Analysis of environmental sustainability reporting in the waste-to-energy sector: Performance indicators and improvement targets of the EMAS-registered waste incineration

Analysis of environmental sustainability reporting in the waste-to-energy sector: performance indicators and improvement targets of the EMAS-registered waste incineration plants in Italy

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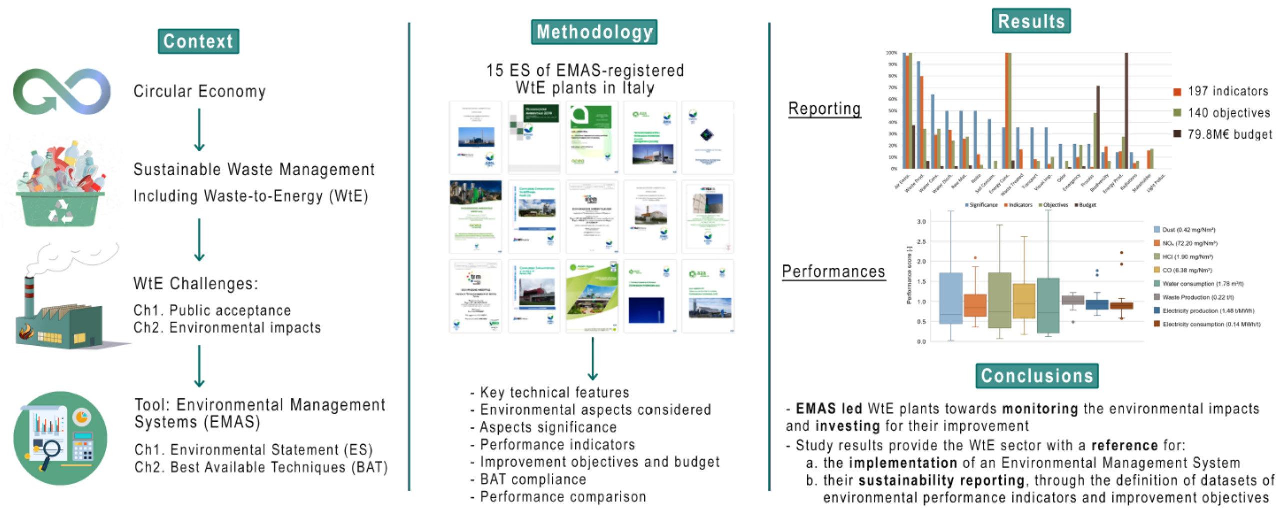


Highlights

- The analyzed organizations defined 197 indicators and 140 improvement goals
- Energy consumption, emissions to air and waste production received high attention
- 79.8 M€ budget was mostly (73%) allocated to process efficiency improvement goals
- A quantitative comparison of the plants' environmental performance is presented
- The results provide a reference for EMAS implementation and reporting in the sector

Abstract

This work analyzed how 15 Italian waste incineration (WI) plants registered to the European Eco-Management and Audit Scheme (EMAS) in 2020 reported to the public their environmental sustainability. Their EMAS Environmental Statements (ESs) were analyzed to identify the environmental performance indicators and metrics used by the companies, the improvement actions planned, and the adoption of the Best Available Techniques (BAT) for WI. 197 environmental performance indicators and 140 improvement objectives, with an overall allocated budget of 79.8 M€, were inventoried. WI companies emphasized reporting and improvement of energy consumption, emissions to air, waste production, process management and energy production. Current values of 8 key performance indicators (HCl, NO_x, CO, and dust concentrations in flue-gas, water consumption, waste production, and electricity consumption/production per 1 ton of treated waste) were assessed and compared. GHG reporting and compliance with the BAT for WI (on emissions to air, energy and raw materials consumption, and waste production), although often not detailed, w also analyzed. Requesting companies to report a pre-defined subset of key metrics, possibly related to the BAT emissions levels, and an explicit section on the adopted BAT could provide an even more representative description of the environmental performances of the WI plants. This study shows a novel approach that could be extended to other industrial sectors to analyze their environmental performance from a consistent, validated, and publicly available data source (EMAS ESs). It also provides metrics and recommendations that could be useful references for the environmental reporting of the WI sector.

Keywords: waste incineration; environmental management system; environmental performance indicator; Best Available Techniques; environmental improvement.

1. Introduction

As global waste generation continues to increase due to demographic changes and growing wealth and consumption (Jia et al., 2022; Smejkalová et al., 2020), adopting effective and sustainable waste management solutions has become a priority (Rodrigues et al., 2018). At least 10 out of 17 Sustainable Development Goals established in the United Nation's 2030 Agenda can be linked to waste management (Pujara et al., 2019; Sharma et al., 2021). Decreasing the waste generated through reduction, reuse and recycling is essential (Giannetti et al., 2020), and the research focusing on this direction is steadily expanding. For instance, various studies demonstrated waste reduction effectiveness through modification of supply chains (Garai and Sarkar, 2022; Sarkar et al., 2021, 2022a, 2022b) or remanufacturing (Sarkar et al., 2022c; Yu et al., 2021; Moon et al., 2022). However, for waste that cannot be otherwise prevented, reused, or recycled, waste-to-energy (WtE) processes (e.g., waste incineration - WI with energy recovery) offer an appealing alternative to landfill (Sarkar and Seo, 2021; Sarkar and Chung, 2021; Somorin et al., 2017). They also support the achievement of the Circular Economy EU targets through materials recovery in synergy with recycling operations (Abis et al., 2020) and help to "close-the-loop" also on the energy side (Tomić and Schneider, 2018). The main technical bottlenecks of WI are: handling of the flue-gas cleaning (FGC) ash and of uncontrolled emissions (Munir et al., 2021); recovery of fly ash (Astrup et al., 2016); and bottom ash management (Bruno et al., 2021; Blasenbauer et al., 2020). Environmental groups and local communities usually contest WtE plants. While WI is preferred over landfill, few residents are in favor of hosting a WI plant due to perceived health risks (Baxter et al., 2016), demographic issues (Liu et al., 2021), and low trust in the information provided by the local government (Subiza-Pérez et al., 2020). However, the WI sector is based on mature and well-established technologies that can limit and control its environmental impacts. The Best Available Techniques (BAT) reference document (BREF) for WI (Neuwahl et al., 2019), i.e., the reference in EU-27, identified the emissions to air and water, waste production, noise, energy production/consumption and raw materials consumption as crucial environmental issues. Moreover, through a benchmark analysis in the EU and the world, the BREF for WI inventoried the currently available applied technologies that could minimize the emission levels originated by WI plants. The BAT Conclusions for WI (Neuwhal et al., 2019) included a list of the recommended BAT, their associated emission levels and monitoring actions and identified the implementation of an Environmental Management System (EMS) as BAT to manage this type of plants.

EMS are voluntary schemes built on the “plan-do-check-act” iterative cycle (Fet and Knudson, 2017) that the companies can adopt to assess and improve their environmental performances. The international reference standards for EMS implementation are the ISO 14001 (ISO, 2015) and the European Eco-Management and Audit Scheme (EMAS) (European Commission, 2009). ISO 14001 and EMAS exhibit significant differences (Testa et al., 2014) and are often both adopted by companies (Murmura et al., 2018). Specifically considering EMAS, two key distinguishing features can be highlighted. Firstly, before the release of the EMAS registration to an organization, the National Competent Authority carries out a formal assessment through the support of the Environment Agency to verify its compliance with the applicable legal environmental requirements. Secondly, EMAS requires the registered organizations to publish an Environmental Statement (ES), annually validated by an independent environmental verifier, containing the relevant environmental information related to its registered installation(s). The consequences of EMS implementation on the environmental performances of organizations have been questioned in the scientific literature. Some authors outlined reductions in air emissions, waste production, and water/energy/materials consumption after EMS implementation (Russo, 2009; Martin-Pena et al., 2014). Johnstone and Hallberg (2020) highlighted environmental performance improvements linked to operational advancements. It is vital that companies registered to EMAS declare significant environmental indicators and reliable improvement objectives in the ES, and apply a continuous monitoring of the related operational advancements and objectives’ achievement. The key shortcomings of EMAS application are related to the limited use of eco-efficiency indicators (Heras-Saizarbitoria et al., 2020a), the symbolic adoption of EMS to obtain certifications (Heras-Saizarbitoria et al., 2020b), or to advancements occurring mainly in the initial implementation phase (Testa et al., 2014).

Nevertheless, the EMAS process is rigorous; companies are requested to identify their significant environmental aspects and to keep them under continuous quantitative monitoring through operational procedures. EMAS ESs contain detailed and publicly available data on site-specific environmental performances, are verified by the National Competent Authorities, and validated by an independent environmental verifier. Therefore, the ESs represent a significant source of validated and verified site-specific environmental data (Comoglio and Botta, 2012; Petrosillo et al., 2012), and provide reliable information in a more consistent and specific way compared to other environmental sustainability reports (Tsalis et al., 2020; Iosifov and Ratner, 2018). For those reasons, ESs have been repeatedly used as a quality data source in literature. Various authors analyzed the ESs to evaluate trends in the environmental performances reported by several companies (Daddi et al., 2011; Marrucci and Daddi, 2022; Heras-Saizarbitoria et al., 2020a). Castelluccio et al. (2022) performed an environmental assessment of the performances of the Italian bio-waste sector based on the data disclosed in the EMAS ESs. Sisani et al. (2022) used data retrieved from EMAS ESs of WI plants with other literature data to define the significant environmental aspects (waste treated, recovered energy and slag treated) to conduct a Life Cycle Assessment (LCA) of the incineration of municipal solid waste.

LCA remains the most common tool to perform environmental assessments in the WI sector. Few authors used LCA to analyze the environmental performances of WI plants on a national scale, highlighting benefits for most of the considered impact categories (Beylot et al., 2018; Sisani et al., 2022). Other authors used LCA to compare the performance of WI with other waste management alternatives or with thermoelectric powerplants, often observing that WI outperformed most alternatives (Abuşoğlu et al., 2017; Adeleke et al., 2022). LCA allowed to analyze the impacts of different WI plants (Havukainen et al., 2017), and of the reuse of bottom ash (Margallo et al., 2015). However, LCA has bottlenecks described in the scientific literature. It provides detailed results related to a specific context, sometimes controversial, and may present relevant problems related to data integrity and uncertainty (Khandelwal et al., 2019; Zhang et al., 2021), and definition of system boundaries (Olofsson and Börjesson, 2018). Another relevant area that has received the attention of researchers is the specific impact on the human health of WI. A review (de Titto and Savino, 2019) found no studies indicating that modern-technology waste incineration plants are a cancer risk factor or adversely affect reproduction or development.

In the described framework, this study analyzed the reporting of the environmental performances of the WI sector in Italy, based on the data described in the ESs of the plants registered to EMAS in 2020. Other studies describing the environmental assessment of WI and of waste management operations or other processes at local/national scale, based on literature data and/or ESs, and reporting the environmental performance and impacts, are available (Table 1). However, to our knowledge, no literature exists reporting the environmental assessment of full-scale WI processes based not only the environmental performance and impact evaluation, but also on the indicators and improvement objectives set by the companies, and on their compliance with the BAT for WI.

Therefore, although state-of-the-art research on WI impacts

Table 1. Comparison of the existing literature on the environmental assessments of various processes and waste management operations (WI = Waste incineration; ESs = Environmental statements).

Authors	Sector	Scale	N. of plants analyzed	Data source	Performance levels	Impacts evaluation	Indicators used by companies	Improvement objectives	BAT compliance
de Titto and Savino (2019)	WI	-	-	Literature	-	Yes	-	-	-
Margallo et al. (2015)	WI	-	-	Literature	-	Yes	-	-	-
Havukainen et al. (2017)	WI	Local	4	Primary, Literature	Yes	Yes	-	-	-
Adeleke et al. (2022)	Waste management	Local	-	Primary, Literature	-	Yes	-	-	-
Abuşoğlu et al. (2017)	WI	Local	1	Primary, Literature	-	Yes	-	-	-
Sisani et al. (2022)	WI	National	39	ESs, Literature, Primary	Yes	Yes	-	-	-
Beylot et al. (2018)	WI	National	90	Primary, Literature	Yes	Yes	-	-	-
Daddi et al. (2011)	Various	National	64	ESs	-	-	-	-	-
Heras-Saizarbitoria et al. (2020b)	Various	National	268	ESs	-	-	-	-	-
Marrucci and Daddi (2022)	Manufacturing	National	414	ESs	-	-	-	-	-
Castelluccio et al. (2022)	Bio-waste	National	16	ESs	Yes	-	Yes	Yes	-
Present study	WI	National	15	ESs	Yes	Yes	Yes	Yes	Yes

(based on LCA and/or EMAS ESs) is established, our literature review highlighted the following research gaps:

- The environmental performances of WI installations are rarely assessed (Sisani et al., 2022) through publicly available and validated data, such as those present in EMAS ESs.
- The performance analysis is mostly performed through LCA, considering specific case studies (Adeleke et al., 2022; Havukainen et al., 2017; Abuşoğlu et al., 2017); the few national-scale studies are context-specific due to the application of the LCA approach (Sisani et al., 2022; Beylot et al., 2018).
- There is an overall lack of focus (Table 1) on which environmental aspects WI companies consider significant, how they quantify their impacts and plan to improve their environmental performances.

