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Research Paper

Techno-economic impact of lower emission standards for waste-to-energy acid gas emissions

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A B S T R A C T

Acid gas removal is one of the main drivers of operating costs in the flue gas cleaning lines of waste-to-energy (WtE) plants. In the light of updated technical and normative references, such as the revised Best Available Technology reference document for waste incineration in the EU, plants are required to comply with increasingly lower emission limit values (ELV). In the case of existing WtE plants, this requires selecting the appropriate option among three alternatives: intensification of current operations, installation of additional equipment (retrofitting) or substitution of equipment (revamping). The identification of the most cost-effective solution to meet the new ELVs is thus paramount. In the present study, a comparative techno-economic assessment is performed with reference to the relevant options available to WtE plants equipped with a dry acid gas treatment system, explicitly taking into account the influence of several technical and economic variables by a sensitivity analysis. The results show that retrofitting based on furnace sorbent injection is a competitive option especially in the presence of high acid gas loads in the flue gas. Despite the high investment cost, revamping based on conversion to wet scrubbing can also reduce the overall cost of treatment compared to intensification, but only if no constraints are present on flue gas temperature downstream of the acid gas treatment. If flue gas reheating is needed, e.g., for the compatibility with a downstream DeNOx treatment or to avoid plume visibility at stack, the associated costs make revamping not competitive with retrofitting or intensification. Sensitivity analysis confirms that these findings are robust even in presence of relevant variations in cost entries.

1. Introduction

Waste management systems rely on waste-to-energy (WtE) facilities for the safe treatment of waste fractions for which recycling is technically or economically unfeasible (Malinauskaite et al., 2017), with the twofold goal of phasing out disposal to landfill sites (Wang et al., 2020) and harnessing the residual value of waste as energy for district heating and electricity generation (Istrate et al., 2021; Magrini et al., 2022).

The main drawback of WtE operation is the release of a variety of air pollutants from waste combustion (Huang et al., 2021). Thus, flue gas must undergo proper treatments to avoid potentially adverse effects on local air quality and, ultimately, on population's health (Cole-Hunter et al., 2020). Under the joint drivers of increasingly ambitious international policies on integrated pollution control and concerns on adverse effects by local communities (Zheng et al., 2021), WtE plants in Europe, North America and East Asia have to comply with the lowest emission limit values (ELVs) across industrial sectors for several pollutants (Van Caneghem et al., 2019). In particular, in the European Union, the recent update of the Best Available Technology (BAT) reference document on waste incineration (BREF WI, European Commission, 2020) has established ambitious performance levels for emission control. Within four years of the release of the BREF WI, the environmental permit of each existing WtE plant in the EU will have to be reviewed by local authorities, considering the performance levels stated by the BREF WI as the basis for the determination of new ELVs.

Among the pollutants considered in BREF WI, acid gases, i.e., hydrogen halides (mainly HCl and HF) and sulfur oxides (SOx), are present in the flue gas generated in waste incineration as a consequence of the presence of halogens and sulfur in the waste feed (Zhang et al., 2019). The removal of acid gases is among the more expensive steps in flue gas treatment of WtE plants (Dal Pozzo et al., 2016; Quicker et al., 2014). It is typically carried out by neutralization reactions of the acid gases with solid sorbents or liquid solutions (Vehlow, 2015). Thus, the acid gas removal process is associated to costs pertaining both to reactant procurement and to the management of solid or liquid exhaust process streams (Margallo et al., 2015).

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Currently, dry methods for acid gas treatment, based on the injection of solid sorbents in the flue gas, are the technological alternative more frequently adopted in Europe. A recent survey found out that more than half of European WtE facilities adopt dry acid gas removal techniques (Dal Pozzo et al., 2018). Dry techniques exhibit several advantages compared to wet scrubbing, including lower investment costs, simpler layout and absence of a visible wet plume at stack (Presotto et al., 2005). On the other hand, acid gas removal with dry sorbents typically requires higher stoichiometric excess of reactant feed compared to wet scrubbing (Vehlow, 2015) and generates a hazardous waste stream of partially converted solid sorbents that needs to be landfilled at high costs (Maresca et al., 2022; Nedkvitne et al., 2021). Therefore, in case stricter ELVs will be adopted, the overall operational costs of dry acid gas removal processes may increase dramatically due to sorbent delivery and waste disposal. In this perspective, multiple options for a cost-effective transition to more ambitious emission targets, including retrofitting or revamping the flue gas cleaning lines, should be considered.

A limited attention was devoted to date to the operational consequences of new ELVs on flue gas treatment systems in the scientific and technical literature. Quicker et al. (2014) analyzed the economic advantages of converting semidry or wet acid gas abatement units to a dry bicarbonate system, while Dal Pozzo et al. (2017) investigated the trend of operating costs with decreasing ELVs for different types of dry acid gas removal systems. More recently, Ardolino et al. (2020) focused on a specific municipal solid waste incinerator, showing its capability to comply with new ELVs based on BREF WI without layout modifications.

The present paper aims at analyzing the economic implications of the adoption of lower ELV for acid gases for WtE facilities equipped with a dry acid gas treatment system. A comparative techno-economic assessment of the different technological alternatives that may be adopted to comply with stricter ELVs is performed. The variability in waste feed is considered in the analysis, assuming different acid gas load conditions for the treatment system, while the variability in cost entries is systematically explored by a sensitivity analysis.

2. Methods

2.1. Problem statement

As discussed above, the objective of this study is to perform a comparative techno-economic assessment of technological alternatives that can be considered to adapt WtE plant operation to the compliance with stricter ELVs of acid gases. As outlined in Fig. 1, three different technological alternatives were selected:

(i) ***Intensification:*** the plant continues operating with the existing dry treatment system, by increasing the feed rate of reactant fed to the system. This option might require the installation of new screw feeders and/or storage silos and it might be limited by operational constraints of the fabric filter (see section 3). Apart from that, no investment is required.

(ii) ***Retrofitting:*** the plant installs an additional acid gas treatment unit (e.g., furnace sorbent injection) upstream of the existing dry treatment system. This option requires a low investment cost and entails a minimal impact on the overall plant layout.

(iii) ***Revamping:*** the plant substitutes the existing dry treatment system with a wet scrubbing system, including related wastewater management. This option requires a high investment cost and entails a potentially relevant impact on the overall plant configuration, depending on the integration with other existing flue gas treatment equipment (see section 3).

