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Are EU waste-to-energy technologies effective for exploiting the energy in bio-waste?

Francesco Di Maria[a,b,*], Federico Sisani[a], Stefano Contini[a]

[a] LAR[5] Laboratory, Dipartimento di Ingegneria, University of Perugia, Via G. Duranti 93, 06125 Perugia, Italy
[b] CIMIS Consortium, via G. Duranti 67, 06125 Perugia, Italy

HIGHLIGHTS

- Replacement of primary energy by EU WtE exploiting bio-waste was assessed.
- CHP mode is mandatory for effective replacement of primary energy.
- Primary energy replacement by MSWI up to 16 times higher than AD.
- R&D resulted very promising for improving AD performances.

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ABSTRACT

The present review compares the most diffused full-scale waste-to-energy technologies in the EU28, incineration and anaerobic digestion (AD), for exploiting the energy content of bio-waste for replacing primary energies. The comparison was performed following a life cycle approach using the cumulative energy demand index (CED) (MJ/Mg) and by the definition of the *ad hoc* hybrid primary energy index (HPE) (MJ/Mg), also able to account for the energy content of the waste. High values of CED for input flows for incineration were associated with auxiliary fuel consumption, up to 7000 MJ/Mg, slag disposal, about 500 MJ/Mg, and with the chemicals necessary for flue gas treatment, up to 1000 MJ/Mg. The CED values associated with electricity and heat replacement by those recovered from waste combustion ranged from about 4000 MJ/Mg up to about 24,000 MJ/Mg. The main CED associated with the input flows for AD was from maintenance of the gas engines, ranging from about 40 MJ/Mg up to 120 MJ/Mg. The CED associated with the avoided production of mineral fertilizer ranged from about 0.05 MJ/Mg to 0.7 MJ/Mg. The CED associated with electricity and heat replaced by energy recovery ranged from about 3000 MJ/Mg to about 6000 MJ/Mg. The expanded energy balance performed by the HPE (MJ/Mg) indicated that combined heat and power mode is a key factor for allowing efficient and effective replacement of primary energies by incineration. There was also a similar effect for AD but with more limited benefits. Recent research trends show a higher potential for improving the performances of AD compared to incineration.

1. Introduction

At the EU28 level the recovery of energy from waste, in general, and bio-waste, in particular, is a practice that has been widely implemented in many member States, making the European Union a leader in this field. Bio-waste and biomass are considered sustainable and renewable energy sources able to contribute to achieving the EU 2020 [1,2] and EU 2030 goals [3], which are: GHG emission reduction compared to 1990 ≥40%; energy needs generated by renewable sources ≥27%; increase in energy efficiency ≥27%. Various technologies based on biological, chemical and thermal treatments [4–6] have been proposed for this issue. Currently the most diffused waste-to-energy (WtE) full-scale facilities are by municipal solid waste incinerator (MSWI) with energy recovery and anaerobic digestion (AD). The share of these plants for energy production in the EU28 is about 1.5%. These technologies have also been indicated by the European Commission [7] as the ones able to continue to play a prominent role in the recovery of energy from waste in the near future.

On a more global scale in the last 50 years the world population has risen from about 3 billion to more than 7 billion with a projection of

* Corresponding author at: LAR[5] Laboratory, Dipartimento di Ingegneria, University of Perugia, Via G. Duranti 93, 06125 Perugia, Italy.
E-mail address: francesco.dimaria@unipg.it (F. Di Maria).

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Nomenclature

AD	anaerobic digestion
ADM1	anaerobic digestion model n°1
BFB	bubbling fluidized bed
BMP	biomethane potential (N m^3/kgVS)
CHP	combined heat and power
CED	cumulative energy demand (MJ)
CFB	circulating fluidized bed
DGGE	denaturing gradient gel electrophoresis
EU	European Union
FISH	fluorescence *in situ* hybridization
HPE	hybrid primary energy index (MJ)
HDPE	high density polyethylene
HRSG	heat recovery steam generator
HRT	hydraulic retention time (day)
HTS	high throughput sequencing
LFD	landfill directive
IPPC	integrated pollution prevention control
LHV	lower heating value (MJ/Mg)
MC	moisture content (%w/w)
M	mass (Mg)
MSW	municipal solid waste
MSWI	municipal solid waste incinerator
OLR	organic loading rate (kgVS/m^3 day)
PAH	polycyclic aromatic hydrocarbons
PCDD	polychloro-dibenzo dioxin
PCDF	polychloro-dibenzo furan
PCR	polymerase chain reaction
PM	particulate matter
SADB	solid anaerobic digestion batch
TOC	total organic carbon (%TS)
TS	total solids (%w/w)
VS	volatile solids (%TS)
WFD	waste framework directive
WtE	waste to energy

Subscripts

in	inlet
out	outlet
waste	bio-waste

reaching about 9 billion by 2025 [6]. This will also have a significant effect on the amount of waste generated. In fact, as reported in Fig. 1, the total waste generated is expected to increase from about 1.2 billion Mg in 2010 to about 2.2 billion Mg in 2025. Assuming an average lower heating value (LHV) of about 9000 kJ/kg, Dornberg and Faaij [8] and Bogner et al. [9] estimated an energy potential of waste ranging from about 13EJ to about 30EJ.

