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ENVIRONMENTAL IMPACTS OF WASTE-TO-ENERGY PROCESSES IN MOUNTAINOUS AREAS: THE CASE OF AN ALPINE REGION

MARCO TUBINO, LUCA ADAMI & MARCO SCHIAVON
Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, Italy.

ABSTRACT

Despite the efforts made towards circularity approaches in waste management, waste-to-energy (WtE) processes still represent a key step because they allow recovering energy from waste, reducing the amount of waste residuals that require landfill disposal and reusing part of the residuals for specific purposes (e.g. in the construction sector). However, the direct (incineration) or indirect (gasification) combustion of waste generates relatively high emissions of several air pollutants, with different levels of toxicity. In specific situations, the presence of a waste combustion plant may be incompatible with the presence of population nearby, especially in areas where the dispersion of air pollutants is limited by the local morphology and/or by unfavourable meteorological conditions. In such contexts, an alternative option exists: the conversion of the syngas produced by waste gasification into commercial products or fuels. This alternative would guarantee a significant reduction of the impacts on the local air quality, and it is expected to increase the level of acceptability of the WtE sector by the population: the syngas would not be burned locally to generate energy, but it would be used to produce valuable products or replace traditional fuels with more sustainable alternatives. Thus, this paper aims at discussing the potential local impacts of traditional WtE plants and the opportunities related to alternative WtE approaches that may increase the level of sustainability of this sector. This paper will make a specific reference to mountainous regions, where the atmospheric dispersion of air pollutants may be negatively affected by the local morphology. To better illustrate the potential issues involved, some case studies located in an Alpine valley of Italy will be presented and discussed.

Keywords: air pollution, atmospheric dispersion, emissions, gasification, human exposure, incineration, syngas, waste management.

1 INTRODUCTION

The landfilling of waste may cause several environmental problems, ranging from land occupation and landscape spoiling to odour nuisance, emission of toxic air pollutants, potential groundwater contamination and greenhouse gas emissions [1–5]. Even if properly managed to limit environmental impacts, municipal solid waste (MSW) landfills are destined to reach saturation in the long term, especially in areas with low availability of space. By 2035, a new regulation (Directive 1999/31/EC, updated on 4 July 2018) [6] obliges the member states of the European Union (EU) to reduce the amount of MSW sent to landfills to a maximum of 10% the MSW produced.

Within this framework, the sector of waste-to-energy (WtE) plays a crucial role [7]. Thermo-chemical processes such as MSW incineration, gasification and pyrolysis allow for significant reductions in the mass of MSW that otherwise would be sent to MSW landfills: according to Arena *et al.* [8], a waste mass reduction of up to 88% can be achieved, but the residual amount of waste could be further reduced if options for bottom ash recycling are taken into account. If properly combined with an efficient selective collection system and with mechanical–biological treatments (MBTs) within integrated waste management schemes, WtE plants could be adopted during the transition towards resource circularity to limit the use of landfills and reduce the related environmental problems in developed and developing countries [9–14].

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At the end of the 20th century, the WtE sector has been the object of strong opposition by the public opinion [15]. The main reason for this was the low level of attention to combustion processes and the lack of appropriate gas cleaning technologies to guarantee emission levels compatible with the presence of population located near WtE facilities [16]. During the last decades, thanks to technological improvements in terms of energy efficiency and emission control and following the introduction on more stringent emission limits to preserve human health, the release of air contaminants from WtE facilities has generally decreased, especially for persistent organic pollutants [17]. The reduction in POP emissions has let other air pollutants emerge and become the major contributors to the overall health risk of the exposed population: this is the case of heavy metals, especially hexavalent chromium (Cr VI) [18].