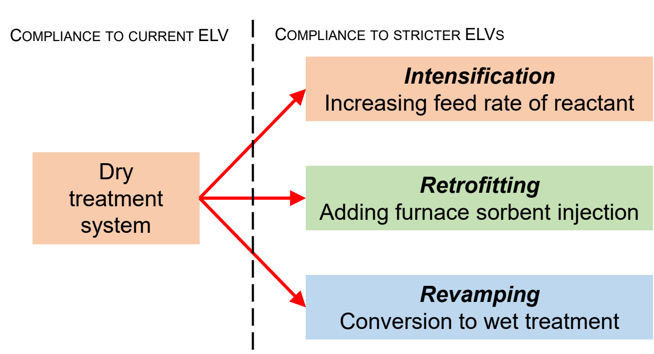


Fig. 1. Options considered for the compliance to stricter acid gas ELVs of WtE plants.

This section outlines the methodological approach adopted for the comparative analysis, while a case study, referring to specific process schemes for the three options, is presented in section 3.

2.2. Modelling of acid gas system performance

In order to assess and compare the three alternative strategies shown in Fig. 1 to comply with lower ELV for acid gases, the performance assessment of dry and wet-based acid gas treatment is required. Simplified process models correlating the acid gas removal efficiency to the mass flow rates of reactants and process residues/wastewater were used in the present study.

In the case of dry systems, based on the gas–solid reactions triggered by the in-duct injection of powdered sorbents, the widely adopted model proposed by Antonioni et al. (2014) was used to describe the non-linear relationship between the conversion of the acid gas A (X_A) and the feed rate of reactant:

$$X_A = \frac{SR^{n_A} - SR}{SR^{n_A} - 1} \quad (1)$$

where SR is the stoichiometric ratio, i.e., the ratio of reactant fed to the system to the theoretical neutralization demand for the inlet flue gas (Vehlow, 2015). The model offers a simplified approach to the description of acid gas removal, lumping the influence of all the variables affecting the reaction (sorbent properties and flue gas operating conditions) in a set of empirical parameters n_A, which can be tuned by calibration with plant-specific data. The calibration dataset is obtained either analyzing the past performance of a treatment unit (calibration through process data analysis) or performing test runs at controlled feed rates of reactants (calibration through dedicated test runs). Model calibration on operational data in several Italian WtE facilities demonstrated that the values of parameters n_A are robust and consistent from plant to plant (Dal Pozzo et al., 2018). Section S1 of the Supporting Information (SI) reports further details on the suggested values of the n_A parameters.

The model in Eq. (1) was used as follows. Considering the abatement of the generic acid gas A, the conversion X_A required to the acid gas treatment system, assuming constant flue gas flowrate $\dot{V}$ through the system, is given by:

$$X_A = 1 - \frac{C_{A,out}}{C_{A,in}} \quad (2)$$

where $C_{A,in}$ is the concentration of A in the raw gas coming from waste combustion and $C_{A,out}$ is the concentration of A leaving the system, dictated by the ELV.

Consider the generic neutralization reaction of a dry acid gas removal process:

$$aA(g) + bB(s) \rightarrow cC(s) + dD(g) \quad (3)$$

where B is the solid reactant, C a solid product, and D a gaseous product.

Thanks to Eq. (1), a set value of X_A from Eq. (2) is translated into the associated consumption of reactant. By definition of SR, the mass flow of reactant required to achieve the conversion X_A is:

$$\dot{m}_B = \dot{m}_{B,th} \bullet SR(X_A) \tag{4}$$

where $\dot{m}_{B,th}$ is the stoichiometric demand of reactant according to Eq. (3).

The mass of solid residues generated by the process can then be calculated as follows:

$$\dot{m}_{res} = \dot{m}_C + \dot{m}_{B,unreacted} = \left(\frac{c}{a}\dot{V} \bullet C_{A,in} \bullet X_A \bullet \frac{MM_C}{MM_A}\right) + \left(\dot{m}_B - \frac{b}{a}\dot{V} \bullet C_{A,in} \bullet X_A \bullet \frac{MM_B}{MM_A}\right) \tag{5}$$

where *MM* are the molar masses of the compounds.

For wet systems, the typical configuration of a dual scrubbing system, composed by a first acid scrubber for the physical absorption of HCl and a second neutral scrubber for the chemical absorption of SO_2 with a sodium hydroxide solution (Vehlow, 2015), was considered.

The acid scrubber was modelled as an equilibrium stage and was assumed to operate with a recirculated water stream. The amount of make-up water was quantified by assuming a set pH to maintain in the liquid, also considering the reintegration of water loss to evaporation. In the neutral scrubber, the consumption of the sodium hydroxide solution was calculated considering an SR of 1.2 (Vehlow, 2015). The liquid effluents from both stages were assumed to undergo physicochemical treatment before discharge. The main input for the treatment, calcium hydroxide for pH correction, was quantified according to stoichiometry. Section S1 of the Supporting Information (SI) describes in detail the process models adopted for the two stages.

2.3. Costing method

The following cost structure was considered for the operation of the acid gas treatment system:

$$TC = OC_{reactants} + OC_{proc\_waste} + OC_{energy} + EAC_{equipment} \tag{2}$$

where the total cost *TC* is the sum of the equivalent annual cost *EAC* of the equipment and of the operating costs, *OC*. Three main categories of operating costs were considered: i) $OC_{reactants}$, related to the consumption of reactants; ii) $OC_{proc\text{-}waste}$, deriving from the generation of process waste (solid residues and/or wastewater streams); and iii) OC_{energy}, due to the consumption of energy (electricity and heat). Only the differential costs between the alternatives were considered.

For the operating costs, it was necessary to retrieve representative data of the unit costs for the cost entries relevant to the specific process schemes analyzed in the case study of section 3. The investment cost was estimated by conventional literature methodologies. In the case-study, relevant cost estimate procedures from EPA (2002) and from Peters and Timmerhaus (2005) were used. The investment cost *IC* is then translated to an annualized cost of equipment (EAC), dividing it by the present value of an annuity factor (*AF*), as suggested by Brealey et al. (2016):

$$EAC = \frac{IC}{AF} = IC \bullet \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3}$$

where i is the discount rate and n the lifetime of the investment (in years). In the present study, a discount rate of 5% and a service life of 15 years were assumed.

2.4. Sensitivity analysis

Unit costs are subject to market fluctuations and such uncertainty clearly affects the results of the techno-economic analysis. Therefore, to test the robustness of the cost-effectiveness ranking between the alternatives considered, a sensitivity analysis by means of the Monte Carlo method is carried out. Each cost entry is considered as a stochastic variable with a uniform distribution in a defined range of variation. Monte Carlo runs were used to explore random combinations of the cost inputs within their ranges of variation and the results were collected in the form of discernibility charts (Clavreul et al., 2012), which reports the probability of one alternative of being more cost-effective than the others. The independence of results from the number of combinations in the analysis was tested positively.

