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ENVIRONMENTAL AND MANAGERIAL ADVANTAGES OF TREATMENT PLANTS EXPLOITING BIOGAS FROM FOOD WASTE

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ABSTRACT

The sector of biomethane production is receiving growing consideration in Europe, as an evolution of the conventional exploitation of biogas in combined heat and power (CHP) generators. From the technical point of view, a common need is to have available tools and calculations suitable for analysing the environmental advantages of this approach. The present paper compares the emissions of air pollutants related to three options for biogas valorisation from waste anaerobic digestion (AD) plants equipped with a post-composting stage: (1) CHP generation and electric energy supply to an electricity distribution network, and biomethane production through (2) pressurised water scrubbing and (3) chemical absorption. In the last two cases, biomethane is considered useful for natural-gas buses for the public. The results demonstrate that option (1) produces a lower amount of global pollutants but a higher amount of local contaminants compared to options (2) and (3). Therefore, decision makers should consider what impacts are more important for the specific context in which an AD and post-composting plant will be located. In addition, this paper estimates the benefits in terms of energy balance and surface occupancy when a conventional composting plant is converted into an AD and post-composting process.

Keywords: Anaerobic Digestion, Biogas, Biomethane, Composting, Emissions.

1 INTRODUCTION

The amount of municipal solid waste (MSW) generated by the society has experienced a continuous growth in the last decades even in highly industrialised countries like the European ones. This trend is strictly related to the increasing consumption of a large variety of goods [1], which leads to increasing waste flows that have to be managed for adequate disposal. In order to face this emerging environmental problem, in 1999 the European Union issued the so-called ‘Landfill Directive’ (1999/31/EC), which obliges the Member States to gradually reduce the flow of biodegradable waste to municipal landfills [2]. It is known that a lower content of biodegradable waste allows for lower releases of greenhouse gases (GHGs) by a landfill. This is the case, for instance, of methane (CH_4) and nitrous oxide (N_2O). The mean emission factors of CH_4, N_2O and carbon dioxide (CO_2) were recently estimated as 239, 3 and 2,242 mg/m^2/h, respectively, from an uncovered landfill in China [3]. Such values should be corrected by considering the global warming potentials of CH_4 and N_2O, which are 32 and 282, respectively [4]. In this sense, there is an emerging need to control fugitive GHGs emissions from the waste sector.

More recently, the so-called ‘Waste Directive’ (2008/98/EC) reinforced the clear intentions of the European Union towards a sustainable management of MSW by giving priority (in order of importance) to waste prevention, re-use, recycling, energy recovery and landfilling [5]. In order to fulfil those needs, mechanical–biological treatments (MBTs) of MSW have been largely implemented in Europe and in other industrialised countries in the last decades [6]. The increasing implementation of MBTs has been supported by the growing selection rates of the selective collection of MSW in industrialised countries [7].

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MBTs allow treating different streams of input waste, such as residual MSW, the organic fraction of MSW (OFMSW), green waste and sewage sludge from wastewater treatment plants. The main processes are usually divided into aerobic and anaerobic treatments. Among aerobic treatments, biodrying and biostabilisation operate on the residual fraction of MSW, even though biostabilisation performs the biological treatment only on the humid fraction of residual MSW. Composting works on the OFMSW (and/or sewage sludge), mixed with a fraction of green waste (usually 20–30% in mass in the mixed waste) to ensure a sufficient level of porosity to the waste samples, which is crucial for a uniform transfer of oxygen in the waste heap [8]–[9]. The only anaerobic MBT is anaerobic digestion (AD), which is carried out on OFMSW and/or sewage sludge.

The non-metallic residuals of the biological step of biodrying becomes refuse-derived fuel (RDF), which can be conveniently exploited for energy purposes in co-generation plants. RDF is also one of the final products of biostabilisation and is generated by the oversieve of the primary sifting of biostabilisation treatments, deprived of metals. The product of the biological step of biostabilisation is the stabilised organic fraction, which may be used as a coverage for municipal landfills. Both composting and AD (with a lower degree of stability) generate compost, which may be re-used for agricultural purposes if purity and stability requirements are fulfilled. A further maturation step of the digestate from AD would allow achieving the level of stability of the compost produced by direct composting.

Typically, a composting plant is composed of a waste collection chamber, an aerobic stabilisation stage, a final maturation stage and a storage area for the compost produced. Usually, the discharge of OFMSW and all the operations carried out until the end of the aerobic stabilisation phase occur in a closed indoor environment, where the air is continuously blown and sent to the air treatment line, for the removal of pollutants and odorants. Conversely, the maturation stage and the compost warehousing usually occur in an open hangar. In such conditions, emissions of particulate matter (PM) and odorants from the open compartments into the atmosphere are unavoidable and may cause odour nuisance to residents.

