The overall list of the 14 key environmental and technical aspects and related indicators retrieved from the ESs is reported in Supplementary Material (C). This list is a valuable reference for future research and offers guidance to thermal power plant operators for an effective disclosure of the environmental performance of their facilities.

Table 1 provides an overview of 14 key environmental and technical aspects reported in the ESs, focusing on their quantification through indicators. Most key aspects have been consistently included and described by the companies, and 8 out of 14 were considered in over 90% of ESs. Notably, "emissions to air" and "fuels consumption" were mentioned in all 73 ESs, while, on the other hand, "thermal energy production" (41.1%), "biodiversity" (39.7%), and "transportation issues" (31.5%) were mentioned in less than half of ESs.

When evaluating the significance assigned by the operators of the power plants, only seven aspects were considered significant in over 80% of ESs, e.g., "emissions to air" (98.6%), "fuels consumption" (95.9%), and "water consumption" (93.2%) (Table 1). This aligns with the scientific literature (Peer et al., 2016) and the BREF for Large Combustion Plants (Lacomte et al., 2017). In contrast, four aspects were considered significant in less than 20% of ESs, i.e., "environmental risks and emergencies" (19.0%), "transportation issues" (18.0%), "biodiversity" (1.0%), and "process management" (0.0%).

Across the 73 ESs analyzed, 97 different indicators describing the 14 key aspects were identified. Many indicators were repeated in multiple ESs, resulting in a total count of 1639 indicators. On average, each ES used 22.2 ± 4.5 indicators to quantify the environmental impacts and performance of the thermal power plant. The five most frequently used

Table 1
Overview of the 14 key environmental and technical aspects disclosed in the ESs, including the number of ESs in which each aspect was included, the number of ESs that considered it significant, the number of aspects that were quantified with indicators, and the average number of indicators per ES.

Aspect	Significant [%]	Considered in the ESs [%]	ESs with Indicators [%]	Average No. of Indicators per ES [-]
Emissions to air	98.6	100	98.6	4.7
Fuels consumption	95.9	100	98.6	2.5
Water consumption	93.2	98.6	95.9	2.6
Cons. of raw mat. and chemicals	91.8	97.3	90.5	2.4
Electricity production	89.0	98.6	89.2	2.0
Waste production	89.0	93.2	87.8	3.8
Releases to water	83.6	95.9	94.6	1.6
Electricity consumption	74.0	93.2	78.4	1.4
Local issues	52.0	76.7	29.7	0.3
Thermal energy production	26.0	41.1	39.2	0.4
Env. risks and emergencies	19.0	64.4	2.7	0.0
Transportation issues	18.0	31.5	1.4	0.0
Biodiversity	1.0	39.7	37.8	0.4
Process management	0	52.1	17.6	0.2

indicators were "mass of CO_2 emitted" (73 ESs), "volume of wastewater produced" (70 ESs), "non-hazardous waste produced" (65 ESs), "hazardous waste produced" (64 ESs), and "methane consumption" (63 ESs). 29 out of the 97 distinct indicators appeared in at least 20 ESs (Table 2).

The number of indicators used to quantify each environmental aspect varied (Table 1), with "emissions to air" (4.7 ± 1.0 indicators per ES), "waste production" (3.8 ± 1.6), "water consumption" (2.6 ± 1.2), "fuels consumption" (2.5 ± 0.8), and "consumption of raw materials and chemicals" (2.4 ± 1.1) having a relatively higher quantification (over 85% of ESs), along with "electricity production" and "releases to water" (at least 1 indicator). "Process management" (0.2 ± 0.6 indicators per ES), "environmental risks and emergencies" (0.0 ± 0.16), and "transportation issues" (0.0 ± 0.12) had the lowest number (at least one) of indicators used and were quantified in less than 20% of ESs.