3. Case study

A case-study was defined to exemplify the approach and to assess the relevance of the method in orienting the selection of the appropriate strategy to comply with lower acid gas ELVs. A waste combustion line equipped with a single-stage dry sorbent injection of sodium bicarbonate for acid gas removal from the flue gas was assumed as the base-case, representing the typical state-of-the-art configuration of dry acid gas treatment in the WtE context in Europe (Dal Pozzo et al., 2019; Muratori et al., 2020; Zach et al., 2021; Romero et al., 2020). Sodium bicarbonate is the most widely adopted sorbent for acid gas removal in Europe, being employed, e.g., in 33% and 59% of French and Italian WtE facilities, respectively (see surveys by Beylot et al., 2018; Dal Pozzo et al., 2016). A total of five alternative configurations were identified to comply with lower ELVs, elaborated according to the three different strategies shown in Fig. 1.

3.1. Reference process schemes

Fig. 2 illustrates the process schemes considered for the adaptation of the reference system to new emission standards. In the base-case (BC), a single-stage dry system using sodium bicarbonate, $NaHCO_3$ is present. Once injected in the flue gas in a contact tower, non-porous $NaHCO_3$ decomposes to porous Na_2CO_3 (Hartman et al., 2013), which in turn absorbs HCl and SO_2 via a gas–solid reaction that generates solid reaction products, namely NaCl and Na_2SO_4 (Löschau and Karpf, 2015). These solid residues are collected in a downstream fabric filter and disposed of as solid waste. This system can adapt its operation to a higher acid gas load and/or to a lower emission setpoint imposed at stack by increasing the feed rate of $NaHCO_3$. Thus, a first "intensification" option (A1) is identified. No changes in process layout are required to implement this alternative. Generally speaking, the scalability of the system to higher feed rates is limited by the sizing of the screw feeder and of the reactant silo, as well as by the operational constraints of the fabric filter (i.e., the maximum operating pressure drop through the filter bags; Saleem and Krammer, 2012). However, a properly sized system, as several existing plants in Italy and Europe, can usually withstand at least the doubling of the average feed rate of $NaHCO_3$ without the need of installing new equipment.

A "retrofitting" option, alternative A2 in Fig. 2, was also identified, consisting in the addition of an extra acid gas abatement stage before the existing one by furnace injection of appropriate sorbents (FSI), as dolomitic lime (Biganzoli et al., 2015; Dal Pozzo et al., 2020). This alternative only requires the installation of a reactant feeding system allowing the injection of a solid reactant directly in the combustion chamber of the plant. Dolomitic lime, i.e., a mixture of calcium and magnesium hydroxide derived from the calcination and hydration of dolomite rock was considered as the reactant feed for this alternative (Biganzoli et al., 2015). Since this alternative results in the implementation of a multi-stage system, the combination of a FSI of dolomitic lime and a subsequent bicarbonate-fed dry treatment unit can achieve the same overall acid gas removal efficiency with different repartitions of removal between the two stages. A single configuration of the DOL system was considered in the present study, setting the HCl conversion in the FSI stage at a value of 25%, which is close to the optimal operating points for different inlet acid gas loads identified by Dal Pozzo et al. (2020).

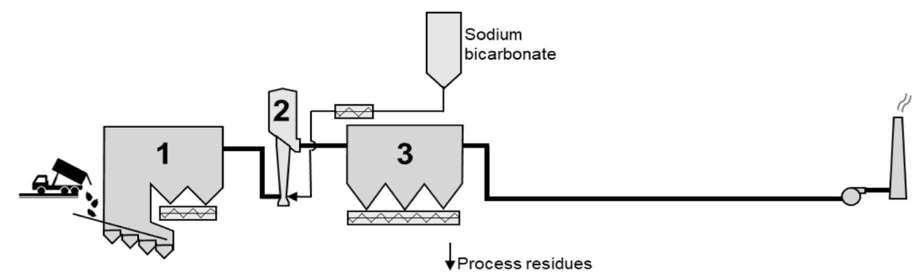
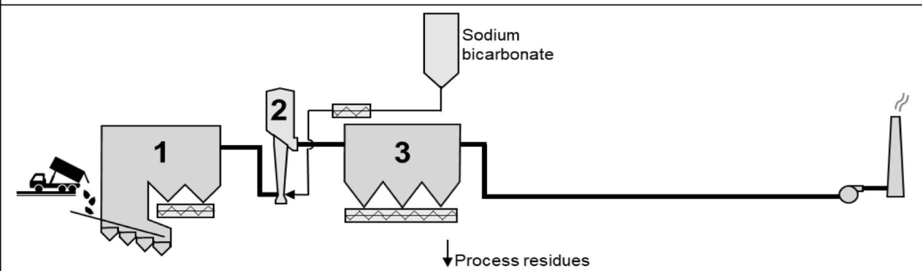
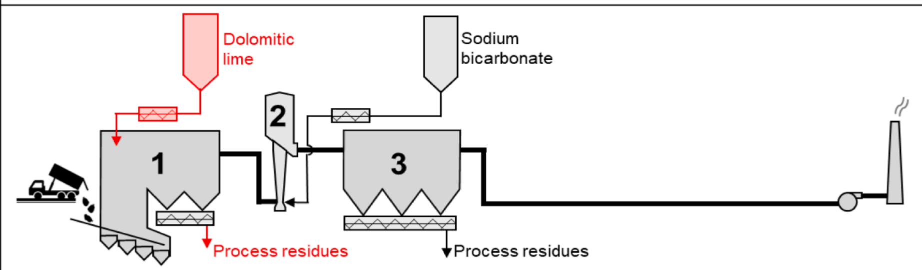
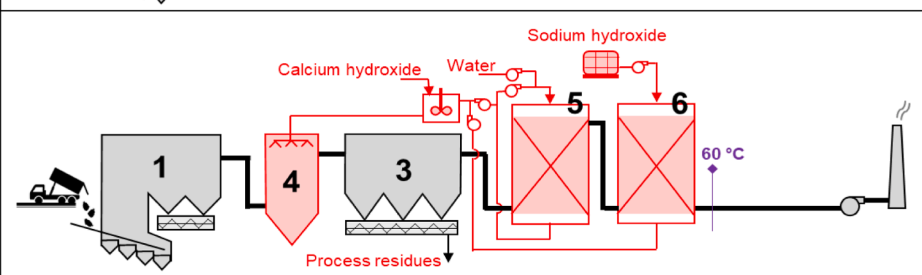
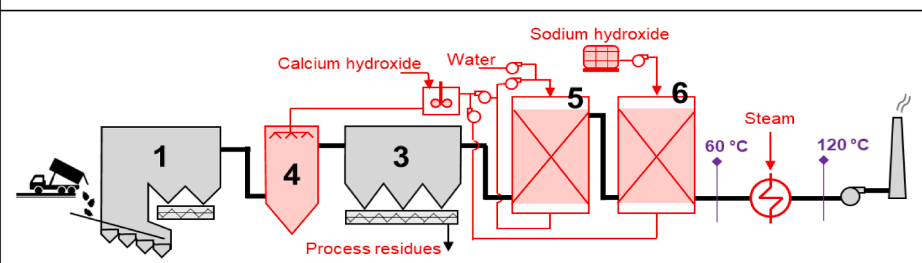
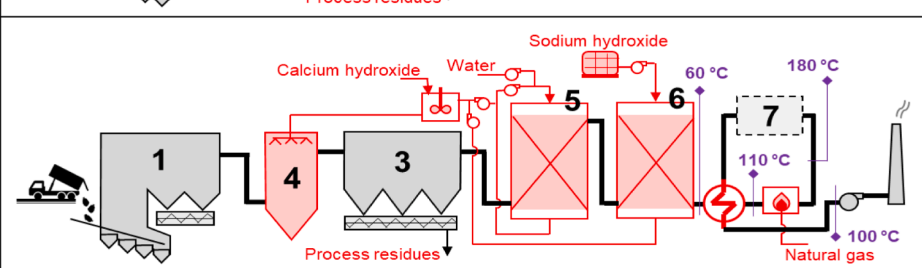
ID	Scheme	Description
BC		Base case: Injection of dry powdered sodium bicarbonate in the flue gas duct, followed by separation of reaction products via a fabric filter.
A1		Intensification of the base case: increase of the reactant feed rate without modification of the plant layout.
A2		Addition of a pre-treatment stage, based on the direct injection of dolomitic lime in furnace, upstream of the existing sodium bicarbonate-fed system.
A3		Substitution of the existing sodium bicarbonate-fed system with a wet treatment system (acid and neutral scrubbers). The wastewater stream generated by the wet system is evaporated in the hot flue gas upstream of the fabric filter after pH correction.
A4		As alternative A3, with the addition of a gas-steam heat exchanger for flue gas reheat up to 120 °C before release at stack.
A5		As alternative A3, with the addition of a gas-gas heat exchanger and a natural gas burner for flue gas reheat up to 180 °C for compatibility with a downstream SCR DeNOx equipment.

