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Renewable energy from solid waste: life cycle analysis and social welfare

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\textbf{ABSTRACT}

In this study, municipal solid waste (MSW) composition in distinct world locations is compared and a case study is assessed. Three waste-to-energy (WtE) techniques are employed within the framework of an industrial partnership. Life cycle assessment (LCA) and a brief social contextualization including the production of renewable energy from the waste generated worldwide were held to attain a holistic view and attract the interest of multiple stakeholders.

Incineration depicted a sustainable profile with improved results for global warming potential and terrestrial ecotoxicity potential. Regular gasification revealed the best results for eutrophication, acidification, marine aquatic ecotoxicity and human toxicity potential. Two-stage plasma gasification showed negative values for all impact categories i.e. achieving environmental credits. The estimate of the electricity produced from the waste generated per capita showed a fair coverage of the electrical demand in distinct world areas.

To the best of the authors’ knowledge, there are no reports connecting the electricity use, the waste production and the renewable energy achieved from WtE for different world regions. Therefore, this study supports the replacement of fossil fuels with renewable alternatives, reducing greenhouse gas emissions while maintaining the comfort and commodities suitable for a comfortable quality of life.

1. LCA overview for thermal conversion techniques

Massive population growth and subsequent society evolution raise problems such as higher levels of waste production, which also become more complex and difficult to treat and dispose correctly (Sinha-Khetriwal et al., 2005; Scharnhorst et al., 2005). Currently, waste management is considered a hot topic and concepts such as WtE are becoming increasingly explored, endorsing residues as one of the possible novel energy sources (Reimann, 2005; Zheng et al., 2014; Ramos et al., 2018a). If conveniently processed, waste may be considered as a renewable energy source as widely reported (Rizwan et al., 2018; Fodor and Klemes, 2012; Ng et al., 2014; Themelis et al., 2002; Young, 2010). Technology related to waste treatment is now at the forefront of development, aiming to manage large amounts of waste in the most sustainable way (Rizwan et al., 2018; Fruehaard et al., 2010; Tavares et al., 2018). Thermal treatments are one of the most commonly employed procedures to deal with numerous waste streams including MSW (Pavlas et al., 2010; Tavares et al., 2019), achieving mass reductions of 70–80% and volume reductions of 80–90% (Bosmans et al., 2015; Münster and Meibom, 2011). Incineration is by far the most widely used thermally-based treatment technique, whereas gasification-based conversion schemes are in lesser use (Astrup et al., 2015). Gaseous emissions related to the thermal treatments depict environmental damages such as dioxin and furans formation, heavy metals, and other contaminants which need further treatment (Lopes et al., 2015; Tabasova et al., 2012; Peng et al., 2016). Otherwise, advanced technologies like regular and plasma gasification apply much higher temperatures and avoid most of the hazardous emissions, enhancing conversion efficiency (Ray et al., 2012; Tang et al., 2013; Ramos et al., 2019a).

LCA enables the quantification of the impacts related to a specific process or combination of processes, e.g. waste management (McDougall et al., 2008). It evaluates the drawbacks and benefits of each step of the overall process from raw material to production, use and disposal of the product, calculating dedicated impact categories, providing easy interpretation and comparison of alternative strategies (Rajaeifar et al., 2015). The International Standard Organization has settled the principles and framework for LCA and four main phases...
have been established. These are goal and scope definition, life cycle inventory (LCI) collection, life cycle assessment (LCA) and life cycle interpretation phase (ISO, 2006). Distinct methodologies are available to characterize the impact categories (Chevalier et al., 2011). CML being one of the most commonly used for environmental assessments (Zaman, 2013; Frischknecht et al., 2007). This methodology was developed by the Institute of Environmental Sciences of Leiden University (CML) and embodies eleven impact categories, namely: global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), abiotic depletion (ADP), ozone destruction potential (ODP), photochemical ozone creation potential (POCP), marine aquatic ecotoxicity potential (MAETP), fresh water aquatic ecotoxicity potential (FAETP), terrestrial ecotoxicity potential (TETP) and human toxicity potential (HTP), detailed in (Strandford et al., 2005).