In details, compared to existing literature on the environmental assessment of WI processes, this study provides the following novel contributions and objectives:

- Assessment of the average environmental performances of the WI sector in Italy using validated data and key performance indicators (KPIs) present in the ESs of the EMAS registered plants
- Inventory of the environmental aspects considered significant by the WI companies and related performance indicators and metrics.
- Identification of the environmental performance improvement targets set by WI companies.
- Analysis of the compliance with the BAT for WI.

This research analyzed the Italian WI sector, a context that is significant and representative of EU reality (Abis et al., 2020). After a preliminary phase consisting in an inventory of the WI plants registered to EMAS in Italy in 2020 and the analysis of their technical features, the research was based on the following research questions: 1. Which are the indicators (and metrics) used by the EMAS registered WI plants in Italy to evaluate their environmental performance? 2. On which environmental aspects, how, and to what extent are the companies managing WI plants committed to improve their performances? 3. Which is the level of adoption of the BAT for WI, and which are the current environmental performance levels of the analyzed WI plants in relation to selected KPIs? This study is not intended to propose a methodology competing with LCA, but rather has the main goal of analyzing how the Italian WI plants registered to EMAS report quantitative data to the public about their environmental sustainability.

The remainder of this paper is structured as follows: Section 2 describes the adopted novel methodological approach. Results are presented and discussed in Section 3. The last section concludes the paper with the study's key findings and recommendations to WI organizations and institutions. The most relevant previous research is compared with the present study in Table 1.

2. Methodology

This research was based on a methodological approach made of seven inter-related phases applied in sequence (Figure 1), as follows.

1. Inventory of the WI plants registered to EMAS in Italy (reference year: 2020) by cross-checking the WI plants database compiled by the national Environmental Agency (ISPRA, 2020) and the National Register of the EMAS-certified sites (ISPRA, 2021), considering the NACE codes "E38.2.x", i.e., waste treatment and disposal (European Commission, 2006) (related to the preliminary phase described within the aims of the research).
2. Analysis of the ESs and initial selection of the plants to exclude from the inventory the facilities involving other processes/activities besides WI (e.g., sites including a manufacturing plant and a WI plant, providing aggregated performance data) (related to the preliminary phase described within the aims of the research).
3. Analysis of the technical features of the selected WI plants by cross-checking the information available in the ESs and in the plants' Integrated Environmental Authorizations (accessed on the Local Authorities websites) (related to the preliminary phase described within the aims of the research).

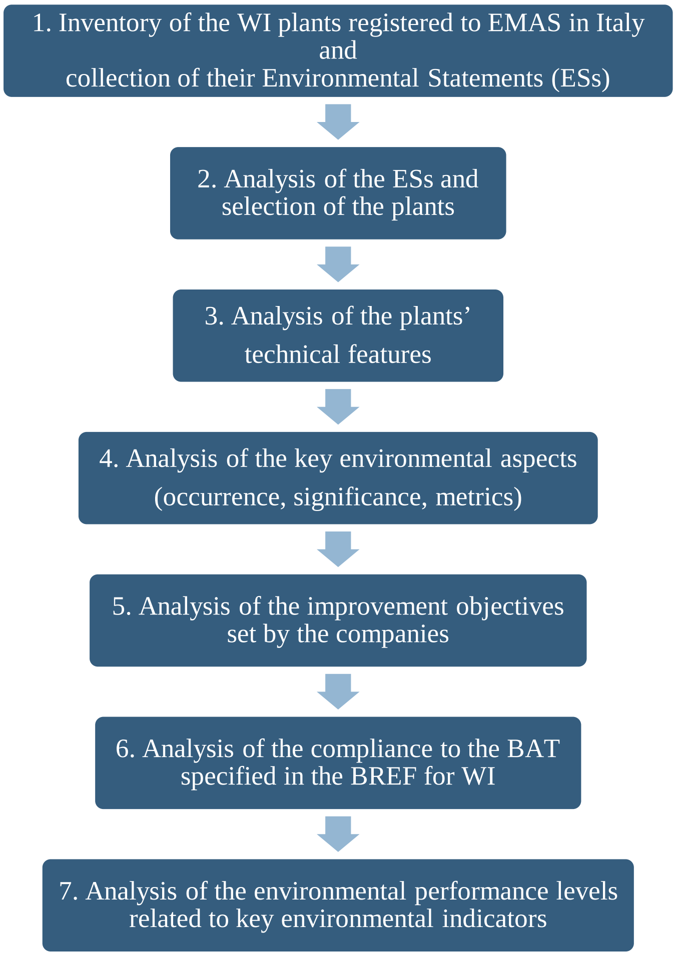


Figure 1. Outline of the applied methodology

4. Analysis of the key environmental aspects, related metrics, and indicators used by the companies in the ESs to describe the impact of their plants (related to research questions 1 and 2). In details, 14 environmental aspects (emissions to air/water, waste production, energy/water/raw materials consumption, odor/noise/light emissions, visual impact, radiations, risks of environmental accidents, soil contamination, and effects on biodiversity) and 5 other aspects not strictly qualifying as "environmental" (type of treated waste, transport, process management, energy production, and stakeholder engagement), were considered. Their occurrence (i.e., if the aspect was reported in the ES) and significance (i.e., the number of ESs considering the aspect as relevant) and the related metrics and indicators were assessed. From this analysis of environmental indicators and metrics,

representative KPIs were selected, based on their occurrence in the ESs and on their relevance to the WI sector, to be subsequently used to analyze and compare the current environmental performance levels of the 15 WI plants (see phase 7).

5. Analysis of the environmental improvement objectives set by the companies managing the selected plants (related to research question 2). The environmental improvement program reported in each ES was analyzed, identifying the objectives set from 2016 to 2019, and collecting data on the specific actions, metrics, and allocated budget.

6. Analysis of the compliance to the BAT specified in the BREF for WI (Neuwahl et al., 2019) (related to research question 3). The ESs were analyzed to retrieve information about the level of adoption by the 15 plants of the BAT for WI related to emissions to air, energy and raw materials consumption, and waste production.

7. Analysis and comparison of the current environmental performance levels of the WI plants of the sample related to the selected KPIs (related to research question 3). The performances reported in the ESs over the period 2017 – 2019 were analyzed and compared based on the following 8 metrics: HCl, NO_x, CO, and dust flue-gas (FG) concentrations, total water consumption, total waste production, and total electricity consumption and production. The ESs report data over a period of 3 years, which is considered by EMAS an adequate short/medium period for monitoring the fulfillment of the declared improvement objectives, and therefore data related to that timespan were used in the analyses. The KPIs related to air emissions were selected among the pollutants continuously monitored in all plants. HCl and CO were chosen to describe acid gas emissions and the combustion quality inside the plant, respectively. Except for air emissions, the other parameters were normalized to 1 ton of treated waste to compare the operational performances of the different WI plants. A performance score (PS) metric was created to describe the performances of the plants related to each KPI, as shown in eq. (1):

$$PS = \frac{\bar{x}}{\mu} \tag{1}$$

where $\bar{x}$ is the average value of the considered KPI reported over the period 2017 – 2019 for a single plant, and μ is the average value of the same KPI calculated for the whole sample of selected plants. Lower scores indicate better performances than higher scores, and a score of 1 equals the sample average. The electricity production values were inverted to assign lower scores to better performances.

2.1. Sensitivity analysis

The linear correlation between the data considered in phases 4, 5 and 7 of the methodology was assessed, and its statistical significance was evaluated through the Pearson correlation coefficient. When samples of plants with distinct characteristics exhibited different performance scores (PS), the statistical significance of those differences was evaluated with the Welch t-test, eq. (2):

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}} \quad (2)$$

Where $\bar{x}_i$, s_i, and N_i are the samples mean, standard deviation, and size. The Welch t-test was selected instead of the Student t-test as it performs better when the groups compared have different sample sizes and variances (Delacre et al., 2017).

3. Results and discussion

3.1. Plants description

From the application of phases 1-3, out of the 37 WI plants operating in Italy in 2020, 27 resulted included in the National Register of the EMAS-certified sites, and 15 were selected according to phase 2 of the methodology. 12 ESs were not included in the sample because other activities besides WI were performed, and it was not possible to retrieve performance data exclusively related to WI process. The 15 plants constituting the final sample (representing 55.6% of the total number of WI plants in Italy) are located mainly in North/Central Italy (12) and fewer in Southern Italy (3)

(Supplementary Materials, Figure I). Considering their technical features (Table 2), the feedstock is mostly municipal solid waste (>88 wt% for 7 plants out of 15), also with non-hazardous special wastes (e.g., sludge from wastewater treatment, bulky waste) in variable amounts (23-50 wt%); two plants treat exclusively refuse-derived fuel or solid recovered fuel, and one plant only special waste. Concerning combustion, all plants involve incineration grates, 33.3 % flue-gas recirculation, and 40 % heat production in co-generation. About the FGC, all plants use bag filters, 33 % electrostatic precipitators. All plants apply dry processes to reduce acidic gases emissions; in 3 plants they are associated with wet processes, and in one with semi-wet processes. All plants apply systems to reduce NOx emissions; selective non-catalytic reactors and selective catalytic reactors are frequently used, also in combination.

Table 2. Main technical characteristics of the considered waste incineration plants. A double tick in the flue-gas cleaning section indicates that the technology is installed twice (MSW: municipal solid waste; SW: non-hazardous solid waste; RDF: refuse-derived fuel; SRF: solid recovered fuel; BF: bag filters; ESP: electrostatic precipitators; DP: dry processes; WP: wet processes; SWP: semi-wet processes; SNCR: selective non-catalytic reactors; SCR: selective catalytic reactors).

	Operational Data				Combustion		Flue Gas Cleaning						
	Treated Waste												
Plant	MSW	SW	SRF/RDF	Capacity	Heat Production	Flue-Gas Recirculation	ESP	BF	DP	SWP	WP	SNCR	SCR
	%	%	%	t/h	-	-	-	-	-	-	-	-	-
Acerra	100			81				✓✓	✓✓	✓			✓
Gerbido	100			67.5			✓	✓	✓				✓
Padova	100			25		✓		✓✓	✓✓			✓	✓
Piacenza	97			15				✓	✓			✓	✓
Schio	96			9.6	✓		✓	✓	✓				✓
Como	94			13.4	✓		✓	✓	✓				✓
Trieste	88	11		25.5				✓	✓		✓	✓	
Silla2	>70	<30		72.5	✓	✓	✓	✓	✓				✓
Granarolo	68	31		25	✓	✓		✓	✓		✓	✓	✓
Trezzo	62	38		21				✓	✓		✓	✓	✓
Brescia	57	23		108	✓	✓		✓	✓			✓	✓
Ferrara	50	50		18	✓			✓✓	✓✓			✓	✓
San Vittore			100	38.5		✓	✓	✓	✓			✓	✓
Pozzilli			100	12				✓	✓			✓	
Terni		100		12				✓	✓			✓	

3.2. Key environmental aspects and related performance indicators

Phase 4 involved the analysis of the key environmental aspects, their significance and related metrics and indicators used by the companies in the ESs to describe the impact of their plants. The ESs revealed a detailed description of aspects, metrics, and indicators (Table 3). 11 key environmental aspects (emissions to air/water, waste production, water/raw materials/energy consumption, soil contamination, risk of environmental accidents, effects on biodiversity, process management and waste treated) were listed in all ESs, over a total of 19 reported aspects. Few aspects have been considered significant in most ESs: emissions to air and waste production (>80 %), water consumption (60 %), raw materials consumption, and water/noise emissions (ca 50 %). These aspects, and particularly emissions to air and waste production, were recognized by literature and the BREF as WI's most relevant impacts (Liu et al., 2021; Di Maria et al., 2021; Tait et al., 2020). An exception was water consumption, considered significant by 60 % of organizations but rarely highlighted as relevant in literature. 8 key aspects were instead considered significant by only 3 or fewer companies and were generally aspects not identified as relevant in the literature. One notable exception was the technical aspect energy production, considered significant only by 13 % of the companies, as energy production efficiency has been highlighted as a critical driver of WI's impacts in literature (Beylot and Villeneuve, 2013; Damgaard et al., 2010).