Fig. 2. Process schemes considered for the compliance to new ELVs (1: Furnace; 2: Contact tower; 3: Fabric filter; 4: Spray dryer; 5: Acid scrubber; 6: Neutral scrubber; 7: Selective catalytic reduction (De-NOx).

Further technological alternatives were considered in the case-study based on the implementation of "revamping" strategy identified in Fig. 1. In particular, the substitution of the dry bicarbonate-based treatment system with a wet scrubbing section was considered (alternatives A3, A4 and A5 in Fig. 2), due to the higher removal efficiency of such systems (Vehlow, 2015). A two-stage wet removal system was considered (Vehlow, 2015). The first stage (acid scrubber, item 5 in Fig. 2) is a spray tower where water is injected and most of the HCl load is removed from flue gas by physical absorption. SO_2 and residual HCl are then removed in the second stage (neutral stage, item 6 in Fig. 2), a packed tower where an aqueous solution of sodium hydroxide (NaOH) is injected to perform a chemical absorption. The effluents of the wet scrubbing operation are diluted hydrochloric acid and heavy metals in trace from the acid scrubber, and mainly sodium sulphates from the neutral scrubber (Löschau and Karpf, 2015). The current trend in wet scrubbing is to avoid the generation of a wastewater stream, as shown in recent studies on WtE wet flue gas cleaning (Dal Pozzo and Cozzani, 2021; Dong et al., 2020; Gall et al., 2022). Therefore, the effluents from the two scrubbers, after mixing and pH neutralization with lime addition, are evaporated by the injection into the hot flue gas stream in a dedicated spray dryer (item 4 in Fig. 2) upstream of the fabric filter (Gall et al., 2022), where the dry residues are collected.

A critical aspect to be considered for these alternatives is the integration of the wet scrubbing section with the existing flue gas cleaning line. The depurated flue gas leaves the wet scrubber approximatively at the equilibrium temperature in the scrubbing solution, which is in the range 60–65*C (Vehlow, 2015). Provided that the concentration of acid pollutants after scrubbing is low enough to avoid corrosion problems, the reheating of the flue gases might be required, depending on plant-specific considerations regarding the release of the flue gas at stack and/or the interaction with NOx abatement equipment. Different assumptions were thus introduced in the three revamping alternatives based on wet scrubbing considered.

In alternative A3 (see Fig. 2), the flue gas is released at stack at a temperature of 60 °C without reheating. This solution is suitable in WtE plants where the wet scrubbing is the last unit in the flue gas treatment system (i.e., NOx abatement is performed upstream, e.g., by selective non-catalytic reduction in the combustion chamber) and no local constraints on the flue gas temperature at stack are present.

In alternative A4 (see Fig. 2), the flue gas is released at stack after reheating up to 120 °C by low-temperature steam in a dedicated heat exchanger. Compared to alternative A3, this solution involves an additional heat exchanger after the neutral scrubber.

Alternative A5 in Fig. 2 considers the flue gas reheating to 180 °C, thus allowing its feed to a tail-end selective catalytic reduction (SCR) DeNOx equipment (item 7 in Fig. 2). The flue gas stream is reheated in a two-stage process: a first stage (up to 110 °C) is based on a heat recovery from the flue gas leaving the SCR in a gas/gas exchanger. The second step consists in direct heating by a natural gas burner.

3.2. Input conditions assumed in the case-study

The comparative analysis of the technological alternatives shown in Fig. 2 was performed considering a volumetric flow rate of flue gas to be treated equal to 50,000 Nm^3/h (roughly corresponding to a waste feed of 200 t/d), which is representative of a standalone small industrial or municipal solid waste incinerator or of one of the parallel lines of a larger WtE facility.

The current ELV for the base-case was assumed equal to 5 mg/Nm^3 for HCl and 10 mg/Nm^3 for SO_2, a typical set of operational setpoints (see, e.g., Romero et al., 2020) that allows a safe compliance to the current emission standards on HCl and SO_2 emission (10 and 50 mg/Nm^3, see Directive 2010/75/EU).

The lower ELV requiring the adoption of the alternatives identified in Fig. 2 was assumed equal to 0.5 mg/Nm^3 for HCl and 1.3 mg/Nm^3 for SO_2. The revised setpoint is an order of magnitude lower than the current setpoint. It was set considering a conservative safety margin following implementation of the new BREF WI, which recommends ELV targets for acid gas emissions respectively between 2 and 8 mg/Nm^3 for HCl and 5–20 mg/Nm^3 for SO_2 (European Commission, 2020).