In the last decades, numerous studies reporting LCA approaches for several waste streams have been published and distinct WeT were evaluated. WeT classifies all the techniques that decompose waste by thermal means, with the double advantage of recovering its energy, enabling the production of power (Zhang et al., 2015a; Ryu and Shin, 2012). This can be applied to the (pre-)construction stage of municipal engineering projects, predicting their impacts and preventing possible adverse situations (Gangolells et al., 2014). In this study, the assessed WeT procedures are incineration, regular gasification and two-stage plasma gasification. Briefly, incineration is the combustion of solid residues in the presence of oxygen producing heat and steam, which are utilized in a turbine to generate electricity (Bosmans et al., 2013). Although temperatures are sufficiently high to burn the debris, pollutants such as ash, slag and contaminated flue gases are produced requiring additional treatment before being sent to the environment (Van Caneghem et al., 2012). Gasification concerns the conversion of solid waste into a synthetic gas (syngas), in sub-stoichiometric conditions at higher temperatures. Syngas is mainly composed of H2, CO, CO2 and short-branched hydrocarbons and may be utilized for the production of power, chemicals, hydrogen and liquid fuels (Siedlecki et al., 2011). This technique is divided into four stages: drying, pyrolysis, oxidation and reduction where specific chemical reactions occur (Ramos et al., 2018a). Two-stage plasma gasification constitutes an upgrade from regular gasification, adding an extra cleaning step to syngas due to the action of plasma (Ray et al., 2012). Plasma is considered the fourth state of matter, part of the gaseous elements being in an ionized form, permitting charged particles to interact with neighbouring ones as well as be influenced by an electromagnetic field created by the other charges as a consequence of the very high temperatures (Pourali, 2010). The combination of these highly reactive species with these elevated temperatures is favourable for waste degradation in which inorganic materials are more efficiently melted and a cleaner syngas is achieved (Lombardi et al., 2012).

Rajaeifar et al. (Rajaeifar et al., 2015) made a compilation of several LCA studies for MSW management systems highlighting the need to report complete and specific information and address malpractices such as deficiencies in goal and scope definition or using unrepresentative waste compositions. Mendes et al. (Mendes et al., 2004), Liamsanguan and Gheewala (Liamsanguan and Gheewala, 2008) and Parkes et al. (Parkes et al., 2015) compared incineration and landfill-based operations in different locations, namely: Brazil, Thailand and England. Taking in consideration the system boundaries and features for each work, the authors reached similar conclusions: incineration created lower environmental impacts than landfill with respect to GWP. Pikon and Gaska (Pikon and Gaska, 2010) compared incineration impacts to non-thermal processes also reporting lower greenhouse gas emissions for incineration. Ouda et al. (Ouda et al., 2016) compared incineration to other options such as bio-methanation for the treatment of MSW in the Kingdom of Saudi Arabia, incineration proving to be efficient and adequate in terms of power generation and cost. Chen and Christensen (Chen and Christensen, 2010) assessed two different incinerators in China and corroborated the environmental savings and sustainability profiles attained by this technique. Zaman (Zaman, 2013) performed a comparative LCA study for MSW incineration and gasification, this last technique showing lower results for GWP and ecotoxicity categories. Al-Salem et al. (Al-Salem et al., 2014), who appraised alternative scenarios for the waste management in the Greater London area, report lower greenhouse gas emissions from a technology based on gasification. Gunamantha and Sarto (Gunamantha and Sarto, 2012) made a LCA assessment between landfilling, incineration and gasification for solid waste in Indonesia and concluded that gasification portrayed the best environmental profile. Regarding advanced WeT options, Tagliaferri et al. (Tagliaferri et al., 2016) analyzed different scenarios in the UK including plasma gasification for the treatment of MSW. This new approach depicted higher efficiency in the production of renewable methane, which might replace natural gas in the future. Evangelisti et al. (Evangelisti et al., 2015a) also assessed this technology obtaining environmental credits for most impact categories. The advanced plasma technique depicted improved overall profile compared to pyrolysis, combustion and classic gasification, mostly due to its higher electrical efficiency. Other studies reported high conversion efficiencies attained with this plasma-based technology (Ray et al., 2012; Taylor et al., 2013) as well as volume reductions of up to 99%, substantially higher than conventional incineration (Byun et al., 2010).