A very strong positive correlation was observed between the significance of an aspect and the number of indicators used to describe it, $r(12) = 0.90$, $p < 0.001$ (Spearman's test). The aspects considered more significant in the ESs, such as "emissions to air" and "fuels consumption", were quantified using a relatively higher number of indicators. Conversely, aspects with lower significance, such as "biodiversity" and "environmental risks and emergencies", had fewer indicators used for their quantification. Some aspects exhibited a greater number of indicators compared to other aspects with similar significance, most notably "waste production" and "emissions to air" (Table 1). Similar findings were observed in environmental reports of hydroelectric power plants (Comoglio et al., 2023) and waste incinerators (Comoglio et al., 2022a). These studies suggested several possible reasons for the detailed quantification of "waste production" and "emissions to air", including stringent regulatory requirements, direct cost implications of waste management, and strong public concerns about air pollution. In contrast, the aspect "local issues" was quantified using fewer indicators compared to other aspects of similar significance, and only in 29.7% of the ESs. This discrepancy may be attributed to the inherent challenges associated with quantifying "local issues" (e.g., visual impact, odor emissions, and light pollution), which can be more complex compared to the quantification of aspects like "waste production" or "emissions to air". The literature (Piccardo et al., 2022; Jiang et al., 2017; Palmer, 2022) has already highlighted the lack of standardized metrics and guidelines for assessing and reporting "local issues" consistently and effectively. Limited data availability resulting from the absence of regulatory requirements and scarce community concerns may have contributed to the lower quantification of these aspects.

Overall, the adopted indicators exhibited varying levels of relevance and efficacy across different environmental aspects. Positive examples are "electricity consumption", "waste production", "fuels consumption", "process management", "releases to water", and especially "emissions to air" and "electricity production". Those aspects were generally adequately quantified, with effective indicators such as self-consumption of electricity, electricity consumption per energy produced, the mass of CO_2 emitted per produced energy, the concentration of emitted pollutants, and the percentage of waste sent for recovery. Relevant indicators were also found for "electricity production" and "process management", but only in a few ESs. For instance, the net electrical efficiency was identified in 16 ESs, the net total fuel utilization in 6 ESs, and the frequency rate of accidents in 8 ESs.

On the other hand, several areas where indicators lacked efficiency have been detected. Considering water use, although the ESs included indicators for "water consumption", they rarely addressed the sustainability of water sources or captured the efficiency of water use in the different production processes. For instance, indicators measuring water consumption for cooling per unit of energy produced were reported in only 10 ESs. Similarly, indicators related to "heat recovery and utilization efficiency" were scarce, limiting the assessment of the plant's efforts to optimize energy efficiency and minimize waste heat. "Biodiversity" indicators presented evident gaps as well. While the ESs included indicators for the total occupied, built-up, and covered areas, they failed to address crucial aspects such as species richness, habitat quality, and presence of protected or endangered species affected by the power plant sites. Likewise, important components of the "local issues" aspect, such as visual impact, vibrations, and odor emissions, were inadequately addressed in the ESs despite their potential to offer valuable information regarding the plant's impact on the local community.

Furthermore, the indicators describing the aspect "consumption of raw materials and chemicals" primarily focused on quantifying the amount used rather than providing a comprehensive understanding of the environmental impact of specific materials and chemicals. Including indicators related to their toxicity, recyclability, or biodegradability would offer a more comprehensive understanding of the potential

Table 2
List of the environmental indicators most frequently reported in the ESs (≥20 ESs).

