

Assessing the environmental performances of waste-to-energy plants: The case-study of the EMAS-registered waste incinerators in Italy

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1 **Assessing the environmental performances of waste-to-energy plants: the case-**  
2 **study of the EMAS-registered waste incinerators in Italy**

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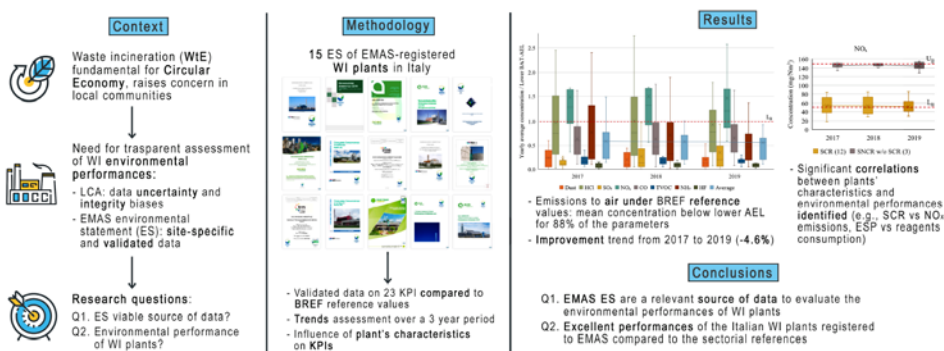
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10  
11 **Highlights**

- 12 - Italian waste incineration (WI) plants registered to EMAS have been analyzed
- 13 - the environmental performances were evaluated through 5 environmental aspects
- 14 - 23 key indicators based on the Environmental Statements were defined and assessed
- 15 - the compliance with BAT-AEL was achieved by all the considered WI installations
- 16 - the influence of technical features on the environmental performances was assessed

17  
18 **Graphical Abstract**



19

20 **Abstract**

21 This study evaluated the environmental performances of 15 Italian waste incineration (WI)  
22 plants registered to EMAS. From the EMAS Environmental Statements, the validated data related  
23 to 5 environmental aspects (emissions to air, energy consumption/production, waste production and  
24 reagent consumption) and 24 key indicators were analyzed to describe and assess the environmental  
25 performances of the plants in 2017-2019 in relation to the best available techniques associated  
26 emission levels (BAT-AELs) and other sectorial reference values. All air pollutants' average  
27 concentrations resulted significantly below the upper BAT-AELs, the majority under the lower  
28 BAT-AELs, with an overall slightly decreasing trend (-4.6%). The specific productions of bottom  
29 and other ashes were steady over time and just above the lower characteristic values. The specific  
30 energy consumption was higher than the average European performance and stable over time, while  
31 the specific reagent consumption was harder to evaluate, with results varying for the different  
32 reagents. An evaluation of the influence of the WI plants' characteristics on the environmental  
33 performances was also performed considering 13 different parameters (e.g., flue gas cleaning  
34 technologies, waste treatment capacity, etc.). A correlation analysis highlighted the positive  
35 influence of the pre-dedusting stages on overall emissions, specific reagents consumption and  
36 specific waste production, and of the plant size on the specific energy production. This study  
37 demonstrated that EMAS can provide a tool to evaluate the environmental performances of WI  
38 plants and compare different installations using certified data. It also highlighted the excellent  
39 performances of the Italian WI plants registered to EMAS compared to the sectorial references.

40

41 **keywords:** Best Available Techniques; environmental improvement objective; environmental  
42 management system; environmental performance indicator; waste incineration.

43

44

## 45 **1. Introduction**

46 Waste-to-energy (WtE) technologies represent a viable option for sustainable waste  
47 management. WtE processes (e.g., waste incineration - WI with energy recovery) allow to minimize  
48 the volume of waste disposed in landfills while producing energy (Tan et al., 2014), helping to  
49 “close the loop” energy-wise (Tomić and Schneider, 2018). They also allow material recovery  
50 through recycling practices applied to bottom ash, in agreement with the European Commission  
51 (EC) Circular Economy policies (Abis et al., 2020). Even though WI is favored over landfill  
52 disposal, WI plants are generally opposed by environmental groups and residents, which rarely  
53 support hosting a plant. WI installations are contested due to perceived health concerns (Baxter et  
54 al., 2016; Liu et al., 2021), and a lack of trust in provided information (Subiza-Pérez et al.,  
55 2020). The key challenges faced by WI are the optimization of bottom ash management (Bruno et  
56 al., 2021; Blasenbauer et al., 2020), the reuse and recycling of fly ashes (Xue and Liu, 2021; Zhang  
57 et al., 2021a) and flue gas cleaning (FGC) residues (Munir et al., 2021), and uncontrolled emissions  
58 to air (Munir et al., 2021).

59 However, WI technology is mature and well-established and it improved its environmental  
60 performances considerably over the last decades (Porteous, 2001), also thanks to the extensive  
61 research dedicated to analyzing its environmental impacts. The EC guidelines for this sector are  
62 described in the best available techniques (BAT) reference document (BREF) (Neuwahl et al.,  
63 2019). The BREF on WI highlights air and water pollution, waste production, energy consumption  
64 and production, noise emissions, and raw materials consumption as critical environmental impacts.  
65 Chapter 3 of the BREF is dedicated to a benchmark analysis of the European WI sector, providing  
66 information on the current ranges of consumption and emission levels, while the BAT conclusions  
67 chapter contains a list of recommended BAT along with the associated emission levels (AELs). The  
68 first BAT refers to the application of an environmental management system (EMS) to improve the  
69 plant’s overall environmental performance. Academia questioned the positive effect of EMS  
70 implementation on environmental performances. Some studies validated this thesis (Johnstone and

71 Hallberg, 2020; Martín-Peña et al., 2014), while others reported weak improvements due to poor  
72 organizational commitment (Heras-Saizarbitoria et al., 2020a and b; Testa et al., 2014).

73 An EMS is a voluntary management tool aiming to enhance an organization's environmental  
74 performance through an integrated and methodical approach dealing with environmental issues  
75 (Zilahy, 2017). The European Eco-Management and Audit Scheme (EMAS) (European  
76 Commission, 2009) and the ISO 14001 (ISO, 2015) are recognized standards for EMS  
77 implementation. Companies often adopt both standards (Murmura et al., 2018), although they  
78 exhibit considerable dissimilarities (Neugebauer, 2012; Testa et al., 2014). Differently from ISO  
79 14001, the companies' compliance with the legal environmental requirements is verified by the  
80 competent national authority, supported by the Environmental Agency, prior to the release of the  
81 EMAS registration. Furthermore, EMAS requires the annual publication of an Environmental  
82 Statement (ES), a report providing the organization's main data and environmental indicators,  
83 verified, and validated by an independent third party (Heras-Saizarbitoria et al., 2020b). The ES can  
84 help the organizations to inform the stakeholders, distinguish themselves for their performances,  
85 and improve their reputation (Heras-Saizarbitoria et al., 2020c), which is of crucial relevance for the  
86 WI sector.