The analysis of the quantitative metrics used in the ESs to describe the 19 aspects, resulted in a total of 197 indicators (Supplementary Materials, Table I). 6 environmental aspects (emissions to air, waste production, water/raw materials/energy consumption and effects on biodiversity) were described by quantitative indicators by all companies. Only 3 environmental aspects (soil contamination, odor emissions and light pollution) lacked quantitative indicators in all ESs. A positive correlation between the significance of an aspect and the number of quantitative indicators was found ($r(17) = 0.68$, $p < 0.01$), similarly to the findings reported in the study of Castelluccio et al. (2022) related to the Italian bio-waste sector. The most significant aspects (emissions to air and waste production) were in fact described by several indicators (avg. 7.7, max 12 and avg. 6.3, max 10, respectively). Interestingly, despite being considered significant by only one-third of the ESs, the aspect energy consumption exhibited the highest number of indicators (avg. 7.9, max 14), presumably because of its direct relationship with operational costs that could have led to accurate monitoring by the companies. Summarizing, the aspects emissions to air, waste production and energy consumption were described in all ESs by at least 3 different indicators. Only 3 other aspects were described on average with over 2 indicators in all ESs: releases to water (2.7) and water (2.3) and raw materials consumption (2.1). Apart from energy consumption, all the other 5 aspects were considered significant by at least 7 ESs. On the other hand, the aspect soil contamination, considered in all ESs and accounted as significant by 40 % of the companies, was never described with indicators, as well as the aspects odor emissions and light pollution.

Table 4 lists the environmental indicators most frequently found (at least in 5 different ESs) for each aspect. 4 indicators were used in all the 15 ESs: mean annual concentrations of pollutants emitted to air, annual mass of waste produced (total and for each type), and total annual reagents consumption. The set of indicators in Table 4 can represent a useful reference for future research to describe the overall environmental performance of WI plants. 53 individual indicators followed the eco-efficiency criteria defined by Heras-Saizarbitoria et al. (2020a), and 42.4% of the total environmental indicators found were also reported following the mentioned criteria. This result is in line with the findings of Erkko et al. (2005) and Heras-Saizarbitoria et al. (2020a), which found that 42% of the analyzed indicators were calculated using minimum eco-efficiency principles.

Table 3. Summary of the key aspects considered in the ESs, significance assessment, and indicators (x: average; vertical line: median).

Aspect	Considered in the ESs %	Significant %	Described by indicators %	No. of indicators per plant [-]
Emissions to Air	100	93.3	100	
Waste Production	100	86.7	100	
Water Consumption	100	60.0	100	
Raw Materials Cons.	100	46.7	100	
Releases to Water	100	46.7	86.7	
Soil Contamination	100	40.0	0	
Energy Consumption	100	33.3	100	
Waste Treated	100	33.3	93.3	
Risk of Env. Accidents	100	20.0	60.0	
Process Management	100	20.0	13.3	
Effects on Biodiversity	100	13.3	100	
Noise Emissions	93.3	46.7	53.3	
Odor Emissions	93.3	20.0	0	
Stakeholder Engagement	93.3	0	46.7	
Transport	86.7	33.3	53.3	
Visual Impact	86.7	33.3	20.0	
Radiations	80.0	13.3	13.3	
Energy Production	73.3	13.3	60.0	
Light Pollution	26.7	0	0	

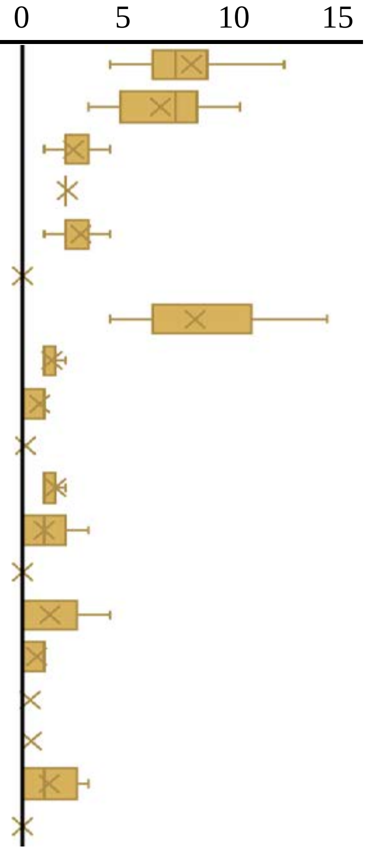


Table 4. List of the most frequently reported environmental indicators.

Aspect	Indicator	Unit	No. ESs
Emissions to Air	Mean annual concentrations of pollutants emitted to air	mg/Nm^3	15
	Total annual mass of pollutants emitted to air	t	14
	Total annual CO_2 mass emitted to air	t	12
	Total annual mass of pollutants emitted to air per treated waste	t/t	11
	Total annual CO_2 mass emitted to air per treated waste	t/t	7
	Total annual mass of pollutants emitted to air per produced energy	t/MWh	6
	Total annual CO_2 mass emitted to air per produced energy	t/MWh	5
	Mean annual concentrations of pollutants emitted to air as a percentage of the authorized limits	%	5
Waste Production	Total annual mass of waste produced	t	15

	Total annual mass of waste produced per typology	t	15
	Total annual mass of waste sent to recycling	t	12
	Mass of waste produced per typology per total annual mass of produced waste	t/t	11
	Total annual mass of waste recycled per typology	t	8
	Total annual mass of waste sent to disposal	t	8
	Total annual mass of hazardous waste produced	t	7
	Total annual mass of waste produced per treated waste	t/t, m^3/m^3	7
	Total annual mass of hazardous waste produced per treated waste	t/t	6
	Total annual mass of non-hazardous waste produced	t	5
	Total annual mass of waste produced per produced energy	t/MWh	5
	Total annual mass of non-hazardous waste produced per treated waste	t/t	5
Raw Materials Consumption	Total annual reagents consumption	t	15
	Total annual reagents consumption per treated waste	kg/t, l/t	10
	Total annual reagents consumption per produced energy	t/MWh	6
Water Consumption	Total annual water consumption	m^3	14
	Total annual water consumption per treated waste	m^3/t	11
	Total annual water consumption per source	m^3	10
	Total annual water consumption per produced energy	m^3/GWh	6
Waste Treated	Total annual amount of treated waste	t	14
	Total annual amount of treated waste per type	t, %	11
Energy Consumption	Total annual methane consumption	t, Sm^3	13
	Total annual electricity consumption	MWh	10
	Total annual self-produced electricity consumption	MWh	10
	Total annual electricity consumption per treated waste	MWh/t	8
	Total annual electricity consumption per produced energy	MWh/MWh	7
	Total annual electricity consumption from the grid	MWh	7
	Total annual oil consumption	t	7
	Total annual energy consumption	MWh	6
	Energy efficiency index Directive 2008/98/EC	-	6
Effects on Biodiversity	Total site area	m^2	13
	Total site area per use	m^2	12
Releases to Water	Mean annual concentrations of pollutants released to water	various	8
	Total annual wastewater volume produced	m^3	5
Risk of Environmental Accidents	Total annual number of emergency events	-	8
Noise Emissions	Maximum noise levels at the plant's boundaries	dB	7
	Maximum noise levels at sensitive receptors	dB	7
Energy Production	Total annual electricity production per treated waste	MWh/t	7
Transport	Total daily number of vehicles entering and exiting from the plant	-	7

3.3. GHG emissions reporting

The impact of the analyzed WI plants in terms of GHG emissions was generally sufficiently detailed and explained in the ESs. This information allowed to analyze how the GHG emissions are specifically inventoried and reported by WI plants, both in terms of emission sources considered and emissions avoided, aspects that were lacking in the scientific literature on WI. Quantitative data on produced GHG emissions were reported in 12 ESs. 8 ESs directly presented the total CO_2 emissions from the flue-gas measuring, generated by the incineration of waste, the use of fuels for auxiliary burners, and the reagents reactions in the FGC section. 5 ESs reported the CO_2 emissions contribution of the fossil fraction of the waste, estimated from analysis of the waste composition. Secondary sources of GHG emissions were considered infrequently and accounted for only 0.3 to 1.9 % of total GHG emissions. 5 ESs reported the estimated emissions from fuels used for auxiliary burners, emergency boilers, or vehicles, and 1 ES estimated the impact of $NaHCO_3$ use. Similarly, the equivalent CO_2 emissions due to N_2O and CH_4 emissions were reported by 5 and 2 ESs, accounting for 0.2 to 1.1 % of total GHG emissions. Despite the generally well-detailed sections on GHG emissions, none of the organizations considered the contributions related to waste transport to the plant, reagents' manufacturing, and WI waste disposal. Neglecting emissions due to the transport of waste from the collecting facility to the WI plant represents a relevant deficiency, since it is a secondary source of GHG emissions that could differentiate the overall performances of different plants based on the origin of the waste treated. The same shortfall has been reported by Castelluccio et al. (2022) regarding the Italian bio-waste sector. Avoided GHG emissions were mentioned by 12 ESs: 7 companies estimated the avoided emissions related to the production of the recovered energy from fossil fuels; 4 ESs estimated those related to landfill disposal of the treated waste. Table II, in the Supplementary Material, presents an exhaustive overview of how GHG emissions were reported in the ESs.

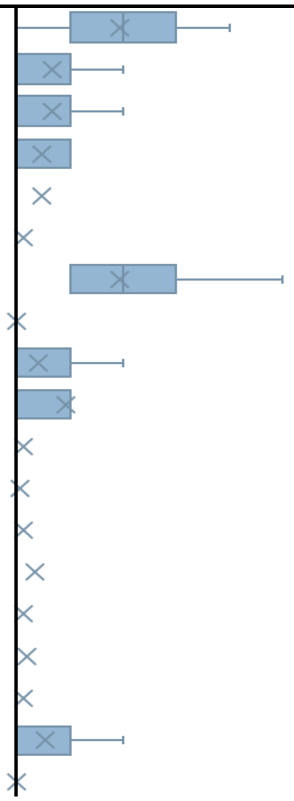
3.4. Improvement objectives

140 improvement objectives were found in the ESs (Supplementary Materials, Table III). Energy consumption resulted the only key aspect with at least one objective set in every ES (Table 5) and with the overall highest number of objectives (29), again showing a specific commitment towards operational costs reductions. 29 improvement objectives were also related to the emissions to air in 13 ESs out of 15. Over 50 % of the ESs specified improvement targets for waste production, raw materials consumption, and process management. 5 out of the 19 considered aspects accounted for 66 % of the total objectives: emissions to air, energy consumption, process management, waste production, and water consumption. Less than one-third of the ESs set improvement objectives for 11 aspects and no objective was declared for light pollution and waste treated. A positive correlation between the significance of an aspect and the number of improvement objectives set was found, $r(17) = 0.49$, $p < 0.05$. This result is in contrast with the findings of Castelluccio et al. (2022) regarding the Italian bio-waste sector, where no correlation between the significance of an aspect and the number of improvement objectives was identified. Energy consumption was again an outlier, being the environmental aspect with the highest number of improvement objectives set despite its low significance. In contrast, noise emissions were defined as significant in 46.7 % of the ESs, with only one improvement objective.

The allocated budget was specified for 74.3 % of the 104 declared improvement objectives, resulting in a total sum of 79.8 M€. The aspects with the highest budget were energy production (33.9 M€) and process management (24.2 M€), for a total of 19 improvement objectives. Emissions to air, energy consumption, waste production and raw materials consumption accounted for a total of 76 objectives (54.3 % of the total) and an overall budget of 18.6 M€ (23.3 % of the total). The environmental aspects with the highest allocated budget were emissions to air, energy consumption, and waste production, with a mean budget per objective between 111 and 581 k€.