For economic reasons, WtE facilities are designed and built to treat hundreds of tonnes of waste per day. Consequently, WtE plants release large exhaust gas flow rates, typically 10^4–10^5 Nm^3/h. Depending on the process and the input waste, the exhaust gas contains a wide variety of air pollutants, whose mass flow rates may pose a risk to the residents in geographical contexts where air mixing is limited. This is the case of many mountainous regions, where the local complex morphology promotes conditions of thermal inversion and strong atmospheric stability, especially at night and during winter [19]. These phenomena limit the dispersion of the air pollutants generated at the valley bottoms, where most of the population resides, and may increase the human exposure to toxic substances compared to other locations that are more favourable from the point of view of atmospheric dispersion and population density [20–22].

Thus, the development of sustainable waste management strategies in Alpine areas is contrasted by two co-existing issues: the need to reduce the use of landfilling and the criticalities of mountainous areas in terms of atmospheric dispersion of air pollutants. Those issues demand for stricter emission limits for WtE plants to reduce the impacts on the inhabitants living nearby. For this reason, with its Air Emission Ceilings Act, Austria decided to reduce the concentration limit value at the stack of MSW incinerators from the European limit value of 200 mg/Nm^3 to 70 mg/Nm^3 [23].

This paper is intended to shed light on the potential problems related to the presence of WtE plants in mountainous areas and suggest possible strategies to reduce the impacts of the WtE sector on human exposure. WtE technologies are here intended as thermo-chemical processes for residual MSW and/or hazardous waste valorisation, namely based on incineration and pyrolysis/gasification, thus excluding processes dedicated to the energy valorisation of waste biomass. This paper will consider the case study of an Alpine valley, where a discussion on how to reduce the use of MSW landfills has recently started. Direct and indirect MSW combustion processes will be compared in terms of emissions of air pollutants and an alternative approach will be presented to increase the level of sustainability of the WtE in context that may be critical from the point of view of human exposure.

2 CASE STUDIES

Adige valley is an Alpine valley located in northern Italy. This valley hosts the Adige river, the second longest river in Italy (410 km). The lowest part of the valley covers the most densely populated area of the Provinces of Bolzano and Trento and includes about 410,000 inhabitants [24]. In its lowest part, the valley is oriented north–south and is an important mean of communication between the Po plain (the most industrialised area in Italy), Austria and Germany. Due to its strategic importance, this valley is crossed by an important highway (A22), accounting for >50 million vehicle transits per year [25]. Like many other Alpine valleys, the Adige valley is affected by atmospheric conditions that penalise the dispersion of the air pollutants emitted by civil and industrial activities. As many Alpine valleys, the Adige valley suffers from atmospheric stability episodes that occur especially at night and are reinforced by down-slope winds, which oppose vertical mixing [26]. Such conditions favour the pollutant stagnation near the valley bottom. These issues, combined with the relatively high population density and with the transit of a high number of vehicles along the A22 highway, are expected to increase the exposure of residents to air pollutants with respect to less disadvantaged geographical contexts.

Besides the criticalities mentioned earlier, this valley also face the problem of waste management. It must be said that, rather than a problem, waste management in this area has achieved high levels of performance in the last decades, which is visible in terms of selective collection rate. The criticalities of the local waste management consist in the destination of residual MSW, especially in Trentino, the southern province. This area is characterised by high selective collection rates, partly favoured by the tariff in force, which penalise the production of residual MSW and bad selective collection behaviours by the users [27–29]. Most of the flow of the residual waste produced here has been historically sent to MSW landfills, which are now reaching saturation. A minor flow of residual waste is currently sent to the Province of Bolzano (Alto Adige), where an MSW incinerator has been in operation since 2013.

The incinerator of the Province of Bolzano (Plant A) has a nominal thermal power of 59 MW_t and is designed to treat 130,000 t/year of MSW and waste assimilated to MSW [30], according to the European Directive 2018/851/EU [31]. From this point of view, Alto Adige has solved the problem of the saturation of MSW landfills, which now receive only the residuals of MSW incineration.