Most of the times, one specific feature of a new technology is emphasized and, rather than conducting an integrated study, other aspects of the low carbon technologies are assessed separately (Braulio-Gonzalo et al., 2015). This results in a reduced social acceptance of a novel project's implementation, especially when waste management is the topic, since people tend to relate it to social discomfort. Hence, Bartolacci et al. (Bartolacci et al., 2019) developed an efficiency indicator combining economic and environmental aspects for companies operating in the collection, transport and treatment of municipal solid waste. Mavrotas et al. (Mavrotas et al., 2015) propose a multi-objective optimization to assess several WeT techniques for MSW management. This provides fruitful information for the decision-maker, enabling the selection of the most adequate option depending on the real context of the project and its primary goals. Bong et al. (Bong et al., 2017) also contribute to the engagement of stakeholders, investigating key strategies required to reach different audiences in the production of biogas. An holistic knowledge of the situation provides a richness of outcomes that enables risk mitigation and enables public understanding and support (Bergeron, 2017; Harris and Spickett, 2011). Lombardi et al. (Lombardi et al., 2017) have recently summarized what has been done regarding urban carbon footprint assessments, stating that combined approaches are the most complete for providing supplementary information related to energy and climate. Also, if the proposed technology affords sub-products with commercial value, the intrinsic worth of the project is strengthened, constituting a social benefit. This may be regarded as an extra argument for the communities and the decision-makers, as well as the environmental and social benefits (Bartolacci et al., 2019). This will have a direct effect on people's living conditions, potentially challenging them to change their habits.

This new study reviews the municipal solid waste composition in several world cities and, as a specific application of the gathered knowledge, presents a case study for the enhancement of a pre-existing facility. The environmental and energetic performances of the thermal treatment of one tonne of MSW by incineration, regular gasification and two-stage plasma gasification are assessed. In order to give a more realistic picture of the opportunities brought by these technologies, an approximate appraisal of the contribution of the energy generated from the amount of personal waste to supply the individual's daily needs in different world areas is also investigated, reflecting novelty in this type of assessments. This evaluation enables the calculation of the ratio between waste produced and energy consumed per capita in several areas, potentially serving as an average indicator for social wealth and development, also showing innovation.
1.1. Waste composition across different regions

Depending on the composition of the waste, different management solutions may be suggested in order to comply with the strategy imposed by the EU (Engineering, 1.15.a.s.a.P, 2011). Ciuta et al. (Ciuta et al., 2015) investigated several MSW streams from different areas and concluded that in urban areas, the plastic fraction is almost six-fold higher than in rural areas, which enhances the calorific content of MSW, enlarging its energy recovery possibilities. This is also seen for different types of waste streams and disposal options (Sinha-Khetriwal et al., 2005), waste availability being also an aspect that contributes to different composition (Bergeron, 2017). The composition and rate of production of MSW contribute to the improvement of the waste management systems, aiding the development of national or regional strategies in order to meet EU regulations.

Park and Lah (Park and Lah, 2018) compared the average composition of MSW in the EU, South Korea and the USA, showing that different standards and definitions applied in diverse world regions/countries/socio-economic organizations leads to ambiguous comparisons: the same MSW component may be understood as waste in one country and as recyclable material elsewhere and this hampers tentative comparisons between MSW compositions. In the EU, the most recent legislation on waste management is based in the Waste Framework Directive (2008/98/EC) and the Directive 2011/753/EU, which establish the calculation methodology for meeting the targets set by the European Environment Agency (Fischer et al., 2013). Within these standards, more than 272×10^6 tons of MSW were generated and almost 27% were recycled in the EU in 2015. In the same year, South Korea, with its waste management system based in more conservative rules and standards, recycled 59% of the MSW generated, whereas the USA recycled approximately 27% of the MSW generated (Development, O.F.E.C-O.A, 2016). Nevertheless, applying the EU standards to South Korea and the USA, the recycling rates increase to roughly 70% and 40%, respectively (Park and Lah, 2018). Different changes are seen when applying each country’s standards to the other participants but the major finding is that distinct definitions of the MSW or recyclable fraction lead to diverse interpretations of the results (Park and Lah, 2018; Kawai and Tasaki, 2016). The discrepancy in definitions is a result of different policies and responsibilities prevailing with respect to the waste cycle, depending on the country or legislative body as well as the political, social and economic framework (Kawai and Tasaki, 2016). Table 1 cites published works that relate specific MSW composition to different world locations.

As noted previously, the composition of MSW for a given location may vary considerably depending on sampling method, collection season or characterization methodology as the data from Beijing in Table 1 (Ramachandra et al., 2018; Xiao et al., 2009). Other discrepancies are seen for various regions within the same country as observed for India and China, the latter country showing variances from nearly 16% to 69% in the organic fraction, and 3% to roughly 17% in the paper fraction (Xiao et al., 2009). In India, the organic fraction varies from 35% to 84% and the plastic share from 2% to 35% (Bolukbas and Akinci, 2018; Naveen, 2018; Ramachandra et al., 2018). Taiwan also presented divergent values among distinct cities, the organic fraction ranging from 24% in Taipei to 40% in Keelung, whereas the plastic varied from 22.5% to 15% in the same locations (Chen, 2018). Metal and glass shares also varied significantly among the Taiwanese cities. By contrast, in smaller countries such as Portugal, different cities present similar MSW compositions as the consumption patterns and economic level of the population are similar (Ramos et al., 2018b; Marçal et al., 2015). This has further promoted the research of a case study for a dedicated purpose, as described and discussed in chapters 2 and 3 of the present work. Tourism is also a great contributor for the composition of residues in a given location (Diaz-Farina et al., 2020), geophysical features (as dry and wet seasons) also promoting diverse waste compositions in specific countries (Ibikunle et al., 2020).