Table 5. Summary of the environmental improvement objectives and allocated budget (cross: average; horizontal line: median).

Aspect	Tot allocated budget k€	Budget per objective k€	ESs with objectives %	No. of objectives per plant [-] 0 2 4 6
Emissions to Air	12,778	581	85.7	
Waste Production	2,326	291	53.3	
Water Consumption	775	129	46.7	
Raw Materials Cons.	1,046	149	53.3	
Releases to Water	762	152	20.0	
Soil Contamination	20	20	13.3	
Energy Consumption	2,448	111	100	
Waste Treated	0		0.0	
Risk of Env. Accidents	739	185	33.3	
Process Management	24,216	2,018	66.7	
Effects on Biodiversity	0		6.7	
Noise Emissions	95	95	6.7	
Odor Emissions	499	499	13.3	
Stakeholder Engagement	51	13	20.0	
Transport	60	60	13.3	
Visual Impact	30	30	20.0	
Radiations	35	18	13.3	
Energy Production	33,920	4,846	40.0	
Light Pollution	0		0.0	



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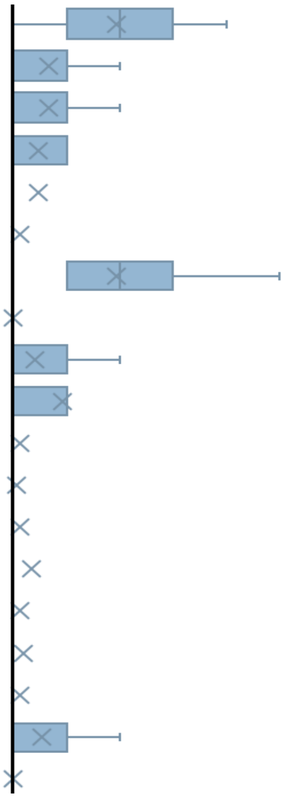

InTable 6 the objectives set at least by two of the analyzed WI companies are listed. The ones with the highest occurrence were related to the introduction of LED technology (12 ESs) and components replacement (8 ESs) to reduce electricity consumption, and to the update of the emissions to air monitoring systems (8 ESs).

Table 6. List of objectives set at least by two of the analyzed WI companies.

Aspect	Objective	Action	No. of ESs
Energy Consumption	Electricity consumption reduction	Replacement of lighting with LED technology	12
		Components replacement	8
	Energy consumption reduction	Energy efficiency monitoring	2
Emissions to Air	Emissions management improvement	Updating of emission monitoring systems	8
	Diffuse emissions reduction	Fly ashes discharge optimization	4
	NOx emissions reduction	DeNOx system installation	3

	Keeping emissions at current levels		2
	Greenhouse gas emissions reduction	Connection as a supplier to the district heating network	2
	Plant impact assessment	Air contaminants dispersion models	2
	Emissions management improvement	Installation of activated carbon dosage system	2
Water Consumption	Reduction of water consumption	Use of groundwater as process water	3
		Reuse of treated wastewater	3
		Water leaks elimination	2
Waste Production	Bottom ashes management improvement	Implementation of an iron removal system	3
	Waste management improvement	Improvements to the waste storage area	2
	Fly ashes management improvement	Transport optimization	2
Raw Materials Consumption	Reagents consumption reduction	Improvement of the acid gas dry abatement system efficiency	3
	Paper consumption reduction	Computerized management	2
Releases to Water	Sewer discharge management improvement	Water discharges separation improvements	3
		Increasing the capacity of the wastewater treatment plant accumulation tank	2
Process Management	Line performances improvement	Refurbishment	2
	Plant security improvement	Construction of a new perimeter fence	2
	Improvement of vapor generator reliability	Installation of a new superheater	2
Risk of Environmental accidents	Fire management improvement in the waste storage bunker	Installation of thermal cameras for fire detection	2
Stakeholder Engagement	Increased awareness	External initiatives	2
Transport	Traffic circulation improvement	Construction of a new waste weighing system	2
Radiations	Radioactive waste detection improvement	Installation of a new radioactive material detection system	2

45 % of the improvement objectives had direct implications in reducing the plant’s operational costs or improving production, contributing to increasing the number of objectives set for aspects such as energy consumption and production. This suggests that environmental sustainability was not the only driving force that led to setting improvement objectives in the environmental program. Contrarily to the direct relationship found between the significance of an aspect and the number of improvement objectives set, no correlation occurred between the significance of an aspect and the

budget allocated to its improvement ($r(17) = 0.04$, $p < 1$). The 73 % of the total budget was in fact allocated to improvement objectives related to energy production and process management, considered significant by 2 and 3 ESs, respectively. Excluding these 2 aspects, the correlation between significance and budget allocated improved ($r(15) = 0.66$ $p < 0.01$).

Finally, it must be outlined that for over 25 % of the improvement objectives, the allocated budget was not disclosed in the ESs. Furthermore, although information on the progress of the actions related to the objective's achievement was usually reported, indicators allowing to track it and to relate each action to a quantified improvement of an environmental aspect were rarely set. Modifying the environmental program accordingly could help to better reveal the extent of the organizations' commitment and the real effectiveness in improving environmental performance, thus increasing public perception of information transparency.

3.5. Compliance with the BAT for WI

3.5.1. Emissions to air

Table IV in the Supplementary Materials summarizes the information contained in the ESs about the compliance to the BAT specified in the BREF for WI (Neuwahl et al., 2019) related to the emissions to air. It must be outlined that in no ES a specific section clearly detailing the plant's compliance to the applicable BAT was present. Therefore, the information had to be obtained by thoroughly analyzing technical details describing the plant's operations within the environmental sustainability reports of the companies managing the considered WI plants. BAT 4 regulates the monitoring frequency (continuous or discontinuous) of the contaminants' concentrations in the flue-gas. All plants fulfilled the indications for NO_x, NH_3, CO, SO_2, HCl, dust, total volatile organic compounds (TVOC), and polychlorinated dibenzodioxins and furans (PCDD/F). On the contrary, only one ES reported monitoring N_2O emissions, even if requested explicitly by BAT4. As for the other contaminants, 13 out of 15 ESs reported monitoring metals emissions, and 14 ESs HF, Hg, and Benzo[a]Pyrene (BaP). While 6 ESs declared the implementation of advanced control systems (BAT 15), no details about monitoring campaigns performed during the start-up and shut-down of the incinerator (BAT 5) were provided, and this represents a remarkable gap: in fact, emissions to air during other than normal operating conditions are a relevant issue, since emission peaks during start-up and shut-down of WI plants have been observed for TVOC, CO, and HCl, and PCDD/F emission loads equivalent to several months of normal operation have been associated to single cold start events (Neuwahl et al., 2019).

About diffuse emissions, 7 ESs reported sufficient information about their containment from waste storage (BAT 21) and 3 from slags and bottom ashes handling and treatment (BAT 24). All plants declared to adopt at least one of the techniques indicated in BAT 29 for reducing NO_x, N_2O, and CO emissions. 2 ESs did not mention any measure to minimize the slip of the NH_3 used for NO_x removal. 6 ESs reported the implementation of FG recirculation technology (BAT 20), which can further reduce NOx emissions.

Regarding acid gas emissions (SO_2, HCl, and HF), all ESs reported at least one of the technologies indicated in BAT 27, and 3 ESs also the automated dosage of reagents (BAT 28). All ESs mentioned at least one of the techniques specified in BAT 25 and BAT 31 to reduce the channeled emissions of dust, metals, and mercury. No ES reported complete information regarding extraction, treatment, and analysis of air from the enclosed treatment of slags and bottom ashes (BAT 26), while only 2 ESs declared the adoption of all the techniques required by BAT 30 to reduce emissions of organic compounds, including PCDD/F and BaP. From the information in the ESs, it was possible to deduce the compliance to at least one BAT for all the major air pollutants. Exceptions were micropollutants such as TVOC, PCDD/F and BaP because BAT 30 requires the application of a specific combination of techniques. This result, although based only on the data included in the ESs, supports the findings of the study of Di Marco and Manuzzi (2018), which highlighted that the 3 WI plants analyzed adopted the BATs to limit the emissions for each pollutant of concern.

3.5.2. Energy consumption, raw materials consumption, and waste production

BAT compliance about energy and raw materials consumption, and waste production is detailed in Table V of the Supplementary Materials. With regards to energy consumption, the BREF for WI focuses on the ratio between consumed and produced energy, and on the production of electricity and heat in relation to the treated waste mass. 14 out of 15 ESs reported sufficient information to obtain the energy ratio. One ES reported the calculated gross electrical efficiency (BAT 2), while 13 ESs referred to at least one of the techniques prescribed in BAT 20 to increase the plant's energy efficiency.

About waste production, all ESs mentioned the ratios between bottom/other ashes and treated waste. These indicators were present 8 and 6 times, respectively, and were derivable 7 and 9 times. However, the picture concerning other ashes management was uneven, partly because of the conjunct analysis of the boiler and fly ashes, as they were mostly disposed of together. Furthermore, different FGC technologies can lead to differences in the fly ashes composition and thus to the European waste code definition. All plants complied with BAT 35, requiring separate handling and treating of bottom ashes and FGC residues, and 8 ESs reported the adoption of at least one of the bottom ash treatment techniques described in BAT 36.

Finally, considering raw materials' consumption, 4 ESs contained the necessary information to derive the ratio between oil consumption and treated waste, and 3 ESs directly used that indicator. In comparison, 13 ESs contained data to calculate the methane consumption to treated waste ratio, and 3 ESs used that indicator. Concerning the reagents for the FGC, both the neutralizers and the ammonia to treated waste ratio were reported 9 times. Sufficient data to calculate that indicator were present 5 times. As previously stated, 3 ESs reported the automated dosage of the reagents (BAT 28), thus limiting their consumption.

3.6. Comparison of plants' performances

Figure 2 presents the plants' performance scores for the 8 selected KPIs and the average performance values calculated for the 15 WI plants over the period 2017 – 2019. Regarding emissions to air (Figure 2A), most plants alternated performances above and below the sample average for the 4 different pollutants. This result was expected as different contaminants are often removed through separated FGC steps. Interestingly, few plants (4 out of 15) performed significantly better than the sample average for all considered pollutants. In general, it was impossible to identify the specific technical characteristics of the plants that led to these positive results, although electrostatic precipitators' adoption significantly reduced the dust concentration in the FG ($p = 0.004$, Welch t-test). Apart from water consumption, the performance scores related to the other aspects exhibited less variance compared to air emissions (Figure 2B). Once again, few plants outperformed the average score in all categories (of these, only the Acerra plant was also among the outperformers in air emissions), but, again, no correlation with plants characteristics could be clearly established, apart from lower performances in electricity production by WI plants where heat production in co-generation was carried out (e.g., Como plant). Additionally, the plant located in Terni exhibited excellent performance scores for electricity production and consumption and the best ones related to water consumption and waste production. The Terni plant is characterized by a specific feedstock, paper pulper, which led to a very low production of bottom ashes and could have also influenced the excellent performances related to the other KPIs.

In Figure II in the Supplementary Material, the performance scores of the plants are plotted against the budget allocated for the improvement of the respective environmental aspects. No significant correlation was found between the two variables, although the plants that allocated the highest budget to improve water consumption and waste production performed worse than the sample average, probably indicating that significant investments were aimed at the improvement of poor performances.