In the same province, a proposal for a modern WtE plant (Plant B) was delivered to the local environmental agency in the past years. This plant was designed to treat 95,000 t/year of refuse-derived fuel, industrial waste and non-hazardous residuals from MBT facilities [32]. Contrarily to the previous plant, Plant B is based on a gasification process of the input waste and combustion of the syngas produced. The nominal thermal power delivered is estimated as 63 MW_t.

The third plant considered in this study (Plant C) was proposed in Trentino in 2009, in an attempt to solve the critical situation of the local MSW landfills. According to its feasibility study, the plant should have treated a total of 103,000 t/year, mainly composed of residual MSW and bulky waste, delivering a total thermal power of 60 MW_t [33]. Figure 1 presents the study area and the locations of the three WtE plants considered in this paper. Among the three plants, only Plant A exists at present.

In Europe, the Directive 75/2010/EU [34] sets concentration limit values for several air pollutants at the stack of WtE plants. The regulated pollutants are total suspended particles (TSP), nitrogen oxides (NOx), carbon monoxide (CO), sulphur dioxide (SO_2), ammonia (NH_3), total organic carbon (TOC), cadmium and thallium (Cd + Tl), mercury (Hg), other heavy metals, polycyclic aromatic hydrocarbons (PAHs), dioxin (PCDD/Fs) and polychlorinated biphenyls (PCBs). Among the heavy metals other than Cd, Tl and Hg, the regulation considers an only limit value for the sum of arsenic (As), cobalt (Co), chrome (Cr), copper (Cu), manganese (Mn), nickel (Ni), lead (Pb), antimony (Sb) and vanadium (V).

Table 1 reports the main characteristics of the main stack of the three WtE plants considered to represent the situation of the Alpine context. Table 2 presents the concentration limit values at the stack of the air pollutants regulated by the European legislation (Directive 75/2010/EU) [34], the respective concentration values of Plant A measured at the stack during the year 2021 and the concentration values guaranteed at the stack by Plants B and C at the time of the proposal [32, 33]. Concerning Plants B and C, no limit value was established

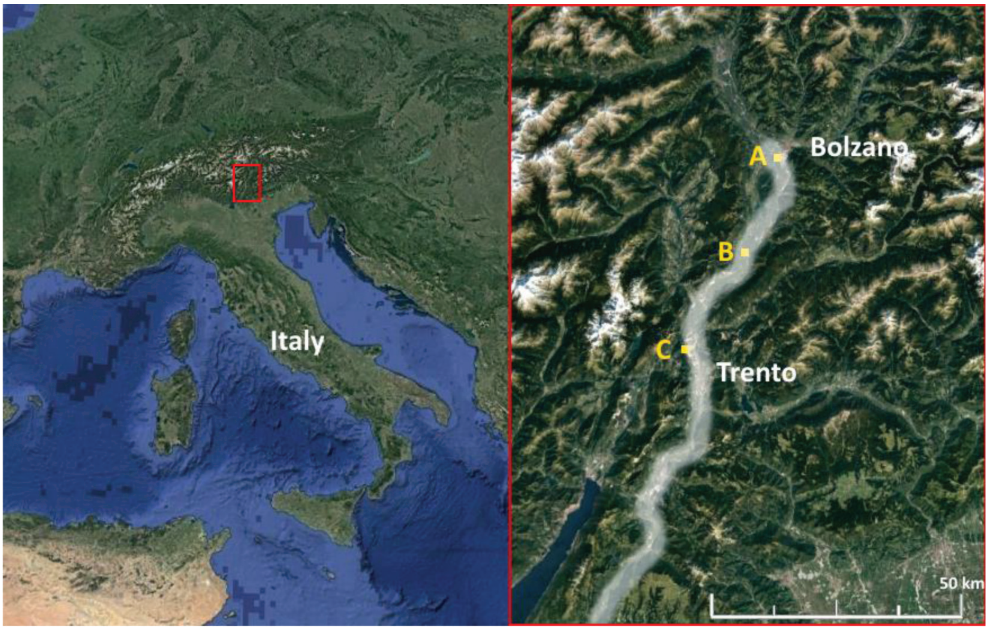

Figure 1: Detail of Adige valley in its lowest part (highlighted in white) and locations of the three WtE plants (yellow squares).