Compared to direct composting, an AD and post-composting process not only abates the potential uncontrolled emissions of GHGs by stabilising the biodegradable input waste, but also allows enhancing the controlled formation of a gas with high energy potential like CH_4. Conventionally, biogas can be locally exploited by a CHP generator. The energy from the biogas combustion could be used to cover the thermal energy requirements for AD and produce electrical energy for distribution within the electricity network and for waste aeration. Therefore, AD followed by composting of the digestate allows for both energy recovery and material recycling in the same facility [10]. Such an approach goes in the direction of the model of circular economy, promoted by the United Nations 2030 Agenda for Sustainable Development [11].

When an AD stage followed by post-composting is preferred to direct composting, in addition to obvious advantages in terms of biogas production, potential benefits are expected also from the point of view of emissions into the atmosphere, since the phase that most contributes to the release of odorants is now managed in a closed environment, i.e. the digester. Its solid output (the digestate) is a semi-stabilised material, whose respirometric index is relatively low, typically close to (or even below) 1,000 mg_{O2} kg^{-1} h^{-1} of volatile solids (VS) [12]. Compared to direct composting, the aerobic biodegradation of an almost stable waste results in a reduced release of odorants in the maturation phase. In addition, the process requires a lower amount of air for the aerobic phase and, consequently, the odorant load in the air treatment line is lower. However, other emissions are produced, due to the local combustion of biogas or to CH_4 leaks.

AD also allows for an emerging alternative for biogas exploitation: biogas can be upgraded to biomethane, which could be suitable to replace conventional fossil fuels in the automotive sector. Biomethane is a novelty in many European countries. In some cases, the novelty is absolute, while in other cases the regulation of the sector is already defined or close to be. The reasons of this inhomogeneity depend on the different approaches in organising food waste collection and in supporting the sector of CH_4 production from discarded biogas. A very efficient separate collection is a crucial requirement to ensure the generation of a biogas with high quality, which is important for an efficient extraction of CH_4 from the biogas. Regulatory issues are another obstacle to the implementation of biomethane upgrading plants, since some countries still do not have a regulation on the authorisation of biomethane upgrading plants, on biomethane usages and on the incentives which a company in entitled to, if this decides to convert biogas into biomethane instead of exploiting the local electrical energy generation. In spite of the above-mentioned problems, the extraction of CH_4 from biogas opens to new perspectives for its exploitation.

In the light of the considerations expressed so far, this paper aims at comparing the emission balance from three different options for biogas valorisation: CHP generation and electrical energy supply to an electricity distribution network, biomethane production through pressurised water scrubbing and biomethane production through chemical absorption. In the last two cases, biomethane will be considered for usage by public buses fed with natural gas (NG). A case study representing and AD and post-composting plant will be presented in the next section, including the three scenarios for biogas exploitation. In addition, this paper also intends to highlight the advantages of modifying a hypothetical pre-existing composting plant to an AD and post-composting plant, in terms of space required and energy balance. To this purpose, a case study for direct composting will be defined in the next section. Some assumptions made in the presentation of the scenarios in this paper will be referred to the case of Italy, but can be easily replicated in other contexts.

2 CASE STUDY

2.1 Definition of the reference case study for direct composting

A hypothetical composting plant is here presented as a reference case study for the comparison between direct composting and AD and post-composting in terms of energy consumption and space requirements. A flow diagram of a typical composting facility is presented in Fig. 1a. The incoming OFMSW is initially discharged in an accumulation chamber, where it is weighed, grinded, sieved and mixed with 30% green waste. The mixed waste is sent to a second compartment where it is subject to strong conditions of aerobic biodegradation (biostabilisation) by forced ventilation. This first biological step lasts about 30 days. Subsequently, the stabilised waste mixture is sent to a third compartment (second biological step) where it is subject to natural ventilation allowing for the maturation of compost. The duration of this phase depends on the achieved values of the static and dynamic respirometric indexes, but it normally lasts for about 60 days. After this period, the compost is sent to a last compartment, where it is stored, packed and prepared for sale. In summary, from its arrival to the complete maturation o compost, a unit of waste spends about 90 days in the composting facility.

The duration of the treatment could be reduced when introducing an AD step upstream of the former biostabilisation step (Fig. 1b). This phase takes place in a digester, where the only OFMSW is biodegraded under anaerobic conditions through four phases: hydrolysis

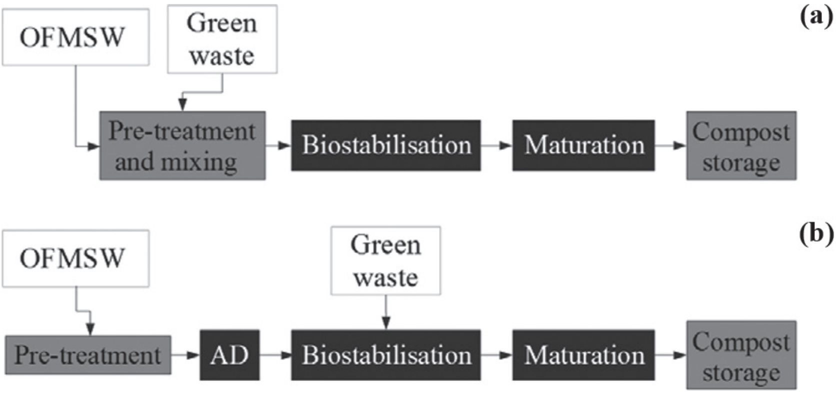

Figure 1: Flow diagrams of (a) the hypothetical composting plant and (b) its conversion to an AD and post-composting plant.