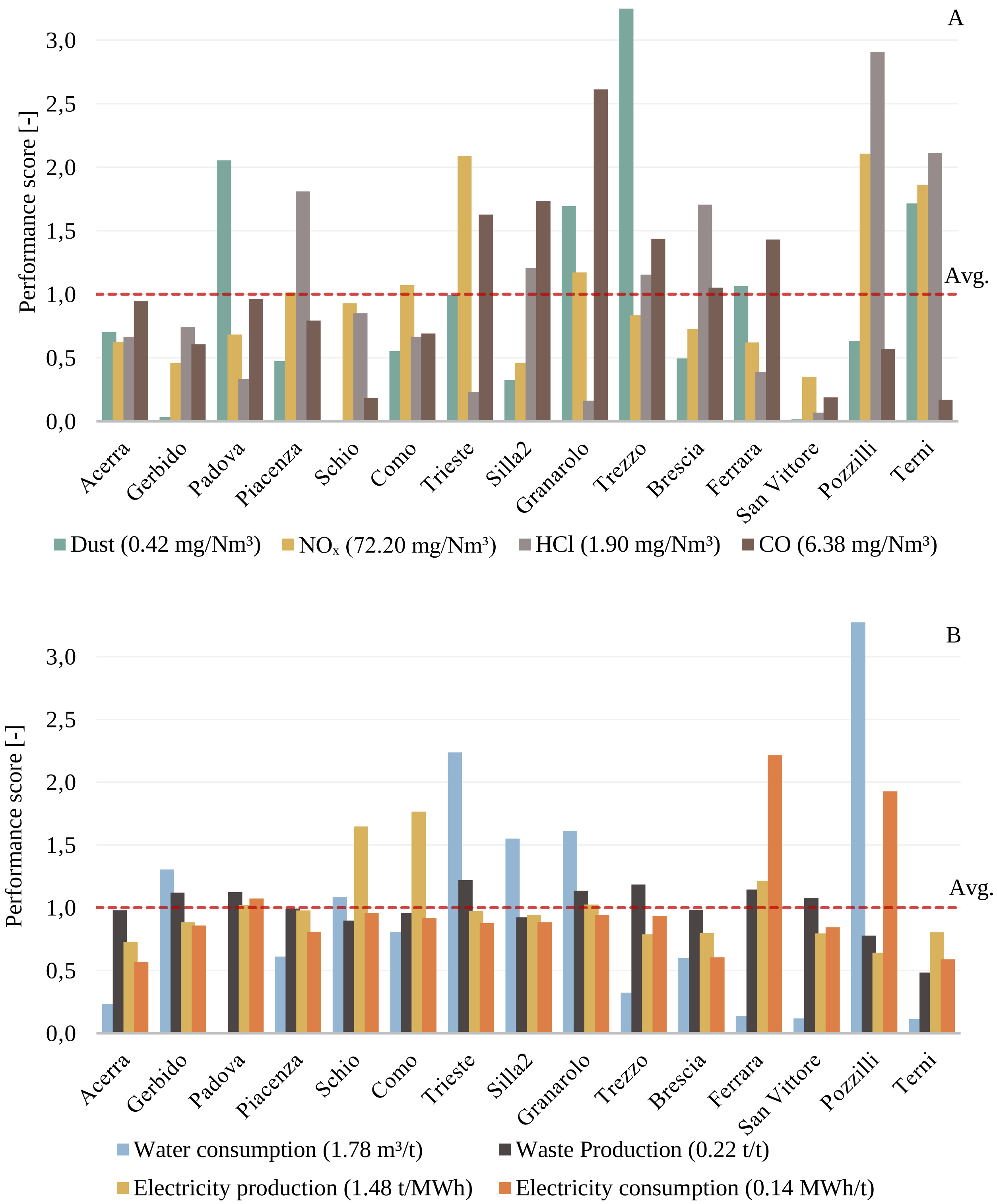

Figure 2. Performance scores of the analyzed WI plants related to: (A) emissions to air; (B) water consumption, waste production and electricity production and consumption. Lower scores indicate better performances and a score of 1 equals the sample average (reported in brackets). The energy production values were inverted to assign lower scores to better performances.

The calculated average specific energy consumption was higher than the mass-weighted average reported by Beylot et al. (2018) for WI plants in France (0.140 MWh/t compared to 0.104 MWh/t). Although a significant correlation between the plants' size and the specific energy consumption was excluded ($r(13) = 0.41$, $p = 0.12$), the mass-weighted average specific energy consumption of our sample (0.123 MWh/t) was lower than the average but still higher than the value reported by Beylot et al. (2018). The calculated average specific electricity production (0.676 MWh/t) confirms the results of Sisani et al. (2022) based on data from 39 Italian WI plants (from 0.448 MWh/t to 0.766 MWh/t). Although the study highlighted the higher specific electricity production of WI plants with higher waste treatment capacity, a significant correlation between those variables was excluded for our sample ($r(13) =0.39$, $p = 0.14$).

4. Conclusions

This study analyzed how the Italian WI plants registered to EMAS in 2020 report to the public about their environmental sustainability. EMAS leads companies to disclose every year their performance data in the ESs, a consistent source of independently verified and validated information. Consequently, the novel methodological approach applied in the present study allowed a quantitative analysis of the WI plants of the sample, and therefore, it could be applied to the analysis of the environmental aspects and performances of other relevant industrial sectors.

From the selected ESs, a comprehensive set of 197 metrics and indicators used to measure the environmental performances of WI plants was created. The indicators are related to 19 different aspects, together with a list of 104 improvement objectives set by the companies of the sample with an overall allocated budget of 79.8 M€. The obtained lists of environmental indicators and improvement objectives can represent a useful reference for other companies of the WI sector willing to assess their environmental performances, and implement an EMS. In some cases, the number of indicators used was not directly related to the significance of the environmental aspect, due to a specific commitment of the companies to keep under control aspects that can lead to a significant reduction of operational costs (e.g., energy consumption). A subset of the collected metrics, possibly more specifically linked to the emissions levels related to the BAT adoption, could instead provide a more representative description of the environmental performances of this sector. In this sense, a specific sectorial guideline issued by the EC on key metrics dedicated to EMAS registered plants would represent a further step forward towards an even more transparent and comparable environmental sustainability reporting. Most companies reported sufficient quantitative data on key environmental performance indicators, thus allowing to identify the current performance levels of the different plants in relation to air emissions (HCl, NO_x, CO, and dust flue-gas concentrations) and water consumption, waste production, and electricity consumption and production related to 1 ton of treated waste. However, no specific correlation was found between plants' performances and budget allocated for the improvement of the environmental aspects. A large portion (73 %) of the declared budget for improvement was attributed to expensive technical interventions beneficial for the overall efficiency of the plant. These limitations did not allow to clearly identify and quantify the direct influence of the EMS implementation on the improvement of the environmental performances of the plants. Again, specific recommendations to EMAS registered companies about drawing explicit links in the ESs between each action of the environmental program and the expected environmental performance improvement, supported by adequate metrics and quantitative data, would increase the transparency of information, thus revealing the company's commitment and the environmental safeguard implications associated with the allocated budget. The main limitations of the adopted methodology are that the sample size is limited by the EMAS adoption rate in the WI sector and the short time spanned by the quantitative data present in the ESs, which limits the ability to assess the statistical significance of correlations and trends. Moreover, data interpretation may be limited by lacking descriptions of plants' characteristics and features in the ESs.

In conclusion, the results of this study showed that the management approach required by EMAS contributed to lead the analyzed WI plants to report to the public about their significant commitments to: monitoring a vast number of environmental performance indicators; investing relevant resources for their improvement, especially in relation to the aspects emissions to air, energy and raw materials consumption, and waste production. EMAS can be considered a useful tool for the WI sector to design and implement monitoring actions, to pursue the improvement of environmental performances, and to transparently report and communicate validated data to the stakeholders, contributing to raise the overall trust of the general public in the sector.

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Supplementary Materials

Figure I. Geographical distribution of the Italian Waste to Energy plants: EMAS registered (in blue) and the others (in grey).

Table I. List of the environmental indicators and related aspects reported in the Environmental Statements (ES). The indicators marked with (*) are static parameters describing the characteristics of the plants.

Aspect	Indicator	Unit	No. of ES
Emissions to Air	Mean monthly concentrations of pollutants emitted to air	mg/Nm^3	2
	- NO_x		2
	- SO_2		2
	- Dust		2
	- HCl		2
	- HF		1
	- CO		3
	- TOC		2
	- NH_3		2
	Total annual mass of pollutants emitted to air	t	14
	- NO_x		12
	- SO_2		5
	- SO_x		7
	- Dust		12
	- HCl		12
	- HF		8
	- CO		12
	- TOC		12
	- NH_3		6
	- Hg		5
	- Zn		1
	- Cd + Tl		3
	- Ni		1
	- Other metals		3
	- PCDD/F		7
	- PCB		1
	- PAH		6
	- $PM_{2.5}$		1
	Total annual CO_2 mass emitted to air	t	12
	Total annual CO_2 mass emitted to air by source	t	3
	- From burning fossil fraction of waste		1
	- From burning municipal waste's fossil fraction		1
	- From burning municipal waste's biogenic fraction		1
	- From burning special waste's fossil fraction		1
	- From burning special waste's biogenic fraction		1
	- From auxiliary boiler		2
	Total annual greenhouse gas mass emitted to air	t	4
	Total annual greenhouse gas mass emitted to air by source	t	3
	- From auxiliary boiler		1

- Due to N_2O		2
- Due to N_2O from the fossil fraction of the waste		1
- Due to N_2O from biogenic fraction of waste		1
- Due to N_2O from auxiliary boiler		1
- Due to CH_4		1
- Due to CH_4 from the fossil fraction of the waste		1
- Due to CH_4 from biogenic fraction of waste		1
- Due to CH_4 from auxiliary boiler		1
- Not due to CO_2		2
Total annual mass of pollutants emitted to air per produced energy	t/MWh	6
- NO_x		6
- SO_2		4
- SO_x		2
- Dust		6
- HCl		6
- HF		3
- CO		6
- TOC		6
- NH_3		5
- Hg		2
- Cd + Tl		1
- Other metals		1
- PCDD/F		2
- DL PCB		1
- PAH		2
- PM_{10}		1
- $PM_{2.5}$		1
Total annual CO_2 mass emitted to air per produced energy	t/MWh	5
Total annual CO_2 mass emitted to air per produced energy by source	t/MWh	1
- From burning fossil fraction of waste		1
CO_2 emissions into the atmosphere avoided	t	2
Mean annual concentrations of pollutants emitted to air	mg/Nm^3	15
- NO_x		14
- SO_2		9
- SO_x		5
- Dust		13
- HCl		14
- HF		11
- CO		14
- TOC		13
- NH_3		14
- Hg		13
- Zn		4
- Cd + Tl		10
- Ni		1

- Other metals		10
- PCDD/F		14
- PCB		6
- DL PCB		3
- PAH		12
- PM_{10}		2
- $PM_{2.5}$		1
N. of continuous monitoring campaigns	-	1
Flue-gas flow rate	Nm^3/h	4
Mean oxygen concentration in the flue-gas	%	1
Mean water vapor content in the flue-gas	%	1
Mean annual CO_2 concentration emitted to air	%	4
Total annual mass of pollutants emitted to air per treated waste	t/t	11
- NO_x		11
- SO_2		7
- SO_x		4
- Dust		11
- HCl		11
- HF		5
- CO		11
- TOC		11
- NH_3		8
- Hg		8
- Zn		1
- Cd + Tl		3
- Other metals		3
- PCDD/F		5
- PCB		1
- PAH		6
Total annual CO_2 mass emitted to air per treated waste	t/t	7
Total annual CO_2 mass emitted to air per treated waste by source	t/t	1
- From burning fossil fraction of waste		1
- From combustion biogenic fraction of municipal waste per treated municipal waste		1
- From combustion of the fossil fraction of special waste per treated special waste		1
- From combustion of the biogenic fraction of special waste per treated special waste		1
- From auxiliary boiler		1
Total annual greenhouse gas mass emitted to air per treated waste	t/t	4
Total annual greenhouse gas mass emitted to air per treated waste by source	t/t	2
- Due to N_2O		1
- Due to N_2O from the fossil fraction of the waste		1
- Due to N_2O from biogenic fraction of waste		1
- Due to CH_4		1

- Due to CH_4 from the fossil fraction of the waste		1
- Due to CH_4 from biogenic fraction of waste		1
Total annual avoided greenhouse gas emissions per treated waste	t/t	3
Total annual avoided greenhouse gas emissions per produced energy	t/MWh	1
Total annual avoided greenhouse gas emissions	t	2
Total annual avoided greenhouse gas emissions by source	t	1
- For the production of electricity		1
- For district heating		1
- For disposal in landfills		1
N. of days of instrumentation unavailability per year	-	1
N. of unavailable half-hourly detections per year	-	1
N. of detections above the emission limit per year	-	4
N. of detections above the emission limit for each contaminant per year	-	1
- NO_x		1
- SO_x		1
- Dust		1
- HCl		1
- HF		1
- CO		1
- TOC		1
- Hg		1
- Other metals		1
- PCDD/F		1
- PAH		1
Mean annual concentrations of pollutants emitted to air as a percentage of the authorized limits	%	5
- NO_x		5
- SO_2		4
- SO_x		1
- Dust		5
- HCl		5
- HF		2
- CO		5
- TOC		5
- NH_3		5
- Hg		4
- Cd + Tl		1
- Other metals		2
- PCDD/F		4
- DL PCB		1
- PAH		2
Greenhouse gas emissions balance	t	1
Mean annual concentrations of pollutants emitted to air per flue-gas flow rate	$kg/Nm^3/h$	1
- NO_x		1