87 In the scientific literature, the assessment of the environmental performances of waste treatment  
88 plants and waste management systems was generally carried out through the Life Cycle Assessment  
89 (LCA) methodology. However, major, and well-documented limitations to its adoption are data  
90 uncertainty and integrity (Zhang et al., 2021b; Khandelwal et al., 2019) and the specificity of the  
91 framework in which the assessment is conducted. LCA studies analyzed the performances of a  
92 single WI installation (Ardolino et al., 2020) or different plants at a regional scale (Morselli et al.,  
93 2007), while, to our knowledge, only two studies analyzed the environmental performances of WI  
94 facilities at a national level (Beylot et al., 2018; Sisani et al., 2022). However, none of those studies  
95 performed a comprehensive evaluation of how WI plants' performances are influenced by their  
96 characteristics (e.g., waste treatment capacity, feedstock, combustion and emissions treatment

97 technologies). Furthermore, those studies lack a thorough comparison with performances reference  
98 values and, due to the LCA approach, the quantified impacts are referred to the local context. On  
99 the other hand, ESs provide substantial site-specific environmental data (Petrosillo et al., 2012;  
100 Comoglio and Botta, 2012) that are also independently validated, therefore reliable and transparent,  
101 characteristics that data contained in other reports lack (Tsalis et al., 2020). Therefore, EMAS ESs  
102 represent a relevant source of validated primary data that can be used to assess and compare the  
103 performances of different WI plants even in a wide geographical context.

104 In the given framework, this study focused on the analysis of the environmental performances  
105 reported by the Italian WI sector, whose main features are representative of the European context  
106 (Abis et al., 2020). The plants were inventoried by cross-checking the National Register of the  
107 EMAS-certified sites (ISPRA, 2021) with the list of WI plants compiled by the National  
108 Environmental Agency (ISPRA, 2020). The ESs of the resulting 15 EMAS registered WI plants  
109 were analyzed in order to carry out a quantitative assessment of their environmental performances  
110 towards the EC BAT-AELs and other sectorial reference values. Overall, three main novelties  
111 distinguish the here presented work: the use of publicly accessible and comprehensive data,  
112 certified at institutional level by the competent national authorities and validated by a third party,  
113 overcoming in this way the limitations of the LCA approach; the assessment of the environmental  
114 performances of WI plants based on indicators and metrics related to EC BAT-AELs and other  
115 sectorial reference values that allow a direct comparison of different facilities; a comprehensive  
116 evaluation of the influence of the plants' characteristics on their environmental performances. This  
117 work was developed from the following research questions: 1. Can EMAS ESs be a viable source of  
118 quantitative data to evaluate WI environmental performances and to compare different installations?  
119 2. Which are the environmental performances of the EMAS registered Italian WI plants compared

120 to the BAT-AELs and sectorial references and how are these influenced by the plants'  
121 characteristics?

122

## 123 **2. Methodology**

### 124 *2.1. Data inventory*

125 The starting point of this research was the analysis of the WI plants registered to EMAS in 2020  
126 in Italy: each of the 15 plants was categorized based on feedstock, waste treatment capacity,  
127 technological features, and FGC technologies. Considering the whole sample, the feedstock was  
128 88.1% municipal solid waste (MSW) or pretreated MSW, 10.6% special waste, and 1.3% other  
129 wastes. The waste treatment capacity distribution and the FGC technology adopted are described in  
130 Figure 1. Concerning the combustion process, all facilities adopt incineration grates, 40%  
131 cogeneration of heat and electricity, and 33.3% flue-gas recirculation. 53.3% of the plants included  
132 3 combustion lines, 33.3% 2 lines, and 13.3% a single line.

133 The data supplied by the ESs overcome any possible limitation of uncertainty and integrity  
134 because they are primary data, provided by the companies managing the WI plants, and they have  
135 been verified and validated by independent third parties (certification body and national Competent  
136 Authority), as required by EMAS.

### 137 *2.2. Selection of key environmental aspects and performance indicators*

138 Table 1 lists the identified key performance indicators (KPIs) and the related BREF reference  
139 values. The BREF for the WI sector (Neuwahl et al., 2019) was analyzed to identify the main  
140 environmental aspects described by BAT-AELs or sectorial reference values. 5 key aspects,  
141 representative of specific environmental impacts of the WI sector and consistently monitored in  
142 most plants were selected: emissions to air, energy consumption and production, waste production  
143 and reagent consumption. The indicators and metrics used in the BREF to define the BAT-AELs or  
144 reference values were chosen as KPIs to describe the environmental aspects emissions to air,  
145 reagents consumption, and waste production. To describe energy production and consumption, the

146 specific energy production (electricity, heat, and total energy per ton of waste) and consumption  
147 (electricity and total energy per ton of waste) were selected as KPIs. The gross electrical and energy  
148 efficiencies, used in the BREF, were not estimated as validated primary data was not available.  
149 Quantitative data regarding the identified KPIs was collected from the ESs of the considered 15 WI  
150 plants.

151 All values reported in the ESs and in the manuscript are referred to 1 normal cubic meter of flue  
152 gas ( $\text{Nm}^3$ ), which refers to a temperature of  $0^\circ\text{C}$ , a pressure of 101,3 kPa and a 11 %-v oxygen  
153 content, as requested by the current applicable legislation.

154

### 155 *2.3. Evaluation of the environmental performances*

156 The data related to each KPI for the period 2017 – 2019 was collected from the ESs and  
157 expressed as the yearly average of each plant's performance. The considered functional unit was 1  
158 ton of treated waste, consistently with the BREF reference values. An exception was the aspect  
159 emissions to air, whose performances were instead described by flue gas concentrations, following  
160 the relative BAT-AELs.

161

#### 162 *2.3.1. KPIs comparison with BREF reference values*

163 The information on the performances of each WI plant, excluding the 4 KPIs related to the  
164 specific energy production and consumption, was compared with the reference values reported in  
165 the BREF (Table 1). Regarding the emissions to air, the analysis was focused on the continuously  
166 monitored pollutants since intermittent sampling is characterized by biases which, depending on  
167 sampling frequency, can be significant (Wang et al., 2020); however, the concentrations in the flue-  
168 gas of all reported contaminants were considered.

169 The reagents consumption analysis was performed considering that for each class of reagents  
170 various options are available. To neutralize acid gases either sodium hydroxide (NaOH), hydrated  
171 lime ( $\text{Ca}(\text{OH})_2$ ), milk of lime ( $\text{Ca}(\text{OH})_2$  solution), or sodium bicarbonate ( $\text{NaHCO}_3$ ) can be used

172 (Neuwahl et al., 2019), thus the specific consumptions of those reagents were considered. Typical  
173 reagents for NO<sub>x</sub> reduction are ammonia, ammonia water (25% NH<sub>3</sub>) and urea solution but, since  
174 the BREF reports reference values only for specific ammonia water consumption, it was the only  
175 reagent considered for NO<sub>x</sub> abatement. The specific consumption of activated carbon was also  
176 considered, as it is generally used to adsorb PCDD/F, mercury, and other metals (Neuwahl et al.,  
177 2019).

178 Concerning the waste production, bottom and other ashes (i.e., fly and boiler ashes, FGC  
179 residues) were considered. The other ashes were considered in combination, even if they are not  
180 assigned to the same European Waste Catalogue codes consistently across the sample, because they  
181 are disposed together in most plants.