(decomposition of organic molecules in simpler ones), acidogenesis (formation of fatty acids, ammonia, carbon dioxide and hydrogen sulphide), acetogenesis (fermentation with formation of carbon dioxide, hydrogen and acetic acid) and methanogenesis (formation of CH_4, water and CO_2). AD can be carried out under thermophilic (about 55°C) or mesophilic conditions (about 35°C). The operating temperature has effects on the duration of this phase, ranging (in the case of a semi-dry technology) from about four weeks, under mesophilic conditions, to about 20 days, under thermophilic conditions [13]. During AD, a 50% reduction of the VS content is typically achieved [14]. This allows for a reduced duration of the subsequent aerobic phases, which can be contained in a total of about four weeks [15]. Consequently, converting a classic composting facility into and AD and post-composting process may reduce the duration of the whole process by five to six weeks (i.e. by approximately 38–47%), depending on the chosen thermal conditions of the AD phase (Table 1).

By knowing the typical duration of each phase and by making realistic assumptions on the typical volumes of the compartments that are necessary for processing the incoming OFMSW, it is possible to compare the surface requirements of each compartment in the hypothetical composting facility and in the modified configuration (AD and post-composting).

To quantify the soil occupations by a plant operating direct composting and by an AD and post-composting plant, it is useful to present an example concerning a typical medium-size composting plant that is able to treat about 50,000 t y^{-1} of waste. The input waste is assumed to be composed of 70% OFMSW and 30% green waste by weight, corresponding to OFMSW

Table 1: Typical duration (in days) of the phases in the three here considered scenarios.

Phase	**Direct composting**	**Mesophilic AD and post-composting**	**Thermophilic AD and post-composting**
AD	–	28	20
Biostabilisation	30	14	14
Maturation	60	14	14
Total	90	56	48

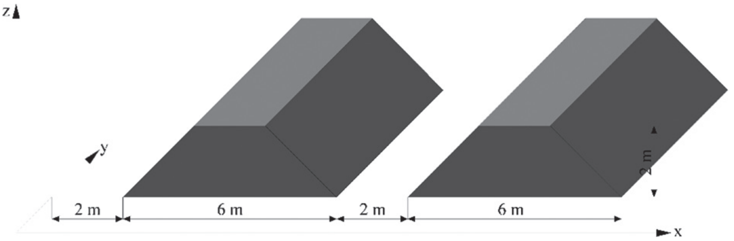

Figure 2: Scheme of the geometric approximation adopted for waste trenches to estimate the surface occupied by the aerobic biodegradation phases.

and green waste mass flows of 35,000 t y^{-1} and 15,000 t y^{-1}, respectively. Considered the typical densities of compacted food (1,029 kg m^{-3}) and green waste (445 kg m^{-3}) [16], the density of the 70–30% mixture results as about 730 kg m^{-3}. The mixed waste is often arranged in parallel heaps or trenches, the top of which may reach 2 m. Each trench can be approximated as a trapezoidal prism. On the cross section, the top base is assumed as equal to the height (2 m) and the bottom base is 6 m, by assuming lateral slopes of 45° (Fig. 2). In order to let operators and forklifts move, each trench can be assumed as surrounded by 2 m of free space on all sides. The same configuration may be adopted in both biostabilisation and maturation phases, regardless of the considered process (composting or AD and post-composting).

2.2 Definition of the case study for AD and post-composting

The case study is based on the conversion of the typical configuration of a composting process into:

- a semi-dry anaerobic digester, operated under thermophilic conditions (55°C), with a biogas productivity set to 142 Nm^3 t_{OFMSW}^{-1}, chosen on the basis of a reference semi-dry anaerobic digester (typical values for this technology are in the range 100–150 Nm^3 t_{OFMSW}^{-1});
- a second biological step, where the digestate is mixed with green waste (accounting for 20% of the total amount of waste) and undergoes aerobic biostabilisation;
- a maturation stage, with subsequent sieving and refining;
- a storage compartment, where high-quality compost is packed.