	- SO_2		1
	- Dust		1
	- HCl		1
	- HF		1
	- CO		1
	- TOC		1
	- NH_3		1
	- Hg		1
	- Cd + Tl		1
	- Other metals		1
	- PCDD/F		1
	- PAH		1
	Total annual avoided emissions of contaminants with high acidification potential per treated waste	kg/t	1
	Total annual avoided emissions of contaminants with high acidification potential	t	1
	Total annual mass of refrigerant gas topped up by type	kg	1
	- R410 refrigerant gas topped up		1
	- R470C refrigerant gas topped up		1
Waste Production	Total annual mass of waste produced	t	15
	Total annual mass of waste produced per typology	t	15
	- EWC 06 05 03		1
	- EWC 15 01 02		1
	- EWC 16 10 02		1
	- EWC 17 04 05		2
	- EWC 19 01 02		5
	- EWC 19 01 12		14
	- EWC 19 07 03		1
	- EWC 19 08 14		2
	- EWC 19 12 02		1
	- EWC 19 12 03		1
	- EWC 19 12 12		1
	- EWC 20 01 01		1
	- EWC 20 03 04		1
	- EWC 20 03 07		1
	- EWC 13 02 05*		1
	- EWC 13 02 08*		2
	- EWC 15 02 02*		2
	- EWC 16 11 05*		1
	- EWC 19 01 05*		8
	- EWC 19 01 06*		4
	- EWC 19 01 07*		2
	- EWC 19 01 11*		2
	- EWC 19 01 13*		7
	- EWC 19 01 15*		2
	- EWC 19 02 05*		1
	- EWC 19 08 13*		2

- Process waste		4
- Waste produced by maintenance or auxiliary activities		3
- Others dangerous		2
- Others not dangerous		3
Total annual mass of non-hazardous waste produced	t	5
Total annual mass of hazardous waste produced	t	7
Total annual mass of non-hazardous waste produced as a percentage of total annual mass of waste produced	%	1
Total annual mass of hazardous waste produced as a percentage of total annual mass of waste produced	%	1
Total annual mass of waste produced per produced energy	t/MWh	5
Total annual mass of waste produced per typology per produced energy	t/MWh	3
- EWC 19 01 12		3
- EWC 19 12 12		1
- EWC 19 01 05*		2
- EWC 19 01 11*		2
- EWC 19 01 13*		2
- EWC 19 01 15*		1
- Others dangerous		1
- Others not dangerous		1
Total annual mass of hazardous waste produced per produced energy	t/MWh	1
Total annual mass of waste produced per treated waste	t/t, m^3/m^3	7
Mass of waste produced per typology per total annual mass of produced waste	t/t	11
- EWC 06 05 03		1
- EWC 17 04 05		1
- EWC 19 01 02		2
- EWC 19 01 12		8
- EWC 19 12 02		1
- EWC 19 12 03		1
- EWC 15 02 02*		1
- EWC 19 01 05*		3
- EWC 19 01 07*		1
- EWC 19 01 13*		4
- EWC 19 01 15*		1
- EWC 19 02 05*		1
- EWC 19 08 13*		2
- Process waste		3
- Waste produced by maintenance or auxiliary activities		1
Total annual mass of non-hazardous waste produced per treated waste	t/t	5

	Total annual mass of hazardous waste produced per treated waste	t/t	6
	Total annual mass of waste sent to recycling per treated waste	%	2
	Total annual mass of waste sent to disposal per treated waste	%	2
	Total annual mass of waste sent to recycling per produced energy	t/GWh	1
	Total annual mass of waste sent to recycling	t	12
	Total annual mass of waste recycled per typology	t	8
	- EWC 19 01 02		4
	- EWC 19 01 12		6
	- EWC 20 03 07		1
	- EWC 19 01 05*		3
	- EWC 19 01 06*		2
	- EWC 19 01 07*		1
	- EWC 19 01 13*		1
	- EWC 19 01 15*		1
	- Other waste		1
	Total annual mass of waste sent to disposal	t	8
	Total annual mass of waste disposed per typology	t	4
	- EWC 19 01 02		1
	- EWC 19 01 12		3
	- EWC 20 03 07		1
	- EWC 19 01 05*		2
	- EWC 19 01 06*		3
	- EWC 19 01 07*		1
	- EWC 19 01 13*		1
	- EWC 19 01 15*		1
	- EWC 19 02 05*		1
	Total annual mass of waste recycled per total annual waste produced	%	3
	Total annual mass of waste recycled per total annual waste produced per typology	%	1
	- EWC 19 01 12		1
	- EWC 19 01 05*		1
	Total annual mass of waste disposed per total annual waste produced	%	2
Raw Materials Consumption	Total annual reagents consumption	t	15
	- Hydrochloric acid		6
	- Sodium hydroxide		10
	- Sodium hydroxide for physical chemical plant		1
	- Ferric chloride		3
	- Acetic acid		1
	- Lime		8
	- Ammonia		9
	- Activated carbon		14
	- Sodium bicarbonate		12
	- Sulfuric acid		6
	- Flocculant		1

- Sorbalite		2
- Sodium hypochlorite		4
- Ferrous sulphate		1
- Sulfamic acid		1
- Phosphate and O_2 reducer		1
- Polymers		1
- Antiscalant		1
- Polyelectrolyte		1
- Oils		2
- Urea		7
- Glycol		1
- Anticorrosive		1
- Antiscalants and anticorrosives		1
- Deoxygenating		2
- Alkalizing		1
- Sequestering agent		1
- Citric acid		1
- Thermal cycle additives		1
- Total		3
Total annual reagents consumption per produced energy	t/MWh	6
- Hydrochloric acid		4
- Sodium hydroxide		5
- Ferric chloride		1
- Acetic acid		1
- Lime		3
- Ammonia		5
- Activated carbon		6
- Sodium bicarbonate		4
- Sulfuric acid		2
- Flocculant		1
- Sodium hypochlorite		1
- Urea		3
- Citric acid		1
Total annual reagents consumption per treated waste	kg/t, l/t	10
- Hydrochloric acid		2
- Sodium hydroxide		4
- Ferric chloride		1
- Lime		4
- Ammonia		6
- Activated carbon		9
- Sodium bicarbonate		9
- Sulfuric acid		3
- Flocculant		1
- Sorbalite		1
- Phosphate and O_2 reducer		1
- Urea		4
- Total		1

Water Consumption	Total annual water consumption	m^3	14
	Total annual water consumption per source	m^3	10
	- Aqueduct		10
	- Well		6
	- Demineralization plant		1
	- Recovered from external plant		1
	- Rainwater		4
	- Shallow waters		1
	- Recovered		1
	- Total water withdrawn		1
	Total annual water consumption per use	m^3	2
	- Demineralized water		1
	- Industrial uses and fire-fighting services		1
	- Services		1
	- Evaporative towers		2
	- Irrigation and services		1
	Total annual water consumption per produced energy	m^3/GWh	6
	Total annual water consumption per produced energy per source	m^3/MWh	2
	- Aqueduct		2
	- Well		2
	- Demineralization plant		1
	- Recovered from external plant		1
	- Rainwater		1
	- Recovered		1
	- Total water withdrawn		1
	Total annual water consumption per treated waste	m^3/t	11
	Total annual water consumption per treated waste per source	m^3/t	3
	- Aqueduct		3
	- Demineralization plant		1
	Percentage of annual water consumption per source	%	2
	- Aqueduct		1
	- Recovered		1
	Percentage of the recovered first flush from impermeable surfaces	%	1
	Percentage of annual water consumption per use	%	1
	- Services		1
	- Evaporative towers		1
Waste Treated	Total annual amount of treated waste	t	14
	Total annual amount of treated waste per typology	t, %	11
	- Urban and special waste		2
	- Hazardous medical waste		1
	- Drugs		1
	- Urban waste and similar		2
	- Urban waste		3
	- Hazardous urban waste		1

	- Non-hazardous municipal waste		1
	- Special waste similar to urban waste		1
	- Special hazardous waste		1
	- Special non-hazardous waste		1
	- Special waste		1
	- Medical waste		3
	- Sludge		1
	- SRF		1
	- Biomass waste		1
	- Bulky waste		1
	- Biodegradable waste		1
	- Other special waste		1
	- Plastic waste		1
	- Cellulosic waste		1
	- Inert		1
	- Remains of sorting		1
	- Organic material		1
	- Metal waste		1
	- Undercut		1
	- Unusable rejects		1
	- RDF		1
	- RDF and SRF		1
	- EWC 03 03 07		1
	Total annual amount of waste diverted to other plants due to plant shutdown	t	1
	Total annual amount of treated waste per produced energy	t/MWh	3
	Total annual amount of treated waste per produced energy per typology	t/MWh	1
	- RDF and SRF		1
	Checked waste loads as a percentage of the total	%	1
	Rejected waste loads as a percentage of the total	%	1
Energy Consumption	Total annual electricity consumption	MWh	10
	Total annual renewable electricity consumption	MWh	3
	Total annual electricity consumption per produced energy	MWh/MWh	7
	Total annual electricity consumption per treated waste	MWh/t	8
	Total annual renewable electricity consumption per treated waste	MWh/t	3
	Total annual renewable electricity consumption per produced energy	MWh/MWh	2
	Total annual energy savings	toe	2
	Total annual energy consumption	MWh	6
	Total annual renewable energy consumption	%	2
	Total annual energy consumption per treated waste	toe/t	1
	Energy efficiency index Directive 2008/98/EC	-	6
	Total annual self-produced electricity consumption	MWh	10
	Total annual electricity consumption from the grid	MWh	7
	Total annual heat consumption	MWh	1

Total annual heat consumption per produced energy	MWh/MWh	1
Total annual renewable heat consumption	MWh	1
Total annual renewable heat consumption per produced energy	MWh	1
Total annual self-produced heat consumption	toe	1
Total annual electricity consumption per total annual energy consumption	%	1
Total annual renewable electricity consumption per total annual energy consumption	%	1
Total annual self-produced electricity consumption per produced energy	%	1
Total annual self-produced electricity consumption per treated waste	MWh/t	1
Total annual energy savings per treated waste	toe/t	1
Total annual energy savings per produced energy	toe/MWh	1
Total annual energy losses	MWh	1
Total annual oil consumption	t	7
Total annual oil consumption by use	t	4
- Automotive		2
- Burners		2
- Warm up		1
- Generating set		1
- Vehicles		1
- Ovens		1
Total annual methane consumption	t, Sm^3	13
Total annual methane consumption by use	t	4
- Burners		2
- Catalyst		2
- Warm up		1
Total annual methane consumption per total introduced energy	-	1
Total annual methane consumption per produced energy	MWh/MWh	4
Total annual oil consumption per produced energy	MWh/MWh	1
Total annual methane consumption per treated waste	Sm^3/t	4
Total annual methane consumption per treated waste by use	Sm^3/t	2
- Burners		1
- Catalyst		1
- Warm up		1
Total annual methane consumption per produced energy	l/t	3
Total annual oil consumption per treated waste	l/t	2
Total annual oil consumption per treated waste by use	l/t	2
- Generating set		1
- Vehicles		1
- Ovens		1