Table 1: Main characteristics of the WtE plants studied [33–36].

	WtE plant		
	A	B	C
Type of combustion	Direct combustion (air-cooled grate kiln)	Indirect combustion (High temperature gasifying and direct melting reactor)	Direct combustion (not specified)
Nominal thermal power [MW_t]	59	63	60
Capacity [t/year]	130,000	95,000	103,000
Frequency of operation [h/year]	8,016	7,500	7,800
Stack height [m]	60	45	100
Outlet velocity [m/s]	7.9	16.5	20
Exhaust gas flow rate [Nm^3/h]	110,000	107,000	109,000
Oxygen content	11%	6.4%	11%
Exhaust gas temperature [°C]	140	130	140

Table 2: Concentration limit values at the stack of waste combustion plants, measured stack concentration values at Plant A and maximum design stack concentration values at Plants B and C [30, 33, 37].

Substance	Unit	Limit values	Maximum guaranteed values		
			Plant A	Plant B	Plant C
TSP	mg/Nm^3	10	1.5	1.5	1.5
TOC	mg/Nm^3	10	10	10	10
HCl	mg/Nm^3	10	2	2	2
HF	mg/Nm^3	1	0.25	0.25	0.25
SO_2	mg/Nm^3	50	10	10	10
NOx	mg/Nm^3	200	40	40	40
CO	mg/Nm^3	50	50	50	50
NH_3	mg/Nm^3	30	10	10	10
Cd+Tl	mg/Nm^3	0.05	0.025	0.025	0.025
Hg	mg/Nm^3	0.05	0.025	0.025	0.025
Other metals	mg/Nm^3	0.5	0.25	0.25	0.25
PAHs	mg/Nm^3	0.01	0.01	0.01	0.0001*
PCDD/Fs	$ng_{I\text{-}TEQ}/Nm^3$	0.1	0.025	0.025	0.03
PCBs	$ng_{I\text{-}TEQ}/Nm^3$	0.1	-	0.1	-

*Guaranteed value only for benzo[a]pyrene.

at the time for PCBs, since the European Directive 75/2010/EU was adopted in Italy in 2014. Figure 1 shows the location of the existing WtE in the region (Plant A) and the locations proposed for Plants B and C in Trentino.

3 RESULTS AND DISCUSSION

The mass flow rates of the regulated air pollutants at the main stack of Plants A, B and C that result from Tables 1 and 2 are presented in Table 3. The mass flow rates are calculated by multiplying the maximum guaranteed stack concentration value of each pollutant by the airflow rate normalised to the oxygen content and by the frequency of operation of each plant. The normalised airflow rate (Q_n) is calculated as follows:

$$Q_n = Q\frac{0.21 - O_2}{0.21 - 0.11}, \qquad (1)$$

where O_2 is the oxygen content (expressed as volume fraction) in the exhaust gas.

Although the WtE plants considered in this paper are similar in size, the mass flow rate of the regulated pollutants in Plant B are higher. This is due to its higher normalised airflow rate, which is a consequence of the lower O_2 content of the exhaust gas released by an indirect combustion process.

The emissions calculated in Table 3 refer to the maximum stack concentration values guaranteed by each plant (Table 2). It is unlikely, however, that a plant emits air pollutants at their maximum design concentrations. In addition, it should be noticed that some differences may exist between direct and indirect combustion processes in terms of emissions. Considering

Table 3: Maximum mass flow rates of the air pollutants regulated in Europe and emitted by the WtE plants considered.