In the case of AD and post-composting, the same mass flow of OFMSW considered in the composting process is adopted (35,000 t y^{-1}). Different from composting, a lower amount of green waste is usually required in the post-composting process, so that the composition of the input waste is usually 80% OFMSW (which undergoes AD) and 20% green waste (which enters the process in the biostabilisation phase). The resulting green waste mass flow is 8,750 t y^{-1}. Considered that: (1) the total solid (TS) content and the VS to TS ratio of food waste can be respectively assumed as 70% and 83% [17], and (2) AD reduces the VS content by 50%, the digestate mass flow rate would result as about 25,000 t y^{-1}. The digestate density can be assumed as 990 kg m^{-3} [18]. By adding the green waste mass flow, a total mass flow of about 34,000 t y^{-1} would undergo the aerobic phases. The mean density of the mixture of digestate and green waste can be estimated as equal to 850 kg m^{-3}. For simplicity, all the calculations assume that the plant operates continuously all year. To further reduce the release of PM and odorants, the maturation and storage compartments are assumed to occur in closed hangars.

2.3 Definition of the scenarios for biogas exploitation

Concerning the modalities of biogas exploitation, three scenarios are considered (Fig. 3):

- Case 1. The produced biogas is sent to a desulphurisation unit and then to a CHP generator. Electrical energy is partly used to cover the electrical consumption of the facility and is partly sent to the electricity distribution network at medium voltage; the heat produced by the CHP generator is used to heat the digester.
- Case 2. 25% of the produced biogas is burnt in a boiler, to generate the heat to keep the digester under thermophilic conditions, while the remaining biogas is sent to a biogas upgrading system consisting in a pressurised water scrubber, with the purpose of producing biomethane to feed public buses.
- Case 3. This case is analogous to Case 2, with the difference that the biogas upgrading is carried out with chemical absorption; the boiler provides heat only to the digester; the necessary heat to regenerate the chemical solvent is supplied by a dedicated heater.

Both pressurised water scrubbing and chemical absorption are consolidated technologies and have been widely employed for biogas upgrading [19]–[23]. Different from chemical absorption, pressurised water scrubbing does not require heat, since water is regenerated by an air current at ambient temperature.

2.4 Definition of the pollutants considered

The estimation of the emissions from the three scenarios considers both global and local air pollutants. The considered global pollutants are CO_2 and CH_4, which are directly responsible

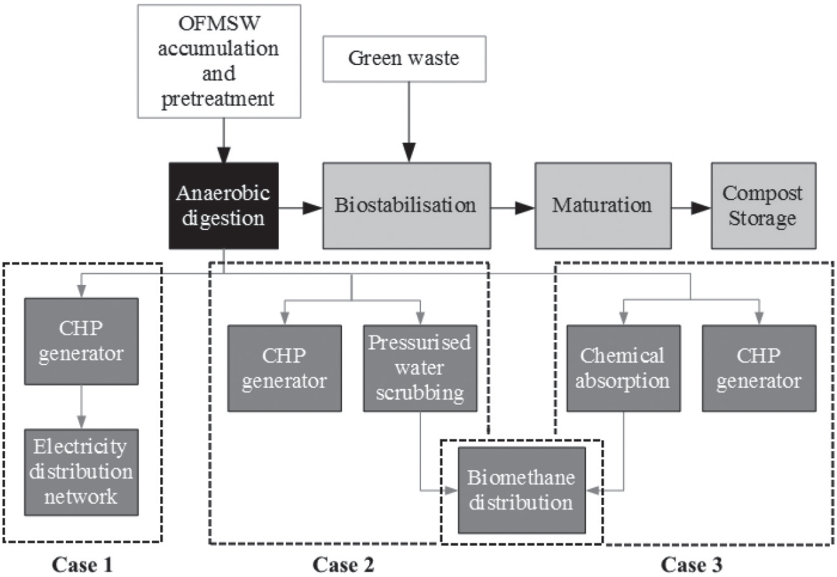

Figure 3: Flow diagrams of the configurations assumed in the three compared cases.

for global warming. The emissions of CO_2 derived from energy conversion of natural non-fossil materials (food and vegetable biomass in this case) are balanced by the CO_2 required for their production and directly absorbed from the atmosphere. For this reason, the CO_2 balance is considered neutral in all three cases. On the contrary, CH_4 emissions are not compensated with absorption by natural organic substances. In addition, the global warming potential of CH_4 is equal to 32 on a reference period of 100 years. CH_4 is released during its usage and through leaks from the upgrading process. The latter are assumed as equal to 1% and 0.1% when pressurised water scrubbing or chemical absorption are adopted, respectively. Among the local air pollutants emitted from the biogas exploitation line, nitrogen oxide (NO_x), sulphur dioxide (SO_2), PM, non-methane volatile organic compounds (NMVOCs) and carbon monoxide (CO) are considered. NO_x and SO_2 are also precursors of secondary PM, whose formation is estimated through application of the hypotheses formulated by [24]. In view of the comparison between the three presented cases, the emissions from the air treatment line of the three configurations are considered as equal in all cases, as an adequate design allows it. Therefore, those emissions will not be considered in the emission balance.