Regarding the composition of the flue gas entering the treatment system, it is worth recalling that WtE plants burn waste fractions of highly variable composition over time (Dal Pozzo et al., 2020; De Greef et al., 2013). Thus, the actual process data of year-long operation of two Italian WtE facilities, a plant receiving only municipal solid waste and a plant receiving mixed municipal and industrial waste streams, were used to assess the typical variability of the concentration of acid gases in the inlet flue gas. These data were transformed into two pairs of log-normal probability distribution of HCl and SO_2 concentration in the raw flue gas, respectively representing a *low acid gas load*, typical of municipal solid waste combustion, and a *high acid gas load*, typical of mixed waste combustion. Details on the selection of the distributions of acid gas concentration in the untreated flue gas are reported in section S2 of the SI.

The two conditions of flue gas composition are summarized in Table 1, alongside the ELVs considered for the base-case and the revised scenario. These data allow defining the acid gas conversions demanded to the acid gas treatment system (see Eq. 2).

3.3. Data considered for the techno-economic analysis

Table 2 reports the unit costs assumed in the analysis and their variability considered in the sensitivity analysis. These values have to be interpreted as average values representative of the European context, obtained by the consultation of the technical literature cited in the table integrated with personal communications from plant operators. The reactant costs refer to the reactants used in the specific process schemes of Fig. 2. With respect to the energy costs related to the flue gas treatment, the following contributions were considered: i) the additional electrical consumption for the draught fan of the flue gas cleaning line due to the increased pressure drop generated by the additional equipment in the line; and ii) the thermal energy required to re-heat the flue gas after treatment in order to comply with the minimum temperature requirement at stack, to avoid plume formation and rain-out. Capital costs pertaining to the implementation of the five alternatives considered were estimated according to the procedures outlined in section S3 of the SI.

It is worth mentioning that the ranges of variation for the sensitivity analysis defined in Table 2 are particularly large compared to previous techno-economic analyses of WtE flue gas treatment systems (Dal Pozzo et al., 2021; Quicker et al., 2014). Such extended variability takes into account the recent price spikes associated with post-pandemic inflation and geopolitical tensions (Tollefson, 2022; Wang et al., 2022) that might persist in the next years.

Table 1
Input conditions for the comparative techno-economic analysis under two inlet flue gas compositions.

Case	Low acid gas load	High acid gas load
Inlet HCl concentration	Log-normal distribution [a] μ = 660 mg/Nm^3 σ = 270 mg/Nm^3	Log-normal distribution [a] μ = 850 mg/Nm^3 σ = 280 mg/Nm^3
Inlet SO_2 concentration	Log-normal distribution [b] μ = 25 mg/Nm^3 σ = 20 mg/Nm^3	Log-normal distribution [b] μ = 240 mg/Nm^3 σ = 35 mg/Nm^3
Current ELV (base-case)	HCl: 5 mg/Nm^3 SO_2: 10 mg/Nm^3	HCl: 5 mg/Nm^3 SO_2: 10 mg/Nm^3
Stricter ELV	HCl: 0.5 mg/Nm^3 SO_2: 1.3 mg/Nm^3	HCl: 0.5 mg/Nm^3 SO_2: 1.3 mg/Nm^3

[a] Derivation of the distributions outlined in section S2 of the SI (see Fig. S1c).
[b] Derivation of the distributions outlined in section S2 of the SI (see Fig. S1d).

Table 2
Reference values for the unit operating costs.

Unit operating cost	Unit	Value	Variability	Source
$NaHCO_3$ supply	€/t	255	240–350	Bazzoni (2014), Dal Pozzo et al. (2021), Giannella (2017), Poggio and Grieco (2010), Quicker et al. (2014), Tondelli (2016)
Dolomitic lime supply	€/t	145	100–180	Dal Pozzo et al. (2020), Pratola (2015)
NaOH(30%wt) supply	€/t	300	250–400	Dal Pozzo et al. (2018), Poggio and Grieco (2010)
$Ca(OH)_2$ supply	€/t	60	40–100	Dal Pozzo et al. (2016), Giannella (2017), Poggio and Grieco (2010), Tondelli (2016)
Water supply	€/m^3	0.6	0.5–0.7	Dal Pozzo et al. (2018), Pratola (2015)
Solid residues to disposal	€/t	195	170–250	Bazzoni (2014), Nethe (2008), Dal Pozzo et al. (2016), Giannella (2017), Tondelli (2016)
Electricity for draught fan	€/MWh	52.3	42–150	EUROSTAT (2021a)
Steam (LP) – flue-gas reheat	€/MWh	52.3	42–150	EUROSTAT (2021a)
Natural gas – flue-gas reheat	€/MWh	33.6	27–100	EUROSTAT (2021b)
Annualized equipment cost	**Unit**	**Value**	**Variability**	
Base Case	€/yr	–	–	Costing method outlined in section S3 of the SI
Option A1	€/yr	–	–	
Option A2	€/yr	1.1×10^4	$1.1–3.3 \times 10^4$	
Option A3	€/yr	1.3×10^5	$6.5 \times 10^4 – 2.0 \times 10^5$	
Option A4	€/yr	1.6×10^5	$8 \times 10^4 – 2.4 \times 10^5$	
Option A5	€/yr	1.8×10^5	$9 \times 10^4 – 2.7 \times 10^5$	

4. Results

Fig. 3 presents an overview of the results of the comparative techno-economic assessment carried out concerning the alternatives required to comply with stricter ELV considered in the case-study. The Figure reports the operating costs and the total costs deriving from the implementation of the alternatives identified in Fig. 2.

As shown in Fig. 3, both operational and total costs increase when the system is required to comply to the lower ELV considered in the case-study. Alternative A1 (intensification) results in a cost increase of about 20% with both the feed compositions considered (low and high acid gas loads respectively). Although the total mass of acid gases to be removed increases by less than 1% from the current to the lower ELV scenario, a significant excess feed of reactant is needed to meet the higher removal efficiency required.

The introduction of FSI of dolomitic lime as a pre-treatment stage (alternative A2) entails a significant reduction of the cost related to $NaHCO_3$ supply, which is only partially compensated by the procurement cost of the cheaper dolomitic lime. Conversely, the cost for the disposal of process residues increases. The net effect is a slight saving on operating costs for alternative A2 when compared to alternative A1, especially in the case of high acid gas concentration, due to the relatively high reactivity of the dolomitic sorbent towards SO_2.

The alternative of substituting the dry treatment line with a wet scrubbing system (alternatives A3, A4 and A5) generates widely different consequences in terms of operating costs, depending on the flue gas temperature at stack. If the flue gas leaving the wet scrubber can be sent directly to stack without reheating (alternative A3), the wet system exhibits significantly lower operating costs than the dry alternatives. Considering a low acid gas load, operating costs are 53% lower than in the base case dry system. The cost-effectiveness of the wet treatment is mainly linked to the advantage of removing HCl by physical absorption in water, without the addition of chemicals, hence to the marked reduction in the cost for reactants and waste- solid disposal. On the other hand, the addition of the two scrubbers on the flue gas cleaning line (see Fig. 2) increases the overall pressure drop, thus the energy consumption at the draught fan.