182

### 183 2.3.2. Trends assessment

184 To evaluate the trends of the environmental performances, the KPIs percentage change with  
185 respect to 2017 levels was calculated. Furthermore, to estimate the overall tendency of the  
186 emissions to air, the average of the normalized concentrations (AVG<sub>NC</sub>) was introduced as new  
187 advanced metric. In details, firstly the flue-gas concentrations of the continuously monitored  
188 contaminants were normalized with the lower BAT-AEL; then, for each pollutant, the average of  
189 the normalized concentrations was calculated across the 15 plants. Finally, to represent the overall  
190 average air emission performances of the sample, a second average of the results obtained for each  
191 contaminant was calculated as in eq. (1):

$$192 \quad AVG_{NC} = \frac{1}{n} \sum_{i=1}^n \frac{1}{m_i} \sum_{j=1}^m \frac{x_{i,j}}{L_{B,i}} \quad (-) \quad (1)$$

193 where  $x_{i,j}$  is the flue-gas concentration of each continuously monitored contaminant for each  
194 plant (mg/Nm<sup>3</sup> or ng I-TEQ/Nm<sup>3</sup>),  $L_{B,i}$  is the lower BAT-AEL of each contaminant (mg/Nm<sup>3</sup> or ng  
195 I-TEQ/Nm<sup>3</sup>),  $m_i$  is the number of sample plants reporting the emissions for each contaminant, and  $n$   
196 is the number of continuously monitored contaminants.

197

198 *2.3.3. Evaluation of the influence of the plants' characteristics on the KPIs*

199 To assess correlations between plant's characteristics and KPIs, several aspects of a WI plant  
200 were considered. Regarding FGC technologies, the adoption of electrostatic precipitators (ESP), bag  
201 filters (BF), dry processes (DP) or wet processes (WP) for the reduction of acid gases, selective  
202 non-catalytic reduction (SNCR) or selective catalytic reduction (SCR) of NO<sub>x</sub> were considered. FG  
203 recirculation and cogeneration of heat and electricity were used to describe the energy recovery  
204 process. The waste treatment capacity, the combustion lines' waste treatment capacity and the  
205 feedstock composition (percentage of MSW, special waste, refuse-derived fuel RDF) were selected  
206 to consider the size effect and the influence of the type of waste treated. The detailed composition  
207 of the treated waste was excluded from the investigated variables as validated data were available  
208 for only 4 plants. The impact of each of the above-mentioned characteristics on the average value of  
209 each KPI calculated over the 2017 – 2019 period was evaluated by conducting a correlation  
210 analysis. The observed correlations were then compared with the information contained in the  
211 BREF for WI and in the literature.

212 To estimate the influence of the plants' characteristics on the emissions to air as a whole, a  
213 second new advanced metric was created, the "combined concentration series" (CCS). The average  
214 of the normalized FG concentrations of the continuously monitored air pollutants was calculated for  
215 each plant through eq. (2):

$$216 \quad CCS = \frac{1}{n} \sum_{i=1}^n \frac{\bar{x}_i}{L_{B,i}} \quad (-) \quad (2)$$

217 where  $\bar{x}_i$  is the average value of each continuously monitored contaminant calculated over the  
218 2017 – 2019 period (mg/Nm<sup>3</sup> or ng I-TEQ/Nm<sup>3</sup>),  $L_{B,i}$  is the lower BAT-AEL of each contaminant  
219 (mg/Nm<sup>3</sup> or ng I-TEQ/Nm<sup>3</sup>), and  $n$  is the number of continuously monitored contaminants. This  
220 metric was aimed at representing the overall emissions to air performances of each WI plant of the  
221 sample. CCS is a weighted indicator based on the continuously monitored contaminants. The  
222 toxicity of the specific contaminants was not considered in the analysis due to the subjectivity that  
223 would be inherent to the determination of ponderation values. CSS was calculated by normalizing

224 (at 273 K, 101.3 kPa, dry gas with 11%-v O<sub>2</sub>) the emission data according to the current applicable  
225 law.

226

#### 227 2.4. Sensitivity analysis

228 To investigate the presence of any linear correlation between the environmental performances  
229 and the plants' characteristics, a correlation test was performed, considering significant the  
230 correlations having  $p < 0.05$ . Z-score standardization was applied when the impact of a plants'  
231 characteristic on a class of indicators was investigated. Z-score was adopted to reduce the effect of  
232 different orders of magnitude and variance among the various indicators of a class, using eq. (3):

$$233 \quad Z_i = \frac{\bar{x}_i - \mu_i}{\sigma_i} \quad (-) \quad (3)$$

234 where  $\bar{x}_i$  is the average value of each KPI calculated over the period 2017 – 2019,  $\mu_i$  is the  
235 average value calculated across the 15 WI plants, and  $\sigma_i$  is the standard deviation.

236

### 237 3. Results and discussion

#### 238 3.1. Emissions to air

239 The pollutants continuously monitored at all the 15 WI installations were dust, HCl, SO<sub>2</sub>, NO<sub>x</sub>,  
240 CO, TOC, NH<sub>3</sub>, and HF. The dust and HF emissions series have only 14 data points since one of the  
241 organizations did not disclose any information on the related emissions. HF emissions were  
242 included even though three companies only reported results derived from interval sampling. Figure  
243 2 presents the results of the normalization of the concentration of the pollutants in the flue-gas (FG)  
244 with the respective lower BAT-AEL (L<sub>B</sub>), showing a considerable variability among the values  
245 related to different WI plants.

246 All continuously measured pollutants displayed average values below the L<sub>B</sub>, except for NO<sub>x</sub>.  
247 However, NO<sub>x</sub> average concentration was  $71.3 \pm 41.1$  mg/Nm<sup>3</sup> in 2019 (48% of the upper BAT-  
248 AEL) and every plant displayed NO<sub>x</sub> concentrations always below the upper BAT-AEL. The  
249 following contaminants showed the best values compared to the reference values: dust ( $0.40 \pm 0.39$

250 mg/Nm<sup>3</sup> in 2019; 0.20 L<sub>B</sub>), SO<sub>2</sub> (1.72 ± 2.03 mg/Nm<sup>3</sup>; 0.34 L<sub>B</sub>), TVOC (0.58 ± 0.46 mg/Nm<sup>3</sup>; 0.19  
251 L<sub>B</sub>), and HF (0.098 ± 0.090 mg/Nm<sup>3</sup>; 0.10 L<sub>B</sub>). CO and NH<sub>3</sub> average concentrations in 2019 were  
252 6.49 ± 4.32 mg/Nm<sup>3</sup> (0.64 L<sub>B</sub>) and 1.08 ± 0.94 mg/Nm<sup>3</sup> (0.54 L<sub>B</sub>).

253 The average FG concentrations of the discontinuously monitored air pollutants were  
254 consistently below the upper BAT-AEL (U<sub>B</sub>) values. Cd + Tl and PCDD/F average concentrations,  
255 1.6 ± 1.8 µg/Nm<sup>3</sup> and 3.4 ± 3.9 pg/Nm<sup>3</sup> are also under the respective lower BAT-AEL (0.33 and  
256 0.34 L<sub>B</sub>). Average metals and Hg concentrations in 2019 were 0.030 ± 0.031 mg/Nm<sup>3</sup> (0.10 U<sub>B</sub>) and  
257 1.2 ± 1.9 µg/Nm<sup>3</sup> (0.24 U<sub>B</sub>).