2.4.1 Case 1

Emission factors for NMVOCs and SO_2 emitted by the CHP generator were retrieved from the CORINAIR methodology developed by the European Environment Agency [25]. Concerning PM, CO and NO_x, emission factors were re-calculated on the basis of the corresponding emission limits set by the European Union [26]. The CH_4 emission factor was retrieved by the Danish emission inventory for stationary combustion plants [27]. The adopted emission factors are summarised in Table 2 and are referred to the unit energy of input CH_4. If considering the biogas productivity of 142 N m^3 $t_{OFMSW}{}^{-1}$, a CH_4 content of 60% v/v, a CH_4 lower heating value of 35.28 MJ N $m^{-3}$and assuming that the CHP generator works for 8,760 h y^{-1}, the specific annual input energy for the CHP generator is 3.01 GJ $t_{OFMSW}{}^{-1}$ y^{-1}. The efficiencies of the CHP generator in terms of electric and thermal energy conversion are assumed as equal to 38% and 40%, respectively. The resulting electric and thermal energy productions are 1.14 GJ $t_{OFMSW}{}^{-1}$ y^{-1} and 1.20 GJ $t_{OFMSW}{}^{-1}$ y^{-1}, respectively. In addition, 10% of the produced electric energy (0.11 GJ $t_{OFMSW}{}^{-1}$ y^{-1}) and 25% of the produced thermal

Table 2: Emission factors (expressed as g GJ^{-1} of input fuel) adopted for the production of energy from the average mix of energy sources in Italy and for CHP generators [25]–[28].

Pollutant	**Average national mix of conventional sources**	**CHP generator**
CO	16.5	28
NO_x	35	21
CO_2	65,000	0
NMVOCs	2.1	45
PM	0.8	2
SO_2	20.7	0.5
CH_4	3	434

energy (0.30 GJ t_{OFMSW}^{-1} y^{-1}) are assumed to be used in the facility to cover the energy consumption for the anaerobic digester and the aeration of the biostabilisation process.

Therefore, the excess electric energy production that is sent to the electricity distribution network is 1.03 GJ t_{OFMSW}^{-1} y^{-1}. The specific annual emissions for electric energy production can be estimated by multiplying this value by the emission factor of each pollutant.

Since no biomethane production for public transportation is considered in this scenario, this missing positive effect must be compensated with emissions from an average fleet of urban buses covering the same distance per ton of input OFMSW, the calculation of which will be discussed in Section 2.3.2. Emission factors concerning the average Italian bus fleet were estimated by the Italian Institute for Environmental Protection and Research (ISPRA) [29], based on the COPERT 4 methodology [25], and are reported in Table 3.

2.4.2 Case 2

In the hypothesis that all the biomethane produced is used by the local fleet of public buses, the emission factors from buses fed with NG were retrieved from the COPERT 4 emission model too (Table 3) [29]. Internal electric and thermal energy consumptions are assumed to be the same as Case 1 and are covered by the CHP generator, which uses the strictly necessary biogas flow to this purpose. The minimum specific amount of biogas for self-sustainment of the facility results as equal to 35.5 N m^3 t_{OFMSW}^{-1}. Therefore, the biogas sent to upgrading is 106.5 N m^3 t_{OFMSW}^{-1}. Considering the CH_4 loss of 1% for pressurised water scrubbing and a 60% content of CH_4 in biogas, the specific biomethane production is 63.3 N m^3 t_{OFMSW}^{-1}. Such value, coupled with the CH_4 density of 656 g m^{-3} and with the biomethane consumption estimated by COPERT 4 (455 g km^{-1}), allows for a specific distance travelled of 91.2 km t_{OFMSW}^{-1}. To compare the three scenarios, the same distance travelled is assumed in Case 1 and Case 3, with the only difference that, in Case 1, the distance travelled will be referred to the average composition of public buses.

The emission balance of Case 2 must account for the missing production of excess electric energy by the CHP generator. This missing contribution is assumed to be replaced by a corresponding amount of electric energy generated by conventional sources. Emission factors for

Table 3: Emission factors (expressed as g km^{-1}) adopted for the estimation of the emissions from the average Italian fleet of urban public buses and from urban buses fed with NG, and average fuel consumptions [29].

Pollutant	Average national fleet of public buses	NG-fed urban buses
CO	1.57	28
NO_x	6.4	21
CO_2	699	0
NMVOCs	0.26	45
PM	0.17	2
SO_2	0.003	0.5
CH_4	0.098	0.98
Fuel consumption [g km^{-1}]	236	455

CO_2 and CH_4 concerning the mix of sources used in Italy for electric energy production in 2013 were adopted in this case [28] and are expressed in terms of unit energy of the input fuel (Table 2). The conversion efficiencies to electric and thermal energies are conveniently assumed as 38% and 40%, as in the case of the CHP generator. In addition, biogas upgrading via pressurised water scrubbing requires an electrical energy consumption estimated as 0.3 kWh N m^{-3} of treated biogas. This additional energy is assumed to be provided by conventional energy sources.