Alternative A3 still shows lower operating costs when high acid gas loads are considered. However, in this scenario the advantages over the dry options are significantly reduced, as a consequence of the higher SO_2 load, requiring a higher feed rate of NaOH in the neutral scrubber.

If the flue gas needs to be reheated, significant additional operating costs are present. The heat duty of the exchangers, calculated as an opportunity cost of avoided electricity generation, represents 38% of the total operating costs in alternative A4 (flue gases reheated at 120 °C), while in alternative A5 the flue gases reheating up to 180 °C, with the combined use of a gas-steam heat exchanger and a natural gas burner, represents 43% of the total operating cost. The high contribution of flue-gas reheating to the operating costs is in line with the findings of Dong et al. (2020), who identified the reheat duty as the main contributor of indirect environmental burdens for wet-based treatment systems.

When total costs are considered, no significant differences are present in the comparison of alternatives A1 and A2 to the base-case, since in these alternatives capital costs are negligible. However, when alternatives A3, A4 and A5 are considered, capital costs play a relevant role, due to the costs of the revamping of the flue-gas treatment required to implement wet scrubbing technologies. As shown in Fig. 3, total costs for alternative A3 are still lower, although comparable, to those of alternatives A1 and A2 in the low acid gas scenario. All other wet scrubbing options, including alternative A3 in the high acid gas scenario, result in total costs higher than those of alternatives A1 and A2.

Fig. 4 presents the variation in the total amount of solid wastes produced considering the different alternatives complying with the lower ELV. The production of solid wastes is an important environmental burden deriving from the implementation of lower ELVs (Dal Pozzo et al., 2023). As a matter of fact, it is likely that, for WtE plant managers, the decision on the best investment option to comply with a lower ELV would take into account not only financial considerations, but also an evaluation of the main environmental cross-media effects, such as process waste generation, which play a relevant role in the permitting process. In this regard, the wet option shows a clear advantage over the dry alternatives, as the higher efficiency of gas–liquid vs. gas–solid reactions limits the need for the stoichiometric excess of reactants and, thus, limits the amount of process residues. Even considering ELVs an order of magnitude lower than current regulations, as in the case study, Fig. 4 shows that the amount of solid process wastes generated by wet scrubbing (alternatives A3, A4 and A5) is about 50% to 30% lower than of that of the base case, respectively considering a high or a low acid gas load scenario. Conversely, alternative A1, consisting in the use of a higher stoichiometric excess of the reactant used in the base case, is associated with a relevant increase (18%) in the generation of process wastes. However, with reference to process wastes, the worst option is alternative A2 in both acid gas load scenarios, due to the inherently high production of solid process wastes in the reaction between dolomitic lime and acid pollutants (Dal Pozzo et al., 2020), also due to the low reactivity of the magnesium fraction of the sorbent towards acid gases (Zhou et al., 2021). Therefore, the cost-effectiveness of the pre-treatment with dolomitic lime has to be balanced against a non-negligible increase in the amount of process waste generated by the acid gas treatment operation.

The above discussion evidences that, when practicable, alternatives A2 (FSI) and A3 (wet scrubbing with no reheating of flue gases) are the