	Maximum mass flow rate [t/year]		
Substance	Plant A	Plant B	Plant C
TSP	1.32	1.76	1.28
TOC	8.82	11.72	8.50
HCl	1.76	2.34	1.70
HF	0.22	0.29	0.21
SO_2	8.82	11.72	8.50
NOx	35.27	46.87	34.01
CO	44.09	58.58	42.51
NH_3	8.82	11.72	8.50
Cd + Tl	2.20E-02	2.93E-02	2.13E-02
Hg	2.20E-02	2.93E-02	2.13E-02
Other metals	2.20E-01	2.93E-01	2.13E-01
PAHs	8.82E-03	1.17E-02	8.50E-05*
PCDD/Fs	2.20E-08	2.93E-08	2.55E-08
PCBs	-	1.17E-07	-

*Only for benzo[a]pyrene.

the same input waste composition, gasification is expected to generate lower outlet concentrations of NOx and organic chlorinated compounds (PCDD/Fs and PCBs) for the following reasons:

- First of all, the combustion of a gas is a more homogeneous and efficient process compared to direct waste combustion; this allows for lower excess air to be used and for lower NOx formation [38].
- Depending on the type of combustion, syngas can be cleaned prior to combustion to remove particles and inorganic contaminants that may be an issue for the combustion stage; this allows reducing the HCl content of syngas, and the content of particles and fly ashes, all these substances being precursors of organic chlorinated compounds, whose content would be consequently reduced [39].
- Even if syngas is not cleaned before combustion, its lower excess oxygen adopted for syngas combustion are believed to limit the formation of chlorinated compounds from HCl [39].

The comparison between the three WtE considered in this paper focussed on the primary stack emissions of these plants for simplicity reasons. However, it is worth mentioning that the role of secondary emissions in WtE plants is not negligible. A recent study on an Italian WtE plant highlighted that the secondary emissions of TOC and TSP represent about 10% and 29% of the total emissions from the plant [40]. Examples of secondary emissions are discharges of air from indoor environments or vents of the air pollution control units. The release of air pollutants from secondary emission sources may be less optimised than primary emission sources: proportionally to the airflow rate emitted, where a stack is present, the release height and the outlet velocity of the off-gas may be lower than the case of primary emissions. This situation may be even worse in the case of diffuse emissions, i.e. emissions not released from a stack. Diffuse emissions should be regarded carefully, as they may entail significant local impacts in the vicinity of a plant [41, 42].

In addition, weaker dispersion is expected to occur in mountainous regions compared to flatland or coastal locations, and this aspect should be considered when choosing the size of a WtE plant. For a preliminary comparison between WtE plants located in different areas, an approach based on the so-called dilution factor (DF) may be used. The DF is defined as the ratio between the maximum ambient air concentration of an airborne substance expected at ground level as emitted by a plant of interest and its respective mass flowrate exiting the plant [43]. DF values are specific for the emission source of interest and for the location of the source. DF values give an indication of the dispersion capability of a system composed of an emission source (with its main characteristics, like stack height, stack concentrations of air pollutants, exhaust gas velocity and temperature) and its geographical context (i.e. the meteorology and morphology of the area). The higher the value of the DF, the weaker the atmospheric dispersion of the reference pollutant. In the case of Plant A, for instance, the DF related to gaseous air pollutants, which can be calculated from the results of a recent study [36], is equal to 6.17E-07 s/m^3. This value can be compared with the DFs of two MSW incinerators located in coastal areas in Italy, which can be calculated from the results of an in-depth study on MSW incinerators carried out in 2013 [44]. The first term of comparison is the MSW incinerator of Ravenna, a town in northern Italy located on the Adriatic Sea. This MSW incinerator has the following characteristics: treatment capacity of 40.000 t/year of MSW, stack height of 60 m, exhaust gas temperature of 100–120 °C, exhaust gas flowrate of 45,000 Nm^3/h and exhaust gas velocity of 11 m/s [45]. According to the NOx mass flowrate measured at the stack and the results of the application of dispersion modelling [33], the resulting DF is 2.67E-07 s/m^3. The second term of comparison is the MSW incinerator of Rimini, a town located in the same region of Ravenna, on the Adriatic Sea. The characteristics of the plant are as follows: treatment capacity of 187.000 t/year of MSW, stack height of 80 m, exhaust gas temperature of 160–180 °C, exhaust gas flowrate of 160,000 Nm^3/h and exhaust gas velocity of 20 m/s [46]. The resulting DF is 2.69E-07 s/m^3 [33]. Both plants show a dispersion capability that is 2.3 higher than the dispersion capability of Plant A. This may translate into ambient air concentrations induced by the WtE plant that are more than double the concentrations that may occur in a more favourable geographical context, like coastal locations.