258 The average of the normalized concentrations AVG<sub>NC</sub> (Figure 3) showed a slight decrease over  
259 time (-4.6% from 2017 to 2019), but the short time spanned by the data does not allow to validate  
260 the trend statistically. However, trends for single pollutants could be identified; HCl, TVOC, Dust,  
261 NH<sub>3</sub> and HF display a decreasing trend, with 2019 FG concentration average values lower than  
262 2017 levels by respectively 4.8%, 7.7%, 14.6%, 27.5%, and 27.9%. Of particular interest are the  
263 decreasing trends displayed by HCl and NH<sub>3</sub> concentrations, since in 2017 they figured among the  
264 worst-performing contaminants, averaging 0.98 and 0.77 times the L<sub>B</sub>. On the contrary, SO<sub>2</sub>  
265 average concentrations in the FG increased by 64.8% keeping, however, an average value lower  
266 than 0.35 L<sub>B</sub>. The other continuously monitored contaminants displayed results close to stationarity,  
267 while discontinuously monitored pollutants showed oscillating results.

268 Figure 4 highlights the influence of the FGC and energy recovery technologies adopted by the  
269 WI plants on the concentrations of air pollutants in the period 2017-2019. Considering acid gases  
270 emissions (i.e., HCl, SO<sub>2</sub>, and HF), the coupling of dry processes with other abatement techniques  
271 (i.e., wet process WP or double stage dry process DP) showed a performance improvement  
272 compared to single stage dry process (1.0 ± 0.8 mg/Nm<sup>3</sup> against 2.4 ± 1.8 mg/Nm<sup>3</sup> for HCl in  
273 2019). NO<sub>x</sub> emissions and SCR adoption were very strongly negatively correlated, r(13) = 0.91, p <  
274 0.001. This result confirmed that NO<sub>x</sub> emissions can be drastically lowered by using a SCR,  
275 described as the best option for NO<sub>x</sub> related impacts in the BREF and in the literature (Beylot et al.,

276 2017; Dong et al., 2020; Neuwahl et al., 2019). Little to no difference was observed in the sample  
277 between the 5 plants that implemented SCR as a standalone NO<sub>x</sub> treatment unit and the 7 plants that  
278 coupled it with SNCR. Dust emissions and ESP adoption were strongly negatively correlated,  $r(12)$   
279 = 0.56,  $p = 0.036$ , suggesting that a combination of electrostatic precipitators and bag filters is the  
280 most effective technology for reducing dust emissions to air. CO and TVOC emissions seemed to  
281 be negatively influenced by FG recirculation, which reduces oxygen concentration in the  
282 combustion chamber. The sum of the standardized series of CO and TOC emissions to air was  
283 moderately positively correlated to FG recirculation, although the result is not statistically  
284 significant due to the limited number of plants implementing FG recirculation,  $r(13) = 0.39$ ,  $p =$   
285 0.146.

286 Moderate negative correlations, although not statistically significant due to the often limited  
287 sample size, were found between the waste treatment capacity and: the air pollutants combined  
288 concentrations series (CSS), calculated as described in section 2.3.3,  $r(11) = 0.42$ ,  $p = 0.149$ ; NO<sub>x</sub>  
289 concentrations,  $r(13) = 0.49$ ,  $p = 0.062$ ; dust concentrations,  $r(12) = 0.41$ ,  $p = 0.144$ ; and TVOC  
290 concentrations,  $r(13) = 0.39$ ,  $p = 0.141$ . This finding suggested that plants with a higher waste  
291 treatment capacity could be more effective in reaching lower FG concentrations. To our knowledge,  
292 the correlation between plants' size and emissions to air has not been investigated yet. A significant,  
293 strong and negative correlation was instead observed between the air pollutants CCS and the  
294 adoption of an ESP,  $r(11) = 0.66$ ,  $p = 0.013$  (Figure 5A). The ESP is adopted by 5 WI plants and  
295 always installed as a pre-dedusting stage before other flue-gas treatments. A pre-dedusting stage  
296 removes part of the fly ashes, which reduces the particulate load on later FGC processes, improving  
297 their operation and reducing emissions to the flue-gas stream (Neuwahl et al., 2019).

298 Regarding the discontinuously monitored contaminants, the influence of the plants'  
299 characteristics on the air pollutants concentrations in the FG was difficult to assess due to  
300 incomplete and highly dispersed data. Even though the results are not statistically significant,  
301 PCDD/F concentrations were strongly negatively correlated with SCR adoption,  $r(11) = 0.51$ ,  $p =$

0.073, FG recirculation implementation,  $r(11) = 0.50$ ,  $p = 0.082$ , and plants' waste treatment capacity,  $r(11) = 0.50$ ,  $p = 0.085$ . Three out of the five plants implementing FG recirculation (Table 1) declared that the recirculation rate is variable and determined by automatic systems. However, the recirculation rate is usually between 10 and 20%-vol.

SCR is responsible for PCDD/F destruction by catalytic oxidation (Neuwahl et al., 2019) and its adoption has been already correlated to lower PCDD/F emissions (Beylot et al., 2017), while the other two parameters could be associated with a better-controlled combustion process that aids the destruction of PCDD/F and its precursors (Neuwahl et al., 2019). Cadmium and thallium concentrations were strongly negatively correlated with the percentage of MSW among the waste treated,  $r(8) = 0.65$ ,  $p = 0.042$ , but the result was highly influenced by the worse performances achieved by the only 2 plants that do not treat MSW and reported Cd + Tl emissions. A strong negative correlation was also found between metals concentrations and cogeneration,  $r(8) = 0.68$ ,  $p = 0.032$ , even though no explication of this result could be formulated. Again, no study was found in the literature analyzing the influence of feedstock composition or cogeneration on emissions.

### 3.2. Reagent consumption

About the reagents used to neutralize acid gases, the specific  $\text{Ca}(\text{OH})_2$  consumption, reported by 5 WI plants, was always within the BREF reference range (2 - 22 kg/t) and its average was  $12.2 \pm 4.5$  kg/t in 2019. NaOH specific consumption could be determined for 11 plants and its average was  $0.8 \pm 0.6$  kg/t in 2019, well below the  $L_B$  value of 7.5 kg/t.  $\text{NaHCO}_3$  specific consumption could be determined for 13 plants and its average was  $16.8 \pm 6.0$  kg/t, higher than the BREF reference range (6 - 12 kg/t). Interestingly, no correlation was found between the sum of the specific neutralizer consumption and the average concentration of acid gases, both standardized as described in section 2.4. Regarding the consumption of neutralizers as a whole, a strong negative correlation was found between the sum of the standardized specific consumption of neutralizers and ESP adoption,  $r(13) = 0.52$ ,  $p = 0.047$  (Figure 5B), outlining how the improvement in the performances of downstream

328 FGC systems due to a pre-dedusting stage, already noticed analyzing the aspect emissions to air,  
329 was also reflected in lower reagents consumption. As expected, NaOH specific consumption was  
330 strongly positively correlated with the implementation of wet processes for acid gas abatement,  $r(8)$   
331 = 0.65,  $p = 0.042$ , since it is mainly used for the operation of wet scrubbers. A very strong negative  
332 correlation was found between  $\text{NaHCO}_3$  specific consumption and the number of dry acid gas  
333 abatement stages (dry sorbent injection + bag filters),  $r(10) = 0.72$ ,  $p = 0.009$ . All the plants in our  
334 sample implement dry processes to remove acid gases, and this result suggested that designing the  
335 removal phase in two separate stages reduces the specific consumption of neutralizers. To our  
336 knowledge, no study that investigates the influence of the design of the acid gas abatement stage on  
337 reagents consumption exists.