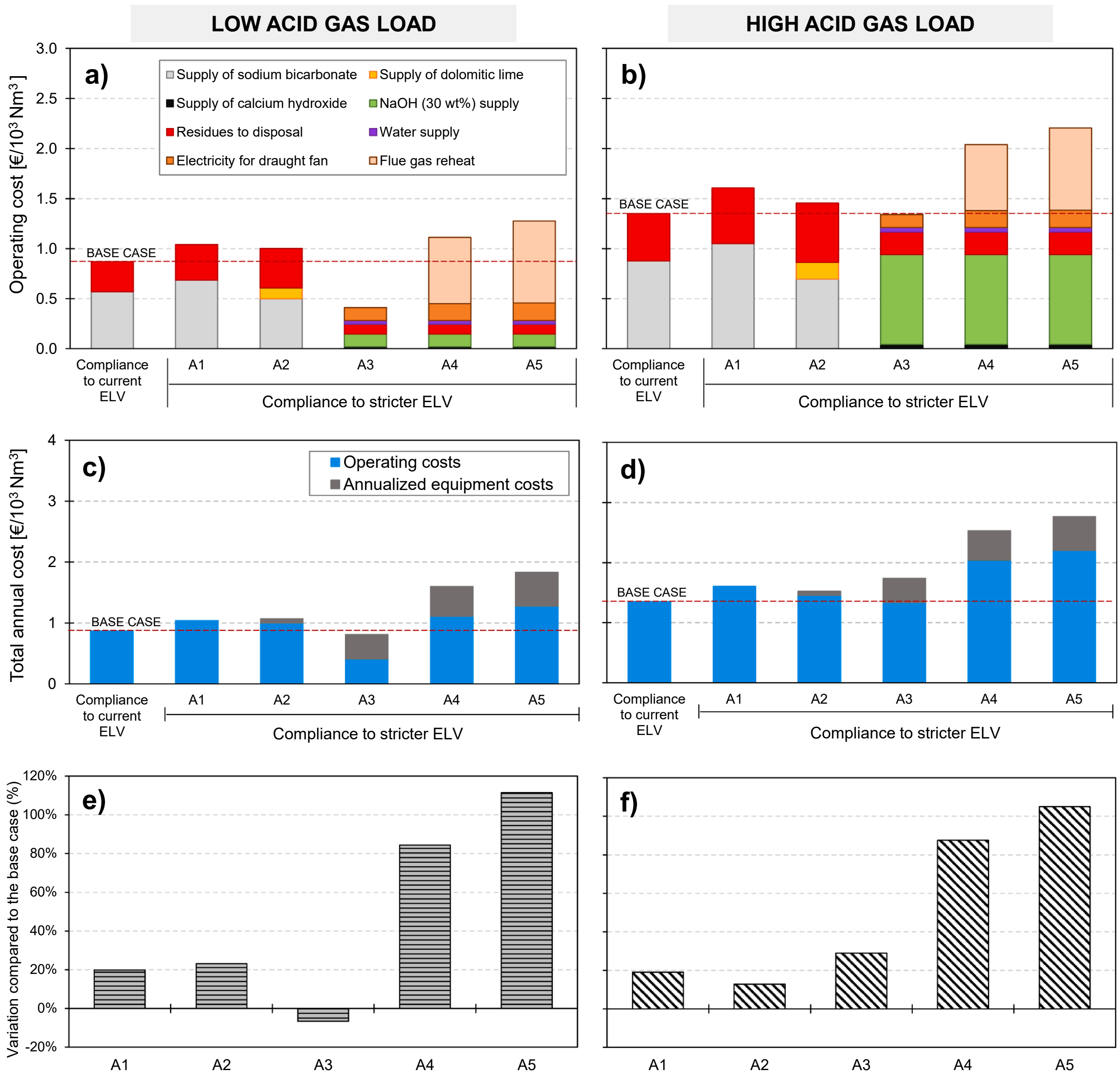


Fig. 3. Techno-economic performance of the acid gas treatment alternative systems considered in the case-study. Operating costs per Nm^3 of treated flue gas (a), total costs per Nm^3 of treated flue gas flue (c) and % variation of total costs with respect to base-case (e) considering low acid gas load. Operating costs per Nm^3 of treated flue gas (b), total costs per Nm^3 of treated flue gas flue (d) and % variation of total costs with respect to base-case (f) considering high acid gas load. Total annual cost including annualized equipment costs considering a flue gas with low (c) and high (d) acid gas load. Technological alternatives are described in Fig. 2. Acid gas loads considered are discussed in Section 3.2.

most cost-effective approaches for the adaptation of existing WtEs to stricter acid gases ELVs. However, the results also evidence the non-negligible influence of the inlet load of acid pollutants. In order to investigate more systematically this effect, Fig. 5 reports the annualized total cost of alternatives A2 and A3 with respect to HCl concentration in the inlet flue gas, considering two reference values of SO_2 concentration (100 and 200 mg/Nm^3). As shown in the figure, total annual costs increase almost linearly with HCl load in both cases. However, a higher slope is present in the case of alternative A2 (FSI), due to the less efficient gas–solid reaction process. Conversely, the increase of SO_2 content in the flue gas has a minor effect on alternative A2, due to the higher reactivity of the dolomitic sorbent towards this pollutant. As a consequence, the results in Fig. 5 suggest that alternative A2 should be preferred when relatively low HCl and high SO_2 contents are expected in the flue gas, while alternative A3 (wet scrubbing) should be preferred in case of high HCl and low SO_2 contents.

The robustness of the above findings with respect to the uncertainty in the cost data reported in Table 1 was assessed by a Monte Carlo sensitivity analysis, carried out as discussed in section 2.4. Fig. 6 shows the results in the form of discernibility charts (Heijungs and Kleijn, 2001), reporting the cumulative probability of differences in the total cost between the alternatives considered in Fig. 2 and alternative A1, which was considered as a benchmark. If the difference reported in the figure is negative, the alternative considered has a lower cost than alternative A1. As shown in Fig. 6a, in the low acid gas load scenario alternative A3 (wet scrubbing with no reheating of flue gas) always outperforms alternative A1 for all the range of variation in the input economic variables considered in the analysis. Differently, when a high acid gas load is considered (Fig. 6b), alternative A3 has only a 25% probability of being more cost-effective than alternative A1. On the

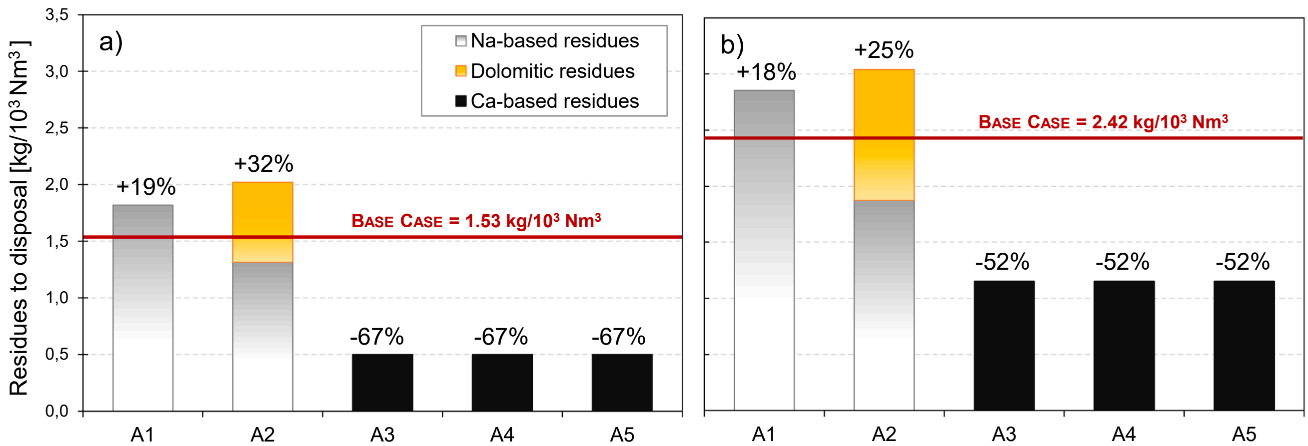


Fig. 4. Generation of process residues per Nm^3 of flue gas treated for a flue gas with a) low acid gas load, b) high acid gas load.

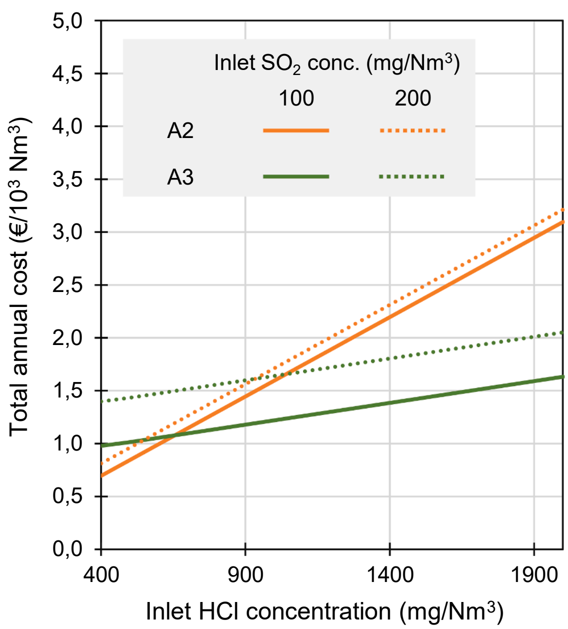


Fig. 5. Total annual cost for the two most competitive options (alternatives A2 and A3 in Fig. 2) variation with respect to the HCl concentration in the flue gas considering two different SO_2 concentrations.

contrary, alternative A2 always outperforms A1 in the high acid gas load scenario, while its performance with respect to A1 in the low acid gas load scenario depends on the variability of the input data (30% probability). The sensitivity analysis confirms the low economic attractiveness of alternatives A4 and A5 (wet scrubbing with flue gas reheating), as they are always outperformed by the other options in both acid gas load scenarios considered.