Aspect	Indicator	Unit	No. of ESs
Consumption of raw materials and chemicals	Consumption of materials and chemicals	kg	62
	Consumption of materials and chemicals per energy produced	kg/GWh	51
	Consumption of materials and chemicals by type	kg	35
Electricity consumption	Energy consumed from the grid	MWh	33
	Self-consumption of electricity	MWh	30
Electricity production	Gross electricity produced	GWh	61
	Net electricity produced	GWh	43
Emissions to air	Mass of CO_2 emitted	t	73
	Mass of pollutants emitted per energy produced	t/GWh	57
	Mass of pollutants emitted	t	50
	Concentration of emitted pollutants	mg/Nm^3	49
	Mass of CO_2 emitted per energy produced	t/GWh	43
	Mass of pollutants emitted in other than normal operating conditions	t	27
	Mass of CO_2 equivalent emitted	t	24
Fuels consumption	Methane consumption	Sm^3	63
	Diesel consumption	t	48
	Methane consumption per energy produced	Sm^3/GWh	45
Local issues	Sound emission levels	dB	22
Releases to water	Volume of wastewater produced	m^3	70
	Pollutants in wastewater	Various	30
Thermal energy production	Net thermal energy produced	GWh	28
Waste production	Non-hazardous waste produced	t	65
	Hazardous waste produced	t	64
	Waste sent for recovery	t	63
	Waste sent for disposal	t	41
	Waste produced per energy produced	t/GWh	26
Water consumption	Water consumption for industrial and civil uses	m^3	59
	Total water consumption per energy produced	m^3/GWh	44
	Water consumption for cooling	m^3	28

environmental risks associated with the substances used. Regarding “environmental risks and emergencies”, only indicators related to reagent storage capacity and the amount of asbestos disposed of were found, and crucial aspects such as the potential for soil contamination and the management of hazardous waste were overlooked. Similarly, the only indicator found to describe the aspect of “transportation issues” was the number of road vehicles used, while indicators for transportation-related emissions and fuel efficiency, which could quantify the carbon footprint and energy efficiency of transportation activities, were absent from the ESs.

Notably, only 45% of the 1639 indicators identified in the ESs were reported alongside their corresponding normalized indicator. As an example, the indicator “total water consumption” (m^3) complies with the minimum eco-efficiency criteria when expressed as “total water consumption per energy produced” (m^3/GWh). This aligns with prior investigations on the ESs of Spanish (Heras-Saizarbitoria et al., 2020) and Italian (Comoglio et al., 2022a) organizations operating in the waste incineration sector. Even companies registered to EMAS, considered front-runners in environmental sustainability, use the eco-efficiency concept limitedly in their reporting (Heras-Saizarbitoria et al., 2020; Erkko et al., 2005). In summary, while certain key environmental aspects were sufficiently addressed by indicators, notable gaps existed in the quantification of most aspects. Addressing these gaps would facilitate a more comprehensive understanding of the environmental impacts of thermal power plants based on their EMAS ESs.

3.3. Improvement objectives

A total of 569 improvement objectives (Supplementary Material (C)) were identified across the 73 analyzed ESs, resulting in an average of 7.8 ± 4.9 objectives per plant. Table 3 lists the most frequently occurring

Table 3
List of improvement objectives (and related key aspects) most frequently reported in the ESs (≥7 ESs).

Aspect	Objective	Action	No. of ESs
Electricity consumption	Reduction of electricity consumption	Replacement of lighting with LED lamps	33
		Efficiency improvement through optimization or replacement of equipment	21
		Optimization of combustion through component modifications	8
Electricity production	Increase in the production of energy from renewable sources	Installation of a photovoltaic system	15
Emissions to air	Improved monitoring of emissions	Installation of new analyzers	16
	Reduction of emissions	Installation of new burners	8
		Optimization of the $DeNO_x$ process	8
		Replacement of a boiler	7
Environmental risks and emergencies	Reduction of soil contamination risk	Tank remediation	11
		Improvement of chemical product storage methods	7
	Risk reduction from asbestos	Removal of structures	17
Fuels consumption	Reduction of fuel consumption	Efficiency improvement through optimization or replacement of equipment	7
Local issues	Improvement of visual impact	Demolition of structures	9
Process management	Improved relationships with stakeholders	Organization of guided tours of the plant	9
	Increase in staff environmental awareness	Training courses	7
	Increased sustainability of external companies	Supplier audits	7
	Process improvement	Use of management software	10
Releases to water	Improvement of wastewater management	Improvements to the wastewater treatment system	16
Transportation issues	Increase in electric mobility	Replacement of traditional vehicles with electric vehicles	10
Waste production	Improvement of waste management	Implementation of the National Electronic Waste Register	14
		Coverage of storage areas	7
		Expansion or construction of new areas for waste management	7
	Reduction of waste production	Reducing the use of single-use plastics	9
Water consumption	Reduction of water consumption	Installation of water recovery systems	13
		Installation or optimization of the demineralization plant	7