338 Regarding  $\text{NO}_x$  reduction, the average specific ammonia water consumption, which could be  
339 determined for 10 plants, was  $2.9 \pm 1.7$  kg/t in 2019, slightly higher than the BREF reference range  
340 ( $2 - 2.5$  kg/t). No correlation between the specific ammonia water consumption and  $\text{NO}_x$  average  
341 FG concentration was observed. The average specific activated carbon consumption was calculated  
342 for all plants and was  $1.1 \pm 0.5$  kg/t in 2019, inside the BREF reference range ( $0.5 - 3$  kg/t). Again,  
343 no correlation was found between specific active carbon consumption and the FG concentration of  
344 its primary target contaminants (i.e., PCDD/F, mercury, and other metals). These findings suggested  
345 that efficient reagent consumption does not hinder the effectiveness of the flue-gas cleaning steps.  
346 A strong negative correlation was found instead between specific activated carbon consumption and  
347 SCR adoption,  $r(13) = 0.63$ ,  $p = 0.012$ . This result was expected as the use of activated carbon and  
348 the implementation of an SCR can be alternatives for the abatement of PCDD/F emissions.

349  $\text{Ca}(\text{OH})_2$ ,  $\text{NaHCO}_3$  and ammonia water average specific consumptions were constant over time,  
350 whereas NaOH and activated carbon average specific consumption appeared to be increasing  
351 (+18% and + 19% from 2017 to 2019, respectively).

352

353 *3.3. Waste production*

354 The average bottom ash specific production was  $16.7 \pm 5.9$  wt% in 2019 (characteristic values  
355 15 – 35 wt%) (Neuwahl et al., 2019), while the average specific production of other ashes was  $4.3 \pm$   
356  $0.6$  wt% in 2019 (characteristic values 3.5 -10 wt%). Both KPIs were stable over time and just  
357 above the lower characteristic values (Figure 6).

358 A strong positive correlation was found between the percentage of MSW in the feedstock and  
359 the specific bottom ash production,  $r(13) = 0.67$ ,  $p = 0.008$ . This result may be influenced by 2  
360 factors: the excellent performance (6.3% in 2019) of the plant treating only special waste (paper  
361 pulper), considering that the specific bottom ash production of plants not treating MSW is highly  
362 variable (Neuwahl et al., 2019); a lower specific bottom ash production of the plants treating refuse-  
363 derived fuels, which is reasonable since non-combustible materials are removed in RDF processing.

364 A strong negative correlation was also found between ESP adoption and the specific production  
365 of other ashes,  $r(13) = 0.57$ ,  $p = 0.027$  (Figure 5C). This result is linked with the finding that ESP  
366 adoption as a pre-dedusting stage improves the operations of downstream FGC systems allowing a  
367 lower specific reagent consumption, which is reflected in a lower FGC residues production.

368

#### 369 *3.4. Energy consumption*

370 The average specific electricity consumption was  $143 \pm 66$  kWh/t in 2019 and was stable across  
371 the 2017 – 2019 period. This value is higher than the average performance of European WI plants  
372 reported in the BREF, 107 kWh/t (Neuwahl et al., 2019).

373 No significant correlations between energy consumption and plants' or feedstock's  
374 characteristics were found, although moderate negative correlations could be observed between  
375 plants' waste treatment capacity and specific energy consumption,  $r(12) = 0.41$ ,  $p = 0.143$ , and  
376 specific electricity consumption,  $r(12) = 0.41$ ,  $p = 0.126$ . These findings suggested that size could  
377 positively influence the energy consumption efficiency of a WI plant. No study was found in the  
378 literature analyzing the influence of plants' size on energy consumption.

379

380 3.5. Energy production

381 The specific electricity and heat production were constant from 2017 to 2019, averaging  $0.72 \pm$   
382  $0.19$  MWh/t and  $0.56 \pm 0.26$  MWh/t in 2019. Consequently, the specific energy production was also  
383 constant,  $0.94 \pm 0.35$  MWh/t in 2019.

384 A very strong positive correlation between the specific energy production and the average waste  
385 treatment capacity of the plant's combustion lines was observed,  $r(13) = 0.78$ ,  $p < 0.001$  (Figure  
386 7A). Similarly, the specific electricity production was influenced by the size of the WI plant (Figure  
387 7B), and exhibited a strong positive correlation, although not statistically significant, with the  
388 combustion lines' waste treatment capacity,  $r(13) = 0.50$ ,  $p = 0.056$ . In 2019, WI plants with a waste  
389 treatment capacity per line exceeding 10 t/h produced an average of  $0.83 \pm 0.24$  MWh/t, while  
390 plants with lower capacity  $0.55 \pm 0.21$  MWh/t. These findings suggested that larger combustion  
391 lines are characterized by higher energy recovery efficiencies, in agreement with previous studies  
392 that investigated the correlation between the size of power plants and their overall efficiency (Bejan  
393 et al., 2011; Wu et al., 2019; Zhang et al., 2014). No significant correlations between energy  
394 production and plants' feedstock characteristics were found.

395 A strong positive correlation was also found between the specific energy produced and both the  
396 FG recirculation,  $r(12) = 0.49$ ,  $p = 0.061$ , and the implementation of cogeneration,  $r(13) = 0.47$ ,  $p =$   
397  $0.074$ . Although both correlations are not statistically significant, FG recirculation and cogeneration  
398 are described in the BREF as techniques associated with increased plant efficiency (Neuwahl et al.,  
399 2019). Specifically, FG recirculation is reported to reduce heat losses with the flue-gas, whereas  
400 cogeneration is defined as one of the available techniques to improve plant's energy efficiency.

401 On the contrary, the specific electricity production exhibited a strong negative correlation with  
402 cogeneration,  $r(13) = 0.61$ ,  $p = 0.016$  (Figure 7C), confirming the results of Beylot et al. (2017). In  
403 our study, the WI plants that produce only electricity consistently outperformed combined heat  
404 power plants, averaging  $0.81 \pm 0.12$  MWh/t against  $0.59 \pm 0.18$  MWh/t in 2019. This finding  
405 confirmed that, although implementing heat production improves the overall energy recovery

406 efficiency of a WI plant, it leads to worse electricity production efficiencies. In locations where the  
407 demand for heat is low, focusing only on electricity production may be the optimal solution  
408 (Neuwahl et al., 2019).