2.4.3 Case 3

Concerning the emissions that originate from the missing production of excess electric energy by the CHP generator, the same emissions as of Case 2 are expected. Differently from Case 2, a lower CH_4 loss (0.1%) is expected when upgrading biogas with chemical absorption. Therefore, the biomethane production is slightly higher and results as 63.8 Nm^3 $t_{OFMSW}{}^{-1}$. The specific distance travelled would result in 92.0 km $t_{OFMSW}{}^{-1}$. However, to compare the three scenarios, the same distance as of Case 2 is considered, and the excess biomethane is assumed to be stored in a gas reservoir.

Biogas upgrading through chemical absorption requires both electric energy and thermal energy to regenerate the solvent. Based on the applications of this technology, the estimated energy consumption for chemical adsorption is 0.1 and 0.5 kWh Nm^{-3} of treated biogas for electric and thermal energy, respectively. In analogy with Case 2, this additional amount of energy is assumed to be provided by conventional sources.

3 RESULTS AND DISCUSSION

3.1 Emission balance

The emissive contributions of electric energy production by the CHP generator (only for Case 1), public transportation, electric energy compensation from conventional sources (Case 2 and Case 3), energy consumption for biogas upgrading (Case 2 and Case 3) and CH_4 losses from biogas upgrading (Case 2 and Case 3) are summarised in Fig. 4. CH_4 emissions were more conveniently converted into equivalent CO_2 emissions (CO_{2eq}). Emissions refer to the unit mass of input OFMSW.

As expected, the contribution of public transportation to the emissions of the considered pollutants is higher when urban buses are not fed with the biomethane produced by the plant (Case 1). The only exception concerns NMVOCs, whose emission factor is higher in NG-fed urban buses, as reported in Table 3. With regard to Cases 2 and 3, the generation of local air pollutants is higher when chemical absorption is chosen as the biogas upgrading method. On the other hand, chemical absorption implies lower emissions of global pollutants (CO_{2eq}), mainly due to lower CH_4 losses. The final choice should be made on the location of the biogas upgrading plant. Indeed, in case resident population is settled near the plant or if the emissive context of the area is already critical due to the presence of several other emission sources or peculiar orographic conditions, the local impacts induced by the biogas upgrading option should be as low as possible. Thus, pressurised water scrubbing would be the preferred choice from the point of view of human health. In comparison with chemical absorption, pressurised water scrubbing also requires lower energy to operate, but this economic convenience is counterbalanced by the higher CH_4 losses and CO_{2eq} generation.

The total emissions of the reference pollutants with respect to the three considered scenarios are presented in Fig. 5. In general, Case 1 generates a higher amount of local pollutants than Cases 2 and 3, with the only exception of SO_2. From the point of view of global

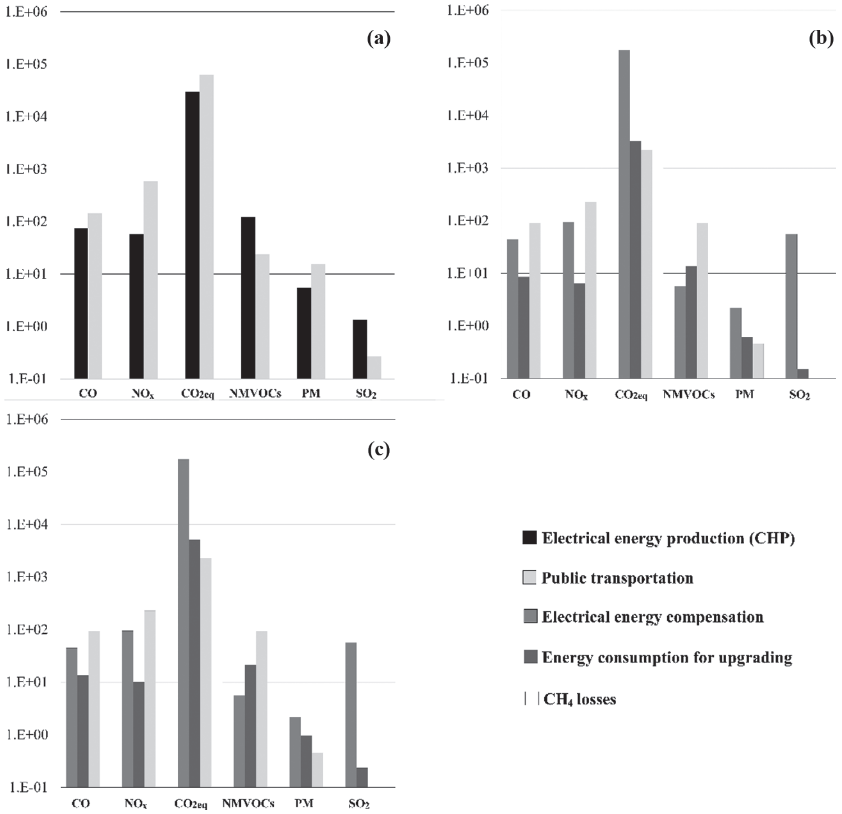

Figure 4: Contribution of each emissive item to the emissions of the considered pollutants from (a) Case 1, (b) Case 2 and (c) Case 3; emissions are expressed as g t_{OFMSW}^{-1} y^{-1}.