To reduce the environmental impacts of WtE plants in critical geographical contexts like mountainous regions, local authorities could adopt different strategies, such as:

- Considering more than one WtE plant, each with reduced size with respect to the single-plant scenario.
- Choosing a different way to valorise waste.

The first strategy relies on consolidated technologies that allow valorising waste and reducing landfill occupation. However, this strategy is critical for the following reasons:

- it requires identifying additional areas for the location of the small-size WtE plants, and this multiplies the risk of non-acceptance by the local communities;
- it implies higher investment costs that may not be sustainable;

- additional meteorological campaigns would be necessary for a complete characterisation of the new sites, and this may prolong the duration of the authorisation procedure;
- lower impacts would be guaranteed only if some characteristics of the main stack were not altered with respect to the single-plant scenario.

Concerning the last point, lower MSW input capacities would translate into (more than) proportionally lower impacts only if the DF of the small-size plants were (lower) equal to the single-plant scenario. To obtain this result, parameters like the exhaust gas velocity, stack concentrations, stack height and exhaust gas temperature should remain the same (or more favourable) with respect to the single-plant scenario.

The second strategy may consider waste gasification and syngas conversion instead of syngas combustion. Compared to MSW incineration, gasification opens to an additional way for waste valorisation. The syngas produced during the gasification step may be converted into valuable chemicals that can replace conventional fuels and ‘move’ the impacts of a WtE plant outside the area. However, this strategy has the following drawbacks:

- syngas conversion is less consolidated than traditional WtE processes;
- syngas conversion requires a certain level of stability in the input waste;
- waste streams may be generated in liquid and/or gaseous form during the conversion process.

4 CONCLUSIONS

Reducing the use of landfills would help limit land exploitation and the known environmental impacts of waste landfilling. Thanks to a new regulation, EU countries are asked to find urgent solutions to limit the use of MSW landfills by 2035. The most immediate strategies to achieve this goal are improving the selective collection of MSW and investing in WtE technologies to further reduce the flow of residual MSW sent to landfills. However, where selective collection has already reached high standards, WtE appears to be the only solution.

This paper highlighted the criticalities involved when conventional WtE schemes are implemented in geographical contexts that may exacerbate the local environmental impacts expected from WtE facilities due to adverse meteorological conditions. This paper proposed possible strategies to reduce the environmental impacts of WtE plants in geographical contexts characterised by complex morphology, like the Alpine region. Ways to reduce their local impacts include subdividing the energetic valorisation of waste into more WtE facilities with lower size and/or opting for gasification process with syngas conversion into chemicals, rather than syngas combustion. Local authorities could apply the first strategy if economic resources are available to cover the higher investment costs. This solution could be more viable if WtE plants were combined with an efficient selective collection system and with MBTs within integrated waste management schemes. The ex-situ valorisation of MSW through gasification and conversion of syngas into chemicals seems more promising and may require lower investment costs than the first solution. However, more research is needed to accurately identify all the possible releases of pollutants to air or to the process water used to clean up the syngas.

Although the present paper analysed the case of an Alpine valley, such strategies could be applied wherever the dispersion of the air pollutants emitted is limited, like other mountainous areas of flatlands characterised by frequent episodes of atmospheric stability.

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