	Total annual mass of combusted fossil fuel avoided by waste incineration	toe, t	2
	Total annual methane consumption per total annual energy consumption	%	1
	Total annual oil consumption per total annual energy consumption	%	1
	Total annual fuel consumption	toe	1
Impact on Biodiversity	Total site area (*)	m^2	13
	Total site area per use (*)	m^2	12
	- Total green spaces area		9
	- Total covered area		5
	- Total impermeable covered area		1
	- Total uncovered area		1
	- Total impermeable uncovered area		5
	- Total permeable uncovered area		1
	- Total impermeable area		5
	- Total built-up area		5
	- Total area subject to planting		1
	- Total site area dedicated to waste storage		1
	- Total site area dedicated to parking		1
	Total site area per produced energy	m^2/MWh	4
	Total site area per produced energy per typology	m^2/MWh	3
	- Total impermeable area per produced energy		1
	- Total built-up area per produced energy		2
	Total site area per treated waste	m^2/t	2
	Total site area per treated waste per typology	m^2/t	2
	- Total green spaces area per treated waste		1
	- Total green spaces area outside the site per treated waste		1
	- Total impermeable area per treated waste		2
	Specific areas per total site area (*)	%	4
	- Total green spaces area per total site area		3
	- Total impermeable area per total site area		2
	- Total area subject to planting per total site area		1
	- Total site area dedicated to waste storage per total site area		1
Releases to Water	Total annual wastewater volume produced	m^3	5
	Total annual municipal wastewater volume produced by source	m^3	1
	- For washing fumes, industrial and from well cleaning		1
	- From slag cooling		1
	Mean daily flow rate of the water discharges	m^3/d	3
	- Mean daily flow rate of the water discharges per receptor		2
	- Sewer		2
	Total annual wastewater volume per produced energy	m^3/MWh	1
	Total annual wastewater volume per treated waste	m^3/t	2
	Total annual wastewater volume	m^3	4

Total annual wastewater volume per receptor	m^3	4
- Surface waters		3
- Sewer		3
Total annual industrial wastewater volume produced	m^3	2
Total annual municipal wastewater volume produced	m^3	1
Total annual industrial wastewater volume sent to treatment	m^3	1
Total annual industrial wastewater volume reused as process water	m^3	1
Total annual industrial wastewater volume entered in the district heating network	m^3	1
Annual blow-down volume from evaporative towers	m^3	1
Mean annual concentrations of pollutants released to water	Various	8
- pH		2
- Suspension solids		4
- BOD_5		1
- COD		4
- Aluminum		1
- Arsenic		1
- Boron		1
- Cadmium		1
- Cyanides		1
- Chlorides		5
- Total chromium		3
- Chromium VI		1
- Iron		5
- Phosphorus		1
- Manganese		3
- Mercury		4
- N-Ammonia		5
- Nickel		3
- N-Nitric		4
- N-Nitrous		2
- Lead		2
- Copper		2
- Selenium		1
- Sulphates		4
- Sulphites		1
- Sulphides		1
- Zinc		2
- Total hydrocarbons		3
- PAH		1
- PCDD/F		1
- Chlorinated solvents		1
- Aromatic organic solvents		1
- Organic nitrogen solvents		1

- Surfactants		2
Mean annual concentrations of pollutants released to surface water	Various	2
- pH		1
- Temperature		1
- Color		1
- Coarse material		1
- Suspension solids		1
- BOD_5		1
- COD		1
- Arsenic		1
- Barium		1
- Boron		1
- Cadmium		1
- Chlorides		1
- Total chromium		1
- Chromium VI		1
- Iron		1
- Phosphorus		1
- Manganese		1
- Mercury		1
- N-Ammonia		1
- Nickel		1
- N-Nitric		2
- N-Nitrous		1
- N-Total		1
- Lead		1
- Copper		1
- Selenium		1
- Tin		1
- Thallium		1
- Zinc		1
- Escherichia Coli count		1
- Fats and oils		1
- Total hydrocarbons		1
- Pesticides		1
- Toxicity Assay - Daphnia Magna		1
- Surfactants		1
Maximum annual concentrations of pollutants discharged to the drainage system	Various	1
- Cadmium		1
- Total chromium		1
- Nickel		1
- Lead		1
- Copper		1
- Zinc		1
Maximum annual concentrations of pollutants discharged to the drainage system as percentage of the authorized limits	%	3

- Suspension solids		1
- BOD_5		1
- COD		1
- Chlorides		2
- Total chromium		1
- Iron		2
- Manganese		2
- Mercury		2
- N-Ammonia		3
- Nickel		2
- N-Nitric		2
- N-Nitrous		2
- Sulphates		2
- Total hydrocarbons		1
Mean annual concentrations of pollutants discharged with grey water	Various	1
- pH		1
- Suspension solids		1
- BOD_5		1
- COD		1
- Chlorides		1
- N-Ammonia		1
- N-Nitric		1
- N-Nitrous		1
- Zinc		1
Mean annual concentrations of pollutants discharged with black water	Various	1
- pH		1
- Suspension solids		1
- BOD_5		1
- COD		1
- Chlorides		1
- N-Ammonia		1
- N-Nitric		1
- N-Nitrous		1
- Zinc		1
Mean annual concentrations of pollutants discharged with grey water as percentage of the authorized limits	%	1
- pH		1
- Suspension solids		1
- BOD_5		1
- COD		1
- Chlorides		1
- N-Ammonia		1
- N-Nitric		1
- N-Nitrous		1
- Zinc		1

	Mean annual concentrations of pollutants discharged with black water as percentage of the authorized limits	%	1
	- pH		1
	- Suspension solids		1
	- BOD_5		1
	- COD		1
	- Chlorides		1
	- N-Ammonia		1
	- N-Nitric		1
	- N-Nitrous		1
	- Zinc		1
Risk of Env. Accidents	Total annual number of emergency events	-	8
	Total annual number of injuries	-	1
	Injury frequency index	-	1
	Days of absence of personnel due to accidents	d	1
	Injury severity index	-	1
Stakeholder Engagement	Total annual number of visits to the site	-	4
	Total annual number of organized initiatives	-	4
	N. initiatives per typology	-	3
	- Meetings		3
	- Conferences and events		3
	- Focus groups		3
	- Committee or work groups		3
	Total annual number of visitors	-	3
	Total annual number of visitors per typology	-	1
	- N. of students or teachers visitors		1
	- N. of other visitors		1
	Total annual number of surveys	-	3
	Total number of website views	-	1
	Total number of website views advanced	-	1
	- N. of unique page views		1
	- N. of accesses		1
	- Bounce rate		1
	Annual average time on website	min	1
	Annual increase in organized initiatives	%	1
	Annual increase in visits to the plant	%	1
	Total annual number of received complaints and reports	-	1
Noise	Maximum noise levels at the plant's boundaries	dB	7
	Maximum noise levels at sensitive receptors	dB	7
	Noise exposition levels per worker task	dB	1
Energy Production	Total annual electricity production per treated waste	MWh/t	7
	Total annual electricity entered into the grid per treated waste	MWh/t	4
	Total annual renewable electricity production per treated waste	MWh/t	2
	Total annual renewable electricity entered into the grid per treated waste	%	2

	Annual balance of total produced and consumed energy	toe	1
	Total annual produced energy per total annual consumed energy	%	1
	Total annual produced energy per treated waste	toe/t	1
Transport	Total daily number of vehicles entering and exiting from the plant	-	7
	Total daily number of vehicles entering and exiting from the plant per function	-	3
	- Delivery of reagents		2
	- Waste disposal		1
	- Disposal of the ashes		1
	- Disposal of the flue gas cleaning wastewater		1
	- Disposal of industrial wastewater		1
	- Cleaning		1
	- Delivery of fuel		1
	- Waste disposal		1
	- Inbound		1
	- Output		1
	- Move		1
	Percentage of the local traffic due to plant's activities	%	1
	Total monthly number of vehicles entering and exiting from the plant	-	1
	Maximum daily number of vehicles entering and exiting from the plant	-	1
Radiations	Magnetic field intensity inside the plant	nT	1
	Electric field intensity outside the plant	V/m	1
	Magnetic field intensity at the plant's boundary	nT	1
	Electric field intensity at the plant's boundary	V/m	1
	Total annual number of findings of radioactive material in incoming waste	-	2
Visual Impact	Chimney height (*)	m	3
	Distance from city center (*)	km	1
	Distance from towns (*)	km	1
Process Management	Total annual training hours	h	1
	Total annual training hours per receiver	h	1
	- Total annual training hours directed to the plant's personnel		1
	- Total annual training hours directed to external workers		1
	Total annual training hours per number of employees	h	1
	Total annual training hours per number of employees per receiver	h	1
	- Total annual training hours directed to the plant's personnel per number of employees		1
	- Total annual training hours directed to external workers per number of employees		1

Table II. Overview of the reporting of GHG emissions in the ES (M: measured; E: estimated; n.a.: not available).

Site	Positive emissions								Negative emissions		
	GHG emitted from waste incineration					Secondary sources					
	CO_2			N_2O	CH_4	$NaHCO_3$ (reagent)	Vehicles (fuel)	Process (fuel)	Considered	Energy production	Landfill disposal
	Total	Fossil	Biogenic								
Padova	M								✓		
Ferrara	M								✓		
Terni		E				E	E	E	✓		
Trezzo	M	E	E	E	E		E	E			
Silla2	na							E	✓	E	E
Piacenza	na			E					✓	E	
San Vittore											
Granarolo		E		E				E	✓	E	E
Pozzilli	M								✓		
Brescia		E							✓	E	E
Como	M			E	E						
Schio	M								✓	E	
Acerra		E					E	E	✓	E	E
Trieste	M								✓		
Gerbido	M			E					✓	E	

Table III. List of the objectives reported in the Environmental Statements (ES) and related aspects and actions.

Aspect	Objective	Action	No. of ES
Energy Consumption	Electricity consumption reduction	Replacement of lighting with LED technology	12
		Components replacement	8
	Energy consumption reduction	Energy efficiency monitoring	2
	Reduction of electricity consumption	Improving the efficiency of the air conditioning system	1
		Optimization of the compressed air network	1
	Reduction of energy consumption	Implementation of ISO 50001	1
		Heat recovery from the DeNOx circuit	1
	Electrical system improvement	Replacing ACN DCS	1
	Reduction of electricity withdrawals from the grid	Using self-produced electricity for remote heating users	1
	Energy management improvement	Adaptation of measurement tools for calculating energy efficiency index	1
	Reduction in the use of natural gas	Implementing a predictive system for boiler maintenance	1
	Reduction in use of natural gas	Installing an exchanger for DeNOx SCR	1
	Reduction in the use of diesel fuel for burners	Use of methane gas	1
Emissions to Air	Emissions management improvement	Updating of emission monitoring systems	8
	Diffuse emissions reduction	Fly ashes discharge optimization	4
	NOx emissions reduction	DeNOx system installation	3
	Keeping emissions at current levels		2
	Greenhouse gas emissions reduction	Connection as a supplier to the district heating network	2
	Plant impact assessment	Air contaminants distribution	2
	Emissions management improvement	Installation of activated carbon dosage system	2
	NOx emissions reduction		1
	Reduction of NOx emissions	Installing a wet cleaning section	1
	Reduction of diffuse emissions	Staff training	1
	Reduction of CO2 emissions	Replacing vehicle	1
	Reduction of indirect emissions	Improved contractor awareness	1

	Plant impact assessment	Monitoring the air quality of the surrounding area	1
	Improvement of HF emissions management	Installing a lime dosing system	1
Water Consumption	Reduction of drawn water consumption	Use of groundwater as process water	3
		Use of recovered water	3
		Water leaks elimination	2
	Increased demineralized water production efficiency	Implementing reverse osmosis	1
	Reduction of water consumption	Installing an in-line condenser cleaning system	1
Waste Production	Bottom ashes management improvement	Implementation of an iron removal system	3
	Waste management improvement	Improvements to the temporary waste storage area	2
	Fly ashes management improvement	Transport optimization	2
	Improvement of waste management	Staff training	1
	Improvement of black water management	Creation of a ground dispersion system	1
	Improvement of waste management	Reuse for bituminous conglomerate	1
Raw Materials Consumption	Reagents consumption reduction	Improvement of the acid gas dry abatement system efficiency	3
	Paper consumption reduction	Computerized management	2
	Elimination of reagent storage	Modifying the demineralization system	1
	Reduction of reagent consumption	Software implementation for automatic control of the waste-to-energy process	1
		Recirculation optimization	1
Releases to Water	Sewer discharge management improvement	Water discharges separation improvements	3
		Increase in capacity of the purifier accumulation tank	2
	Improvement of sewer discharge management	Optimization of wastewater flow	1
	Improvement of the characteristics of discharges in the sewer	Improvements to the chemical-physical treatment plant	1
Process Management	Line performances improvement	Refurbishment	2