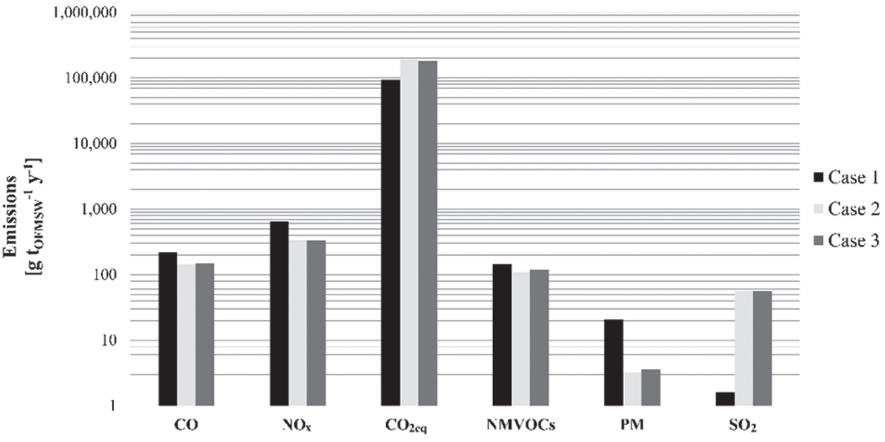

Figure 5: Total emissions generated in the three considered scenarios.

Figure 5: Total emissions generated in the three considered scenarios.

pollutants, CO_{2eq} emissions from Cases 2 and 3 are almost double in comparison to Case 1, although their total CH_4 emissions are almost half the CH_4 emissions from Case 1. The main reason is related to the higher CO_2 emissions due to the missing production of electric energy for distribution in the electricity network, which must be compensated by electric energy produced by conventional sources. Such results are clearly affected by the grid mix considered. In case 100% renewable sources were available, the CO_{2eq} contribution from Cases 2 and 3 would be related only to CH_4 losses from the biogas upgrading plants, which will account for about one-third of the CO_{2eq} emissions from Case 1.

3.2 Energy requirements

Thanks to the generation of biogas, the introduction of an AD step into the conventional composting process allows for obvious benefits from the point of view of the energy balance. Indeed, direct composting implies a negative energy balance, since electrical energy consumption is not compensated by *in situ* electrical energy production by biogas burning. Based on the data available from several plants, the electrical energy required for the aeration of the waste heaps can be estimated by considering that 10% of the specific electrical energy produced by a CHP generator in a combined AD and post-composting plant is sufficient to carry out the biostabilisation of the waste. As reported in Section 2.2.1, the specific electrical energy demand for this purpose is 0.11 GJ t_{OFMSW}^{-1} y^{-1}. In the case of direct composting, no thermal energy is required.

When moving to an AD and post-composting process, the energy balance depends on the chosen technology for AD and on the biogas exploitation option. In Case 1, the production of thermal and electrical energy from the CHP generator allows for a positive net balance: specifically, the plant generates a surplus of 1.03 and 0.90 GJ t_{OFMSW}^{-1} y^{-1}, respectively, for electrical and thermal energy. In Case 2, the electrical and thermal energy required to sustain the plant is provided by the CHP generator. However, pressurised water scrubbing requires an electrical energy consumption estimated as 0.3 kWh N m^{-3} of treated biogas, which results in a consumption of 0.12 GJ t_{OFMSW}^{-1} y^{-1}, which was assumed to be provided by conventional energy sources. The treated biogas is not available to the plant, but sold as biomethane for the automotive sector. According to COPERT 4, the energy consumption (intended as thermal energy) for modern NG-fed buses is 21.84 MJ km^{-1} [25]. Thus, considering the specific distance travelled of 91.2 km t_{OFMSW}^{-1}, the plant potentially generates an annual surplus of 1.99 GJ t_{OFMSW}^{-1} of thermal energy. The same amount is generated in Case 3, but the lower losses from chemical absorption lead to an extra specific energy of 0.02 GJ t_{OFMSW}^{-1} that is stored annually in the gas reservoir. Based on the data assumed, Case 3 involves an annual electrical and thermal energy consumption of 0.04 and 0.19 GJ t_{OFMSW}^{-1}, respectively. The results of the energy balance are presented in Table 4.

Table 4: Results of the energy balance related to the three scenarios for biogas exploitation and to direct composting (values expressed as GJ t_{OFMSW}^{-1} y^{-1}).