Depending on the composition of the waste and on local management strategies and goals, the recovery of energy can play an important role in solving various problems. As an example, on one hand, since the first waste management directive 91/156/EC [10] at the EU level, incineration with energy recovery has been indicated as a suitable solution for reducing the mass and reactivity of non-reused/recycled/recovered waste before its disposal in landfill. On the other hand, anaerobic digestion (AD) has been adopted as a recycling option in a large number of member states for increasing the whole energy and environmental efficiency of bio-waste recycling.

Referring to the year 2014, the whole municipal solid waste (MSW) generated in the EU28 was 240,834,000 Mg, which was managed according to the following average figures [11]: 28% material recycling; 16% bio-waste recycled by composting and/or anaerobic digestion; 27% processed by incineration with energy recovery; 28% landfilled. In some of the more developed areas in the EU28 the share of bio-waste was about 33% of the whole waste generated [12,13].

Several studies have been performed for analyzing the energetic and environmental aspects related to different waste-to-energy solutions. Concerning MSWI Murer et al. [14] reported that the efficiency of an Amsterdam incineration plant was about 30%. Grosso et al. [15] investigated the efficiency of several MSWI using an energetic approach. Tabasova et al. [16] reported power generation ranging from 0.3 to 0.7 MWh/tonne, respectively, for combined heat and power and for electricity recovery plants. Di Maria et al. [17] investigated the lower heating value (LHV) of waste processed in an existing Italian incinerator, reporting an average gross energy efficiency of about 19%.

Tong et al. [18] investigated the impact arising from different WtE options for food waste and reported that combined AD and post incineration gave the best energetic and environmental performances for Singapore. In comparing incineration with AD for the management of bio-waste Di Maria and Micale [19] reported that the former gave the lower impact.

All these findings indicate that, on one hand, there is a general agreement about the positive role of MSWI and AD in energy recovery and environmental protection. However, on the other hand, there is still a lack of information about the extent to which these technologies are able to exploit the energy content of bio-waste more efficiently. This aspect is of prominent importance considering the current EU policy about energy [3] and the circular use of resources [7] and for a better understanding of the role that MSWI and AD can play in their successful implementation.

For these reasons the aim of the present review is to carry out an expanded energy balance of the full-scale WtE technologies currently operating in the EU28. This analysis was performed using a life cycle approach. The cumulative energy demand (CED) [20–22] was used for assessing the primary energy consumption and replacement associated with the main materials, energy and fuel inputs and outputs of full-scale MSWI and AD.

The effectiveness of exploiting the energy content of bio waste was assessed using the definition of the *ad hoc* hybrid primary energy index (HPE).

According to the European biogas association, out of a total of about 17,500 AD facilities operating in the EU in 2015 fewer than 3% had upgraded the biogas to bio-methane for grid injection or transport fuel. Only 244 of these 17,500 plants (*i.e.* < 1.5%) were processing bio-waste as the main substrate. Due to the limited number of AD facilities in the EU recovering bio-methane from bio-waste and the consequent

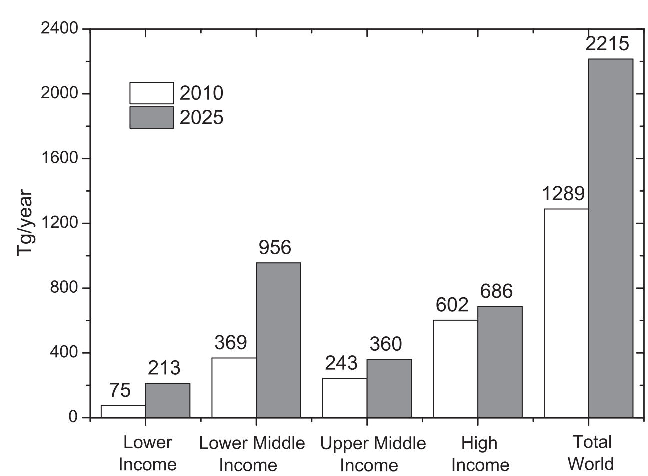

Fig. 1. Waste generation in 2010 and projection to 2025.