	Plant security improvement	Construction of a new perimeter fence	2
	Improvement of vapor generator reliability	Installation of a new superheater	2
	Improvement of the thermal cycle	Modifying the Teflon-coated circuit	1
	Process monitoring improvement	Implementing NFC technology	1
	Improvement of ENEL plant / cabin technical communication	Cabin management system automation	1
	Improvement of procurement	Acquiring a platform for the execution of tenders in electronic format	1
	Reduction of delays and disputes in the disbursement of payments to suppliers	Starting the passive cycle	1
	Increase in sludge and leachate treated	Increasing the storage system	1
	Reduction of waste deposits created during delivery	Replacing waste yard doors	1
	Improvement of incoming waste management	Implementation of documents management software	1
Risk of Env. Accidents	Fire management improvement in the waste storage bunker	Installation of thermal cameras for fire detection	2
	Improvement of the methane gas leak detection system		1
	Improvement in the management of fires in the waste pit	Modifications to extinguishing systems	1
	Reduction of fire risk in the turbine room	Increasing the level of protection	1
	Improvement of safety during the maintenance phase	Means of parapet and waste pit gates adjustment	1
	Improvement of seismic risk safety	Structural adjustment	1
Stakeholder Engagement	Increased awareness	External initiatives	2
	Improvement of communication	Creating ES in video format	1
	Improvement of communication	Revising the visitor path	1
	Communication improvement	Website restructuring	1
Transport	Traffic circulation improvement	Construction of a new waste scale	2
	Improvement of roads	Construction of a new external axis	1
Radiations	Radioactive waste detection improvement	Installation of a new radioactive detection system	2

Energy Production	Increase of combustion efficiency	Implementation of optimization system	1
	Increased combustion efficiency	Modifying the oven grids	1
	Improvement of heat transfer	Installing an automatic boiler channel washing system	1
	Improved heat transfer	Adjusting the boiler walls	1
		Increasing the surface of the heat exchanger	1
	Increased steam generation efficiency	Replacing the generator	1
	Increase of thermal energy produced	Installing heat pumps in the flue gas treatment system	1
		Installing an additional heat exchanger	1
Visual Impact	Improvement of visual perception of the plant	Arranging green areas	1
	Improvement of the mitigation zone	Creating green areas near the flue gas purification system	1
	Check plantation conservation status		1
Biodiversity	Reclamation of the area outside the site		1
	Forest requalification		1
	Wildlife monitoring		1
Odor Emissions	Reduction of disturbance to the community	Carrying out olfactometric surveys to identify odorous sources	1
	Reduction of odor emissions	Improvement of the waste pit air deodorization system	1
Soil Contamination	Improvement of spill containment systems	Creating NH3 tank escape	1
		Modernizing the HCl basin	1
Noise Emissions	Reduction of disturbance to the community	Installing sound-absorbing barriers on machinery	1

Table IV. Overview of the compliance to the BAT mentioned in the BREF for WI related to emissions to air. The sub header of each contaminant reports the monitoring frequency requested in BAT 4 (C = continuous, D = discontinuous) and the applicable BAT numbers. "All" refers to BAT concerning emissions to air in general.

Plant	All	Diffuse	NO_x	NH_3	N_2O	CO	SO_2	HCl	HF	Dust	Metals	TVOC	Hg	PCDD/F	BaP
	na | 5 15	na | 21 24	C | 20 29	C | 29	D | 29	C | 29	C | 27 28	C | 27 28	C D | 27 28	C | 24 25 26	D | 25	C | 30	C D | 31	D | 30	D | 30
Acerra	na | -	na | -	C | 29	C | 29	- | 29	C | 29	C | 27	C | 27	C | 27	C | 25	- | 25	C | -	- | 31	D | -	D | -
Gerbido	na | 15	na | 24	C | 29	C | 29	- | 29	C | 29	C | 27 28	C | 27 28	C | 27 28	C | 24 25	D | 25	C | -	D | 31	D | -	D | -
Padova	na | -	na | -	C | 20 29	C | 29	- | 29	C | 29	C | 27	C | 27	C | 27	C | 25	D | 25	C | -	C | 31	D | -	- | -
Piacenza	na | -	na | 21	C | 29	C | 29	- | 29	C | 29	C | 27	C | 27	C | 27	C | 25	D | 25	C | -	C D | 31	D | -	D | -
Schio	na | -	na | 21	C | 29	C | 29	- | 29	C | 29	C | 27 28	C | 27 28	C | 27 28	C | 25	C | 25	C | -	D | 31	D | -	C | -
Como	na | 15	na | -	C | 29	C | 29	D | 29	C | 29	C | 27	C | 27	D | 27	C | 25	D | 25	C | -	D | 31	D | -	D | -
Trieste	na | -	na | -	C | 29	C | 29	- | 29	C | 29	C | 27	C | 27	C | 27	C | 25	D | 25	C | -	D | 31	D | -	D | -
Silla2	na | -	na | 21 24	C | 20 29	C | 29	- | 29	C | 29	C | 27	C | 27	D | 27	C | 25	D | 25	C | -	D | 31	D | -	D | -
Granarolo	na | 15	na | 21	C | 20 29	C | 29	- | 29	C | 29	C | 27	C | 27	C | 27	C | 25	- | 25	C | 30	D | 31	D | 30	D | 30
Trezzo	na | 15	na | 21	C | 29	C | 29	- | 29	C | 29	C | 27	C | 27	C | 27	C | 25	D | 25	C | -	D | 31	D | -	D | -
Brescia	na | 15	na | 24	C | 20 29	C | 29	- | 29	C | 29	C | 27 28	C | 27 28	D | 27 28	C | 24 25	D | 25	C | 30	D | 31	C D | 30	D | 30
Ferrara	na | 15	na | 21	C | 29	C | 29	- | 29	C | 29	C | 27	C | 27	C | 27	C | 25	D | 25	C | -	C D | 31	D | -	D | -
San Vittore	na | -	na | -	C | 20 29	C | 29	- | 29	C | 29	C | 27	C | 27	C | 27	C | 25	D | 25	C | -	D | 31	D | -	D | -
Pozzilli	na | -	na | 21	C | 20 29	C | -	- | 29	C | 29	C | 27	C | 27	- | 27	C | 25	D | 25	C | -	C D | 31	D | -	D | -
Terni	na | -	na | -	C | 29	C | -	- | 29	C | 29	C | 27	C | 27	C | 27	C | 25	D | 25	C | -	D | 31	D | -	D | -

Table V. Overview of the data collected about energy consumption, waste production, and materials consumption and related BAT compliance. The indicators with performance ranges in the BREF were present (P) or derived (D) from other data. The first indicator was normalized by the produced energy, the following by the treated waste (Energy Consumption: E = Electricity; H = Heat, T = Total energy. Waste Production and Management: 5 = EWC 19 01 05*; 7 = EWC 19 01 07*; 13 = EWC 19 01 13*; 15 = EWC 19 01 15*. Chemicals Consumption: H = Sodium hydroxide; L = Lime; B = Sodium bicarbonate. Only reagents used for flue-gas cleaning are considered)

	Energy Consumption				Waste Production			Materials Consumption				
Site	Energy MWh/MWh	Electricity MWh/t	Heat MWh/t	BAT	Bottom Ashes t/t	Other Ashes t/t	BAT	Oil l/t	Methane m3/t	Neutralizers kg/t	Ammonia kg/t	BAT
Padova	D(E, T)	P		20	P	P(13)	35		D	P(L, B)	P	
Ferrara	D(T)	D		20	P	D(5)	35, 36			P(L. B)	P	
Terni					D	D(13)	35		D	D(B)	D	
Trezzo	P(E)	D		2, 20	P	P(5)	35	D	D	D(H, L, B)	D	
Silla2	P(E)	P		20	P	P(5, 15)	35	D	D	P(B) D(L)	P	
Piacenza	D(E)	P			P	P(5, 13)	35, 36	P	D	P(L, B)	P	
San Vittore	P(E)	D		20	D	D(5, 7, 13)	35		D	D(B)	D	
Granarolo	P(E) D(T)	P		20	D	D(5)	35, 36	D	P	D(H, L)	D	
Pozzilli	D(E, T)	P		20	D	D(13)	35, 36		D	P(B)	P	
Brescia	P(E) D(H, T)	D	D	20	D	D(5)	35, 36		D	D(L)	D	28
Como	P(E) D(T)	P		20	D	D(7)	35, 36	P	P	P(L, B)	P	
Schio	D(E)	D		20	D	D(13)	35,36	P	P	P(B)	P	28
Acerra	P(E)	D		20	P	D(5, 15)	35	D	D	D(L)	D	
Trieste	D(E, T)	P		20	P	P(13)	35		D	P(H, B)	P	
Gerbido	D(E)	P		20	P	P(13)	35, 36			P(B)	P	28

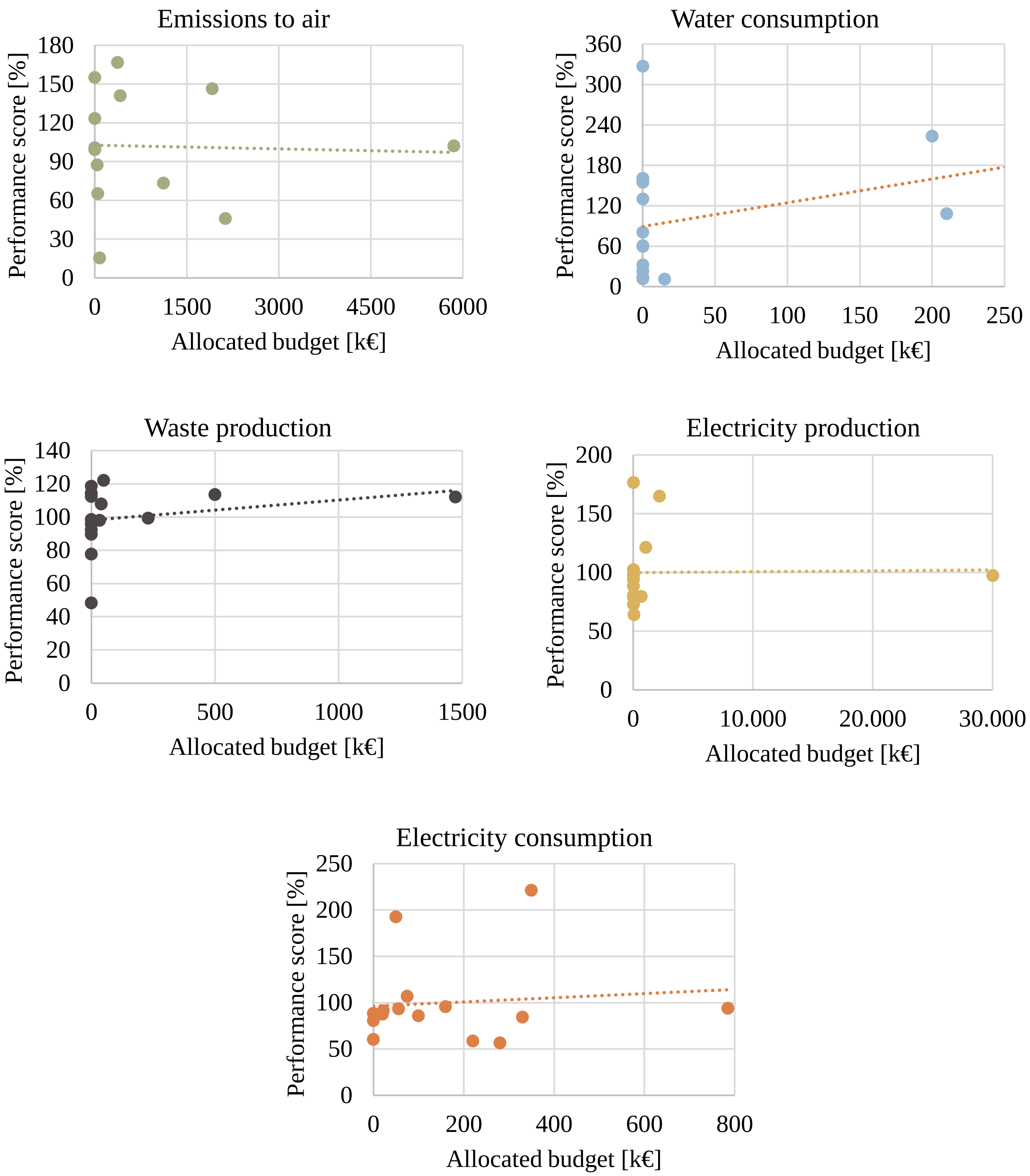

Figure II. Comparison of the performance scores (PS) of the plants and the budget allocated to the improvement of the respective aspect. For emissions to air, the ordinate values refer to the average performance score related to the HCl, NOx, CO and dust concentrations in the FG.