Scenario	**Consumption**		**Production**		**Net production**	
	Thermal	**Electrical**	**Thermal**	**Electrical**	**Thermal**	**Electrical**
Case 1	–	–	0.90	1.03	0.90	1.03
Case 2	–	0.12	1.99	–	1.99	–0.12
Case 3	0.04	0.19	2.01	–	1.97	–0.04
Direct composting	–	0.11	–	–	–	–0.11

3.3 Space requirements

In the case of direct composting, biostabilisation and maturation would last 30 and 60 days, respectively. Considering that the assumed total waste mass flow is 50,000 t y^{-1}, the biostabilisation and maturation compartments can host about 4,100 t and 8,200 t of waste, respectively, corresponding to volumes of about 5,600 m^3 and 11,200 m^3. If adopting the trench configuration presented in Section 2.1 and considering that each trench is 80-m long, the cross size of the biostabilisation building would measure about 74 m, resulting in an area of 5,920 m^2. The maturation building would measure 80 m × 146 m, giving an area of 11,680 m^2. Therefore, the total surface occupied by the composting plant would be 17,600 m^2.

In the case of AD and post-composting, biostabilisation and maturation would last about 14 days each. According to the assumptions made in Section 2.1, the total waste mass flow would be 34,000 t y^{-1}, with a mean density of 850 kg m^{-3}. Therefore, biostabilisation and maturation compartments should occupy a volume of about 1,535 m^3 each. If considering the same configurations assumed for the trenches in the case of direct composting, the biostabilisation and maturation buildings would occupy a total surface of 4,800 m^2. This surface adds up to that required for the anaerobic digester and the biogas exploitation section. Based on a design parameter retrieved by real plants, the volume required by AD may be assumed as 0.75 m^3 $t_{OFMSW}{}^{-1}$. Considering the input OFMSW mass flow of 35,000 t y^{-1} and the duration of AD in the case of mesophilic conditions (four weeks), the anaerobic digester would require a volume of about 2,000 m^3. If assuming that the anaerobic digester is 5-m high, the occupied surface would be approximately 400 m^2. Lower surface would be required if AD was carried out under thermophilic conditions: due to the lower residence time in the digester (about 20 days, compared to the four weeks required under mesophilic conditions), the resulting surface would be 290 m^2. Therefore, a thermophilic AD, followed by post-composting, would require 70% less surface in comparison with the conventional direct composting process. The CHP generator, the desuplhurisation and upgrading systems are characterised by the extreme compactness of such technologies. As an example, a CHP generator capable of developing an output electrical power of 2 MW_{el} (which would be suitable for an input OFMSW flow rate of about 60,000 t y^{-1}) would occupy a surface of about 10 m^2. Even considering additional

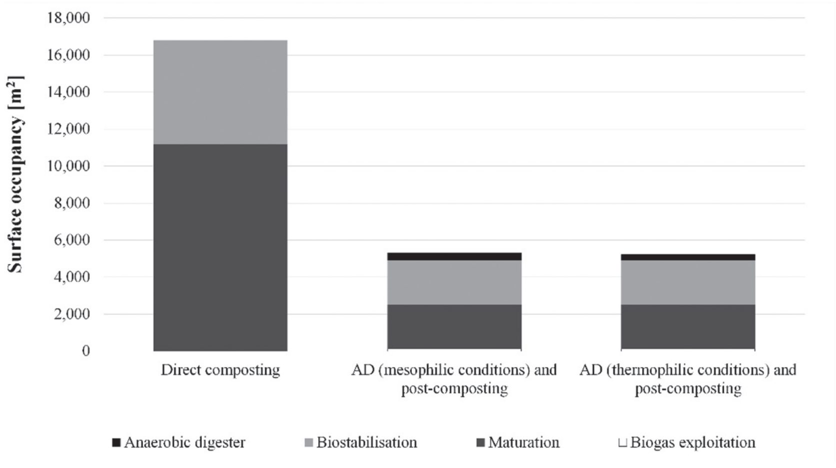

Figure 6: Comparison between the considered scenarios in terms of estimated surface occupancy.

surface for a desulphurisation system (which could be assumed as equal to the surface occupied by the generator) and for a biogas upgrading system (which can assume a precautionary value of 100 m^2), the surface occupancy of the whole biogas exploitation system would represent less than 3% of the total surface covered by the facility. Fig. 6 presents the results of the surface occupancy in the case of direct composting, mesophilic AD and post-composting, and thermophilic AD and post-composting, based on the input waste mass flows considered.

4 CONCLUSION

AD followed by post-composting has the undoubted advantage of generating an energy source as biogas with about 30% of the space requirements of a traditional composting process. Converting a composting process into an AD and post-composting one allows producing a surplus of thermal energy and a positive or close-to-neutrality balance in terms of electrical energy. However, different options to exploit the produced biogas entail different results in the emissive balance. Compared to biogas upgrading and use of biomethane in the public transportation system, the production of electricity through biogas combustion in a CHP generator produces a lower amount of CO_{2eq} but higher amounts of local air pollutants. Between the two options considered for biogas upgrading, pressurised water scrubbing would lead to slightly lower local impacts. In conclusion, the preferred choice should consider what impacts are more important for the specific context in which an anaerobic digestion and post-composting plant will be located. In this framework, the estimation of the emissive balance concerning different scenarios represents a useful tool for decision makers to evaluate the best option to choose.

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