409

#### 410 **4. Conclusions**

411 This study provides a quantitative evaluation of the environmental performances of the 15 WI  
412 plants registered to EMAS in 2020 in Italy, with respect to the BAT-AELs and other sectorial  
413 reference values. Regarding the emissions to air, arguably the most significant environmental  
414 impact of WI plants, most pollutants displayed average FG concentrations below the lower BAT-  
415 AELs values. For waste production, specific bottom and other ashes production were respectively  
416  $47.7 \pm 16.9\%$  and  $42.5 \pm 6.4\%$  of the upper characteristic value in 2019. Specific reagents  
417 consumptions varied widely among reagents due to the possibility of choosing different options for  
418 each class of reagents, while specific electricity consumption was higher than European average  
419 ( $133.7 \pm 61.7\%$  in 2019). Concerning KPIs trends, the average of the normalized air pollutants  
420 concentrations was slightly decreasing ( $-4.6\%$  from 2017 to 2019), while the other aspects generally  
421 displayed stable performances over time. However, the short time spanned by the data did not allow  
422 to validate the trend statistically, nor to analyze longer term trends, therefore the inclusion of data  
423 related to longer periods in the ES is suggested to the WI companies. The analysis of correlations  
424 between WI plants' characteristics and the considered KPIs and advanced metrics produced results  
425 valuable as indications for WI companies. Most notably, it highlighted the positive influence of a  
426 pre-dedusting ESP stage on emissions to air, reagents consumption and waste production. The  
427 presented data also suggested that the coupling of dry processes with other abatement techniques  
428 can lower acid gases emissions and that plants with higher capacities can achieve higher energy  
429 efficiencies and slightly lower emission levels. Furthermore, the presented results confirmed the  
430 positive influences of SCR adoption on  $\text{NO}_x$  and PCDD/F emissions levels, and of cogeneration and  
431 FG recirculation on energy efficiencies. To further deepen this analysis, the addition of the treated

432 waste detailed composition in the ES is strongly recommended to WI companies. This analysis also  
433 exposed the lack of literature investigating the influence of WI plants' characteristics on their  
434 performances and the findings of this research revealed interesting correlations that future research  
435 could further investigate. This study demonstrated that EMAS can be an effective tool to evaluate  
436 the environmental performances of WI plants, and directly compare different installations using  
437 certified, validated and freely available data. Finally, this study also highlighted the excellent  
438 performances of the Italian WI plants registered to EMAS compared to the sectorial references.

439

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444 writing - original draft; Anna Scarrone: investigation, data curation, visualization; Maurizio  
445 Onofrio: review & editing; Silvia Fiore: methodology, supervision, writing-review & editing.

446

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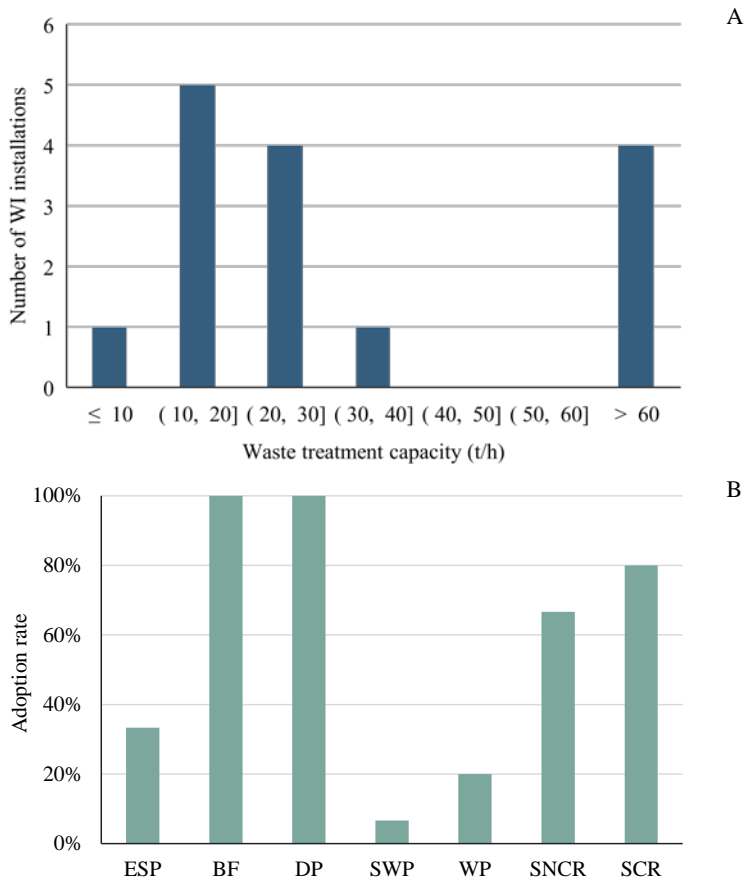
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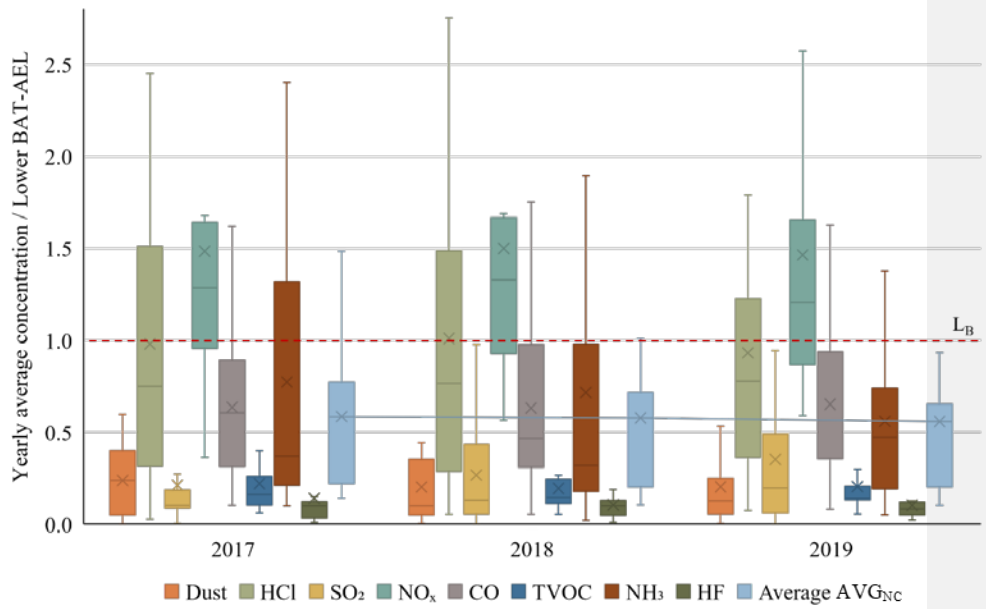
587 Figure 1. Overview of the main characteristics of the 15 WI installations: (A) waste treatment  
 588 capacity distribution; (B) flue-gas cleaning technology adoption rate. (ESP: electrostatic  
 589 precipitators; BF: bag filters; DP: dry processes; SWP: semi-wet processes; WP: wet processes;  
 590 SNCR: selective non-catalytic reduction; SCR: selective catalytic reduction).