objectives (mentioned in at least 7 ESs). The two most common objectives were related to “electricity consumption” and aimed at reducing electricity use by installing LED lamps (33 objectives) and optimizing/replacing equipment (21 objectives). The third most recurring objective was reducing risks associated with asbestos (17 objectives) under “environmental risks and emergencies”. The most frequent aims were to reduce electricity consumption (70 objectives), emissions to air (52 objectives), soil contamination risk (52 objectives), improve waste management (39 objectives), and decrease water consumption (34 objectives). These objectives accounted for 43% of the total.

Table 4 provides an overview of the improvement objectives and allocated budgets associated with the 14 key environmental and technical aspects reported in the ESs. The key aspects associated with the highest number of objectives were “environmental risks and emergencies” (95 objectives), “emissions to air” (88 objectives), and “electricity consumption” (79 objectives). These accounted for 46% of total improvement objectives identified in the ESs and were the only ones for which at least one improvement objective was found in >50% of ESs, alongside “waste management”. Conversely, “biodiversity” and “thermal energy production” exhibited the fewest improvement objectives (<10% of ESs).

The total allocated budget for improvement objectives was 626.44 M€, 25.15 ± 42.36 M€ per plant. The aspect with the highest allocated budget was “electricity production” (427.98 M€, 68% of the total), followed by “environmental risks and emergencies” (62.42 M€) and “emissions to air” (57.12 M€) (Table 4). Despite having a relatively small number of improvement objectives, “electricity production” was characterized by an exceptionally high budget per objective (19.45 M€ compared to less than 1 M€ for other aspects) due to costly technical interventions. The four objectives with the highest allocated budget associated with “electricity production” were increasing plant efficiency by replacing a traditional cycle plant with a combined cycle plant (350.00 M€), replacing a turbine (27.90 M€ and 12.00 M€), and renovating the plant (25.00 M€). The three remaining objectives with budgets above 10 M€ were related to optimizing the $DeNO_x$ process (11.25 M€), remediating contaminated areas (10.70 M€), and reducing soil contamination risks through tank remediations (10.00 M€).

On the other hand, the aspects with the lowest allocated budget were “thermal energy production” (0.55 M€), “biodiversity” (1.13 M€), “transportation issues” (1.47 M€), “consumption of raw materials and chemicals” (1.57 M€), and “fuels consumption” (1.61 M€) (Table 4). These aspects had the lowest number of associated improvement objectives (<25) and of average budget per objective, alongside “process management” (<0.30 M€). Examples of objectives related to these aspects include increasing the area dedicated to nature by planting trees (3 objectives, 17 k€), improving fuel management (1 objective, 10 k€), and promoting electric mobility by installing charging stations (5 objectives, 140 k€).

No correlation was found between the significance of a key aspect and the number of improvement objectives or the budget allocated to it. “Environmental risks and emergencies” had the highest number of associated objectives (95) and the second-highest allocated budget (62.42 M€) despite being considered significant only in 19% of ESs (Table 4). Most of the budget (83% of the total) for this aspect was allocated to reducing soil contamination risks (52 objectives). The remaining objectives addressed risk reduction from asbestos (18 objectives), improving emergency management (8 objectives), reducing fire risk (7 objectives), remediating contaminated areas (5 objectives), reducing the risk to workers’ health (4 objectives), and minimizing natural disaster risk (1 objective). The aspects “process management” and “electricity consumption” also exhibited a higher number of associated improvement objectives compared to other aspects with similar significance, but their allocated budget was in line with other aspects. Additionally, as previously mentioned, the technical aspect “electricity production” had an exceptionally high allocated budget compared to other aspects (68% of the total allocated budget).