Therefore, the sensitivity analysis confirms that the two most effective alternatives to cope with lower acid gas ELVs are alternative A2 (FSI of dolomitic lime) and A3 (wet scrubbing with no flue gas reheating). Alternative A2 is more effective for high acid gas loads, while alternative A3 is preferable for low acid gas load, as confirmed by the direct comparison between the two alternatives shown in Fig. 6c.

5. Discussion

The approach introduced allows the comparison of three alternative strategies (namely: intensification, retrofitting and revamping) to cope with lower ELVs for acid gases in existing WtE facilities. Clearly enough, the three strategies imply a different balance among capital and operational costs: the latter are maximum when intensification is considered, and lower in the case of revamping, while the opposite applies to capital costs. The simplified process modelling introduced in section 2.2 allows quantifying the capital and operational costs for specific alternative design concepts based on the three alternative strategies with a low computational cost.

Although the results discussed in Section 4 are specific of the case-study considered, being highly dependent on the ELV value considered and on the flue gas flowrate assumed for the sizing of the alternative processes compared, still the approach and part of the results obtained have a more general value. A first general conclusion is that a valid comparison of alternatives requires to consider total costs, operating costs representing only part of the picture, in particular when alternatives requiring retrofitting or revamping of existing equipment are considered. A second general finding concerns the relevance of the required temperature at stack when considering alternative flue gas treatments. As discussed above, capital and operating costs of equipment required to re-heat flue gas after specific treatments may affect the economic viability of the process. Thus, the temperature of flue gases after a specific treatment may be used as a preliminary indicator in the screening of alternative technology options.

Finally, it should be remarked that the application of a sensitivity analysis is of fundamental importance in supporting decision-making in the flue gas treatment framework, as the techno-economic viability of a specific solution is heavily influenced by i) pollutant load in the flue gas to be treated, and ii) cost variability for reactant procurement and disposal of residues. For the former, historical process data of a sufficiently long period of normal plant operation (e.g., a year) can be used as input for the calculations, as described in section 3.2, to obtain tailored results that are representative for the specific plants. For the latter, systematic approaches such as the Monte Carlo analysis introduced in section 2.4 are particularly suited, as they allows exploring the effect of all possible variations in cost entries on the ranking between alternatives.

6. Conclusions

The present study addressed the selection of the best investment option for a WtE plant in the perspective application of lower ELVs for acid gases. A simple modelling approach based on consolidated operational process models for different acid gas treatment technologies and conventional costing methods were adopted to perform a comparative techno-economic assessment of the most relevant technological alternatives, also considering the effect of flue gas composition and uncertainty in the unit cost entries.

Even when taking into account reasonable ranges of variation for the

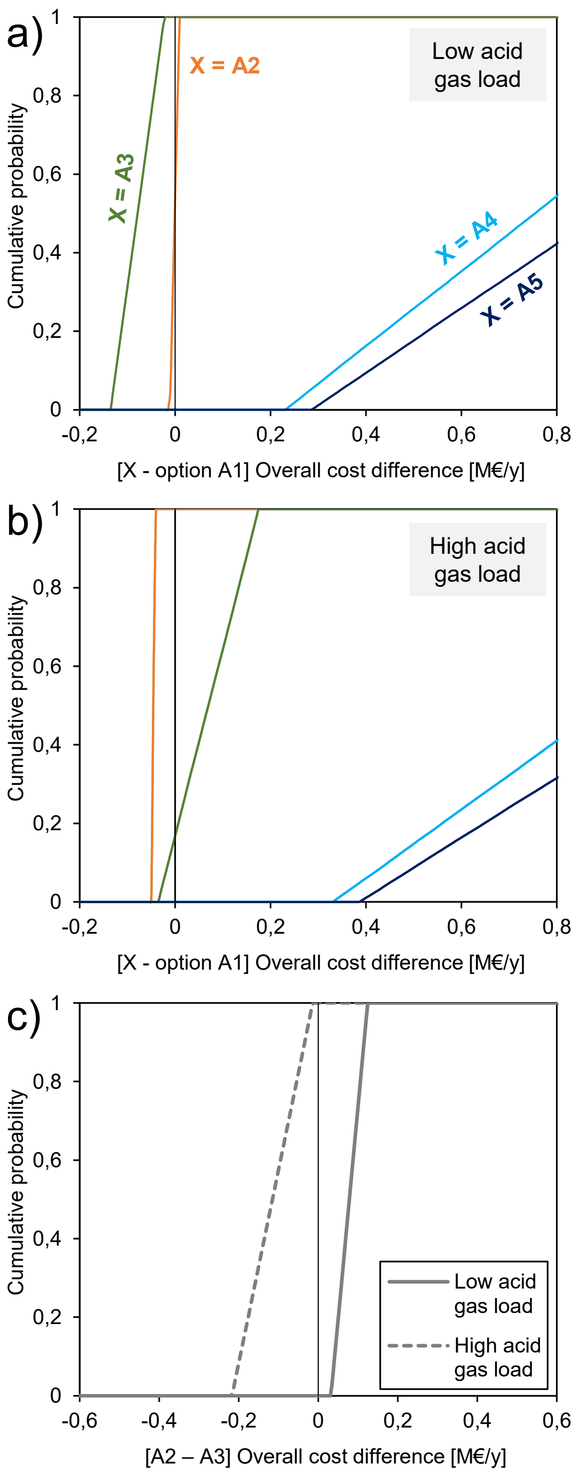


Fig. 6. Results of sensitivity analysis: cumulative probability of the difference in terms of total annual cost between the alternatives defined in Fig. 2: alternatives A2 to A5 compared to alternative A1 for a) low acid gas load, b) high acid gas load. c) Comparison of alternative A2 with respect to alternative A3 in both acid gas load scenarios.

economic variables by means of sensitivity analysis, the results show that the retrofitting with a FSI of dolomitic lime is the most cost-effective option in presence of flue gas streams with high SO_2 to HCl ratio, while the revamping to a wet-based treatment system is the best option in the presence of low SO_2 to HCl ratios when no constraints are present concerning the flue gas temperature at stack. When considering only the costs for reactants and process waste disposal, wet scrubbing is favored over dry options, due its higher stoichiometric efficiency. In particular, it is worth noticing that, for a flue gas stream with a low SO_2 content, the revamping to a wet system complying with a lower ELV may provide net financial savings compared to the dry system under the original ELV, repaying the investment cost within a service life of 15 years. However, if flue gas reheating is needed, the energy penalty makes the wet treatment less convenient compared to the dry options. Nevertheless, in general, requirements external to the acid gas removal process, as the integration with the $DeNO_x$ equipment in the flue gas treatment and constraints on the flue gas temperature at stack, which both influence the possible need of flue gas reheating, are key drivers affecting the selection of the most cost-effective option.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2023.05.013.

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