591  
 592

593 Table 1. Selected key performance indicators (KPI) with corresponding BREF reference, where applicable. The reported BAT-AELs refer to  
 594 existing plants and, for Hg and PCDD/F emissions, to long term sampling periods.

key aspect	metric	parameter	BREF Reference type	value	measure unit
Emissions to air	FG concentration	Dust	BAT-AEL	< 2 - 5	mg/Nm <sup>3</sup>
		HCl	BAT-AEL	< 2 - 8	mg/Nm <sup>3</sup>
		SO <sub>2</sub>	BAT-AEL	5 - 40	mg/Nm <sup>3</sup>
		NO <sub>x</sub>	BAT-AEL	50 - 150	mg/Nm <sup>3</sup>
		CO	BAT-AEL	10 - 50	mg/Nm <sup>3</sup>
		TVOC	BAT-AEL	< 3 - 10	mg/Nm <sup>3</sup>
		NH <sub>3</sub>	BAT-AEL	2 - 10	mg/Nm <sup>3</sup>
		HF	BAT-AEL	< 1	mg/Nm <sup>3</sup>
		PCDD/F	BAT-AEL	< 0.01 - 0.08	ng I-TEQ/Nm <sup>3</sup>
		Metals	BAT-AEL	0.01 - 0.3	mg/Nm <sup>3</sup>
		Hg	BAT-AEL	1 - 10	mg/Nm <sup>3</sup>
		Cd + Tl	BAT-AEL	0.005 - 0.02	mg/Nm <sup>3</sup>
Reagents consumption	Specific consumption (per ton of waste)	NaOH	Reference range	7.5 - 33	kg/t
		Ca (OH) <sub>2</sub>	Reference range	2 - 22	kg/t
		NaHCO <sub>3</sub>	Reference range	6 - 12	kg/t
		Ammonia water	Reference range	2 - 2.5	kg/t
		Activated carbon	Reference range	0.5 - 3	kg/t
Waste production	Specific production (per ton of waste)	Bottom ashes	Characteristic values	15 - 35	t/t
		Other ashes	Characteristic values	3.5 - 10	t/t
Energy consumption	Specific consumption (per ton of waste)	Electricity	European Average	107	MWh/t
		Energy	-	-	MWh/t
Energy production	Specific production (per ton of waste)	Electricity	-	-	MWh/t
		Heat	-	-	MWh/t
		Energy	-	-	MWh/t

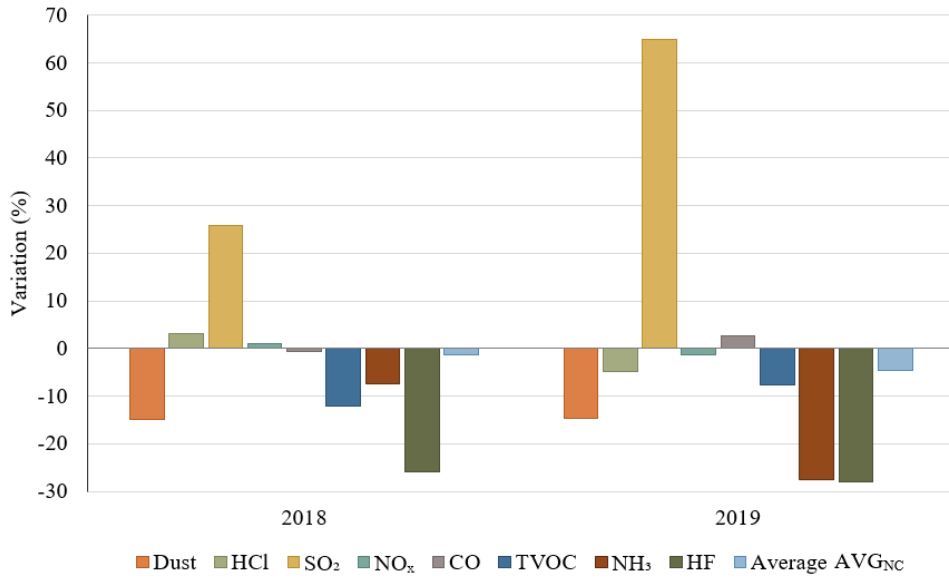
595



596

597 Figure 2. FG concentrations of the pollutants emitted to air normalized with the respective lower  
 598 BAT-AEL. Average of the reported pollutants (AVG<sub>NC</sub>) in light blue. Upper BAT-AEL not  
 599 displayed due to contaminant-specific ratios between higher and lower BAT-AEL (L<sub>B</sub>: lower BAT-  
 600 AEL; cross: average value; horizontal line: median value).

601



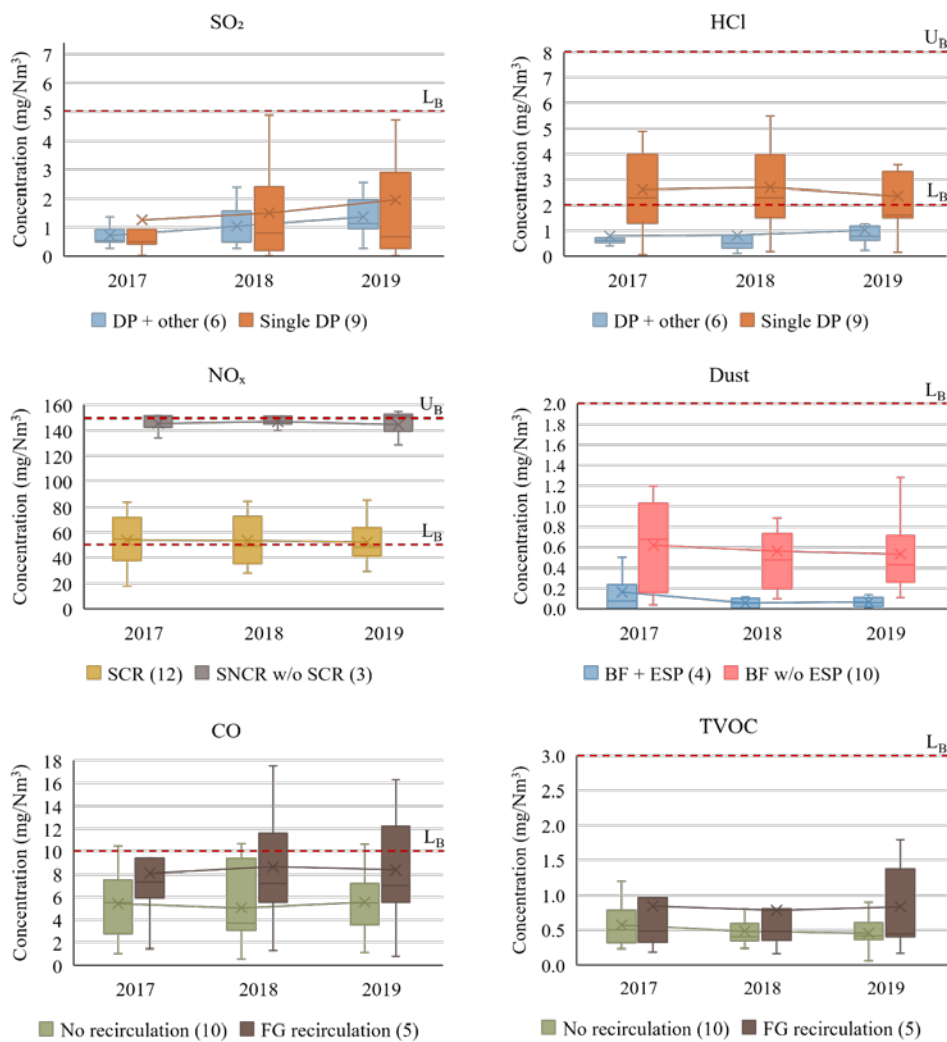
602

603

Figure 3. Variation of the concentration of pollutants emitted to air with respect to 2017 levels