In contrast, the aspects “water consumption”, “fuels consumption”, and “consumption of raw materials and chemicals”, despite being considered significant in over 90% of the ESs, had few associated improvement objectives and limited allocated budget (Table 4).

Except for one study focusing on the waste incineration sector (Comoglio et al., 2022a), previous literature analyzing the energy production sector from hydroelectric power plants (Comoglio et al., 2023) and the biodegradable waste treatment (Castelluccio et al., 2022) also observed a lack of correlation between aspects’ significance and number of improvement objectives or allocated budget. Similar to our findings, these studies found that technical aspects such as “electricity production” or “process management” had a considerably higher number of

Table 4
Overview of the key environmental and technical aspects reported in the ESs, focusing on the presence and number of improvement objectives and the budget allocation.

Aspect	Significant [%]	Tot Allocated Budget [k€]	Budget per Objective [k€]	ESs with Objectives [%]	Average No. of Objectives per ES [-]
Emissions to air	98.6	57,115	921	60.3	1.2
Fuels consumption	95.9	1,610	201	20.5	0.3
Water consumption	93.2	8,231	433	37.0	0.5
Cons. of raw mat. and chem.	91.8	1,565	261	19.2	0.3
Electricity production	89.0	427,972	19,453	38.4	0.4
Waste production	89.0	9,699	294	53.4	0.8
Releases to water	83.6	15,467	859	26.0	0.3
Electricity consumption	74.0	17,648	420	64.4	1.1
Local issues	52.0	19,277	964	30.1	0.4
Thermal energy production	26.0	552	184	4.1	0.0
Env. risks and emergencies	19.0	62,418	811	60.3	1.3
Transportation issues	18.0	1,471	134	16.4	0.2
Biodiversity	1.0	1,131	162	8.2	0.1
Process management	0	2,282	54	39.7	0.8

objectives and allocated budget compared to aspects with similar significance. These results suggest that plant operators allocate resources for reducing environmental impacts based on factors beyond significance evaluations, such as operational costs, potential savings, and the presence of legally binding targets.

Overall, the improvement objectives effectively addressed the impacts of thermal power plants related to the most significant aspects. Regarding "emissions to air", 30 of the 88 improvement objectives targeted an improvement of the emission control technologies with a budget of 46.02 M€. Among these objectives, 18 (25.54 M€) focused on reducing NO_x emissions by enhancing the $DeNO_x$ process or installing low NO_x burners, five objectives on CO emissions, four on dust emissions, and three on SO_x emissions. However, it is worth noting the absence of objectives related to the implementation or study of CCS solutions, which could be an effective strategy for mitigating the environmental impacts related to the substantial greenhouse gas emissions from thermal power plants (McKellar et al., 2010; Singh et al., 2012).

In terms of "fuels consumption", the improvement objectives were generally relevant, addressing various areas such as equipment replacement, waste heat reuse, and plant start-up and shut-down optimization. Nonetheless, the total number of improvement objectives and the allocated budget dedicated to "fuels consumption" was remarkably low. Similarly, the few improvement objectives implemented to reduce the "consumption of raw materials and chemicals" were generally effective, primarily focusing on the reduction of product consumption (16 objectives) and the reduction of danger associated with products' use (3 objectives). However, no mention of objectives aimed at implementing recycling systems for raw materials and chemicals was found in the ESs.

The relevance of the improvement objectives related to water consumption was case-specific. Most objectives included effective actions such as installing water recovery systems (13 objectives) and implementing automatic control and regulation systems (6 objectives). Nevertheless, several objectives featured less directly effective actions, such as installing new measuring systems (3 objectives), optimizing the demineralization plant (7 objectives), or constructing new wells (2 objectives). Moreover, none of the objectives focused on the application of air-cooling systems, which have the potential to significantly reduce or eliminate water consumption (Bustamante et al., 2016; Zhang et al., 2018).

Our analysis also revealed limitations and gaps in the reporting practices of improvement objectives in the ESs. Firstly, the associated budget was disclosed for only 65% of the 569 improvement objectives. Secondly, only 50% of the objectives were accompanied by indicators to track progress and quantify improvements over time. To address these shortcomings, we emphasize the importance of disclosing the allocated budget for each objective and using indicators to measure and track progress. Incorporating these practices would not only enhance transparency in reporting but also provide a clearer demonstration of organizations' commitment towards the improvement of their environmental performance, also enhancing public trust.

4. Conclusions

This study investigated the key environmental aspects, improvement objectives, and budget allocation reported by 73 thermal power plants through the analysis of their EMAS ESs. It identified strengths, such as a strong correlation between the significance of key aspects and the number of indicators used to quantify their impact. Plant operators considered "emissions to air", "fuels consumption", and "water consumption" as the most significant aspects and, accordingly, they quantified them using a substantial number of indicators. However, evident gaps were found in the description and quantification of other aspects such as "biodiversity" and "local issues".

Notably, our results highlighted discrepancies in the distribution of improvement objectives and budget allocation, and a lack of correlation with the aspects' significance. "Environmental risks and emergencies", "emissions to air", "electricity consumption", "local issues", and "releases to water" were prioritized, accounting for 66% of improvement objectives and 88% of the budget for environmental aspects. However, the technical aspect "electricity production" stood out, accounting for 68% of the total allocated budget due to costly technical interventions aimed at efficiency improvements. These results represent a valuable insight into the budget allocation patterns within the evolving power generation sector, where efficient resource allocation is paramount for achieving environmental and sustainability goals. Our findings suggest that plant operators include improvement objectives based on factors beyond significance evaluations and environmental impact reduction, in alignment with previous studies on waste incineration, hydroelectric production, and biodegradable waste treatment sectors (Comoglio et al., 2022a, 2022b, 2023).

The analysis also revealed limitations in the reporting practices of the ESs. No information was provided on fuel characteristics, and most methane-fired plants did not report the implemented emission control technologies. Moreover, the associated budget was disclosed for only 65% of improvement objectives, and only 50% of them were accompanied by indicators to track progress and quantify improvements. These gaps limit comparison and benchmarking among power plants and hinder a clear demonstration of organizations' commitment to improve environmental performance. Incorporating this information would greatly enhance transparency in environmental reporting, thereby increasing public trust. The implications of this study also extend to industry stakeholders and policymakers. Our findings suggest that thermal power plant operators could benefit from adopting environmental management systems. However, the need for substantial improvement in implementing EMSs is evident, especially in the selection of more effective and representative indicators and in the allocation of improvement objectives and budget. Policymakers can play a crucial role by enforcing standardized metrics, guidelines, and regulations to ensure comprehensive and consistent reporting across power plants. Such measures could facilitate the quantification of environmental impacts, enable better comparison among power plants, and drive industry-wide improvements.

Therefore, there is a pressing need for research to develop and propose standardized metrics specific to thermal power plants. Another direction for future research involves evaluating the efficacy of different strategies that companies could adopt in communicating their efforts towards sustainability, comparing the dissemination of environmental reports such as EMAS ESs, the organization of facility tours, and the creation of consortia with stakeholders.

In conclusion, this study provides valuable insights for scholars and stakeholders into the environmental reporting practices, improvement objectives, and budget allocation in the ESs of Italian thermal power plants. It highlights the need for comprehensive reporting, adequate and transparent resource allocation, and standardized metrics to effectively quantify the environmental impacts of power plants. For power plant managers, the results of this study can help analyzing and enhancing the environmental performance of their facilities, and related data disclosure to the public, fostering public trust, and increasing the sustainability of current energy production. For scholars and stakeholders, the findings of this study contribute to the broader understanding of environmental management in the thermal power plant sector and pave the way for future advancements in this field.

CRediT authorship contribution statement

Stefano Castelluccio: Writing – review & editing, Writing – original draft, Visualization, Investigation, Data curation. **Silvia Fiore:** Writing – review & editing, Supervision, Methodology. **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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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