604

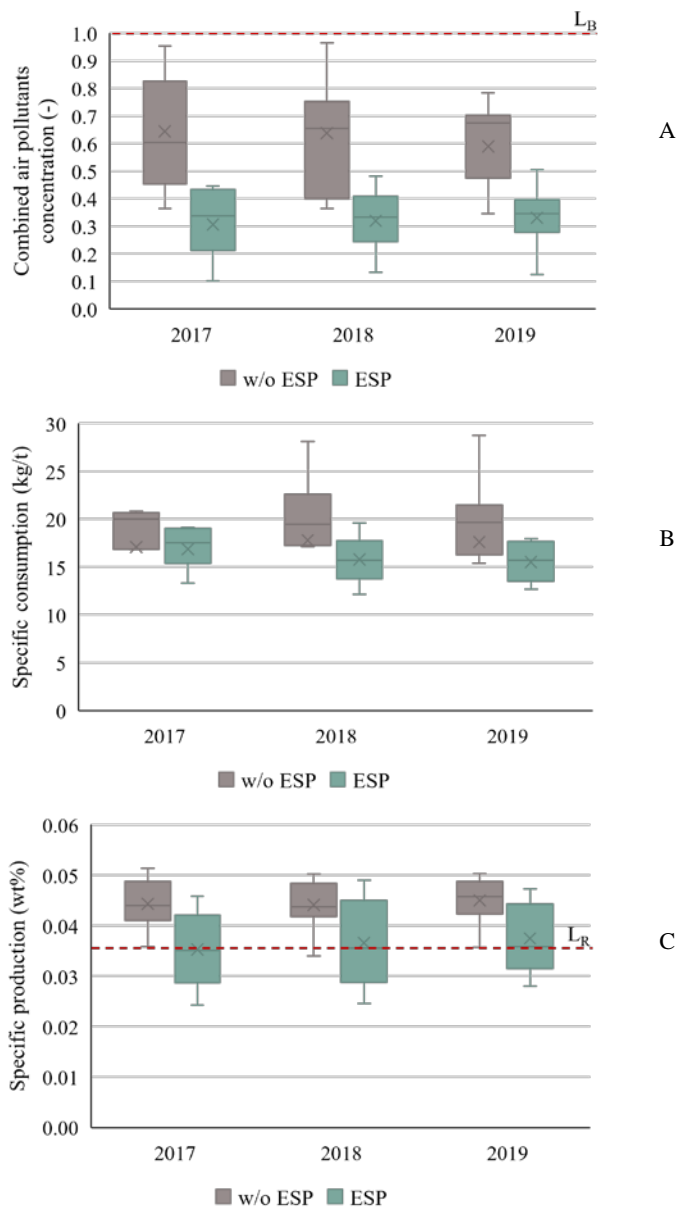
605



606

607 Figure 4. Influence of FGC technologies on the concentrations of air pollutants in the FG: SO<sub>2</sub>  
 608 (single DP vs DP + other (i.e., double stage DP or DP coupled with WP)); HCl (DP vs DP + other);  
 609 NO<sub>x</sub> (SCR (with or without SNCR) vs only SNCR); dust (BF + ESP vs only BF; CO (no FG  
 610 recirculation vs FG recirculation); TVOC (no FG recirculation vs FG recirculation). (DP: dry  
 611 process; WP: wet process; SNCR: selective non-catalytic reduction; SCR: selective catalytic

612 reduction; BF: bag filter; ESP: electrostatic precipitator; L<sub>B</sub>: lower BAT-AEL; U<sub>B</sub>: upper BAT-  
613 AEL; cross: average value; horizontal line: median value).  
614

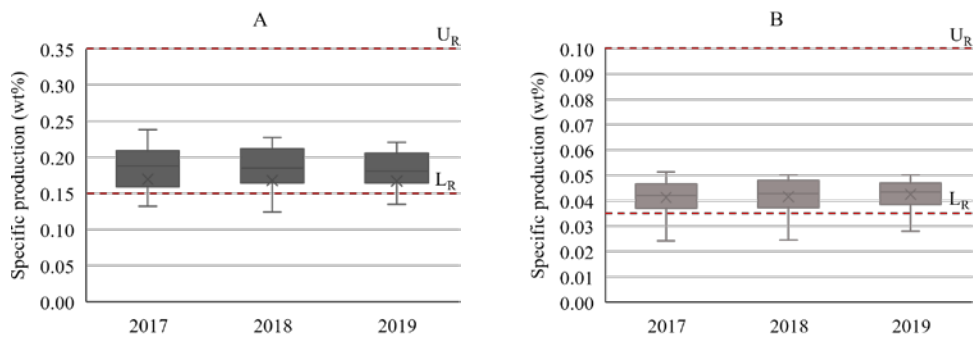


615 Figure 5. Effect of adopting an ESP pre-dedusting stage on: (A) concentration of pollutants in  
 616 the flue-gas; (B) specific consumption of neutralizing reagents; (C) specific production of other

617 ashes (i.e., fly ashes, FGC residues, boiler ashes) (ESP: electrostatic precipitator; L<sub>B</sub>: lower BAT-  
618 AEL; L<sub>R</sub>: lower reference value; cross: average value; horizontal line: median value).

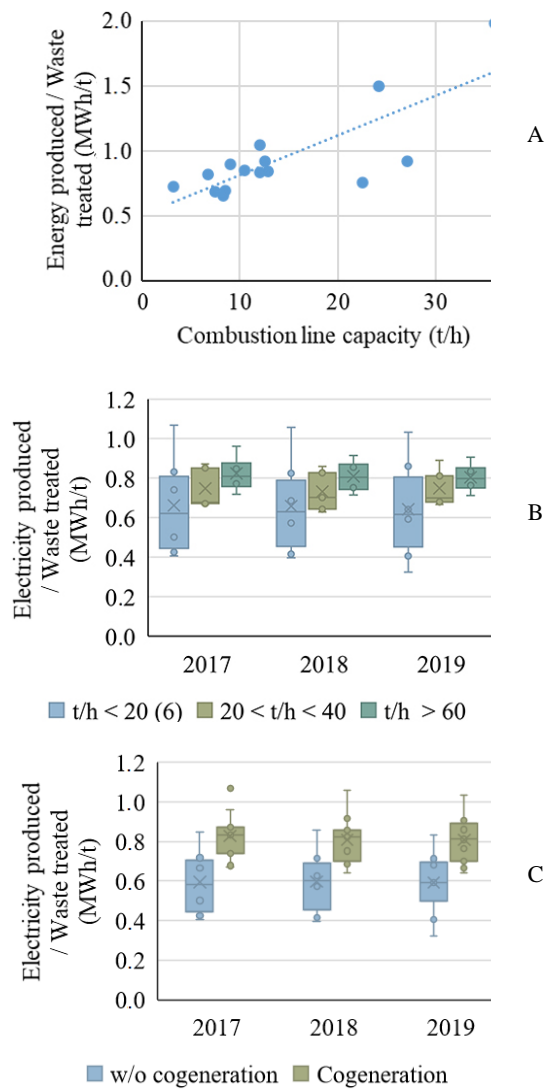
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620



621 Figure 6. Specific waste production: (A) bottom ashes; (B) other ashes (L<sub>R</sub>: lower reference  
622 value; U<sub>R</sub>: upper reference value; cross: average value; horizontal line: median value).

623



624 Figure 7. Influence of WI plants characteristics on the specific production of: (A) energy  
 625 (variable: combustion lines' waste treatment capacity); (B) electricity (variable: waste treatment  
 626 capacity); (C) electricity (electricity production vs electricity and heat production) (cross: average  
 627 value; horizontal line: median value).

628  
 629