In the case of Nigeria, the organic fraction shows the highest discrepancy (more than 10% raise in the wet season), plastic and textile contents dropping nearly 4% and 3.4% respectively.

Most of the selected countries/regions depict the organic fraction as the major MSW component, although there are some exceptions as in the USA, Norway and Israel. Again, distinct legislation and concept definitions appear to be the reasons for these incongruences as well as the markedly different economic, social and cultural backgrounds of the listed countries (Park and Lah, 2018; Bolukbas and Akinci, 2018). Although for the USA, data collected in Table 1 does not mention specific locations, good agreement between the three datasets is achieved for the waste fractions. This is also observed in the Spanish data, which presents similar MSW characterizations although reported for different occasions and time-spans.

Usually, in developed metropolitan areas there is a variety of sectors with commercial, industrial, touristic and educational activities, whereas in districts far from cities the main activities are related to agriculture and forestry. These generate highly specific waste streams with their own characteristic MSW compositions (Bolukbas and Akinci, 2018). This is observed in Table 1 for instance in Turkey, where cities such as Ankara, Gaziantep, Sanliurfa and Tekirdag depict MSW compositions dissimilar to Izmir, for instance (Bolukbas and Akinci, 2018).

Major discrepancies are seen for the paper, metal and others fractions which range from 0.57% to almost 15%, 0.51% to 3.1% and 14% to nearly 40% respectively. Regarding the others share, high yields are seen for several locations in Turkey, India and China. Comparing to the other cited works, this fraction depicts higher values for locations such as Ankara, Bursa, Izmir, Hangzhou and Guiyang (apart from an unidentified city in India). This could be related to the methodology utilized by the authors to describe the waste composition (for instance accounting categories such as textiles and wood in the others category) or even to other geophysical and socio-economical patterns. Also, the climatic conditions can interfere with MSW characteristics such as moisture content, type and yield of biodegradables (Ioornweg and Bhada-Tata, 2012). In the case of India, the two cities Mavalipuru and Bangalore, despite being close to each other, present contrasting MSW compositions. Additionally, the type of recycling or sorting facilities available in situ influences the MSW fraction as if the population is not provided with the appropriate containers to separate different waste elements, they will mostly end up in the MSW segment (or even in open-air dumping sites).

Chand Malav et al. (Chand Malav et al., 2020) assessed the differences in MSW composition depending on the population range, interesting trends being seen: the higher the number of inhabitants, the higher the paper fraction (roughly 3% in population lower than 0.5 million people to approximately 6.5% for a population of 5 million inhabitants or higher), as well as the metal share (0.33% to 0.80% for the same population ranges). Oppositely rubber, leather and synthetic fractions decrease from 0.8% to less than 0.3% in the same population range, while glass follows the same trend although the decrease pace is lower. The compostable matter also depicts a noticeable drop, except when the 2.0–5.0 million inhabitants range is considered (more than 56.5% of the share being seen).

Relative to the waste characterization along the years, a very interesting study is presented by Diaz-Farina et al. (Diaz-Farina et al., 2020), who evaluated the streams of recyclable waste from 2004 to 2015 in Tenerife, Spain. The authors show that while mixed waste has decreased from 95% to roughly 90%, glass has evolved to greater fractions (1% to roughly 3.5%) as well as paper and cardboard (0 to 2%). Light packaging has also shown increasing tendency (0 to 1.5%), whereas the “others” fraction has varied between 4% and 5.5%. Tenerife is a very touristic island and therefore, seasonality effects may contribute to a diverse composition. This can sometimes lead to mismanagement practices, if an over-capacity in the treatment facilities exists. In fact, the utilization of waste management options such as the WIE could profit from this surplus, generating more energy which
becomes available for the highly demanding nowadays’ society.

More recently, the actual pandemic situation that the world is facing due to SARS-COV 2 has led to changes in municipal waste characterization, namely due to the higher amounts of residues such as disposable face masks, rubber gloves and paper tissues (both from medical waste surge and household waste) (Kulkarni and Anantharama, 2020).

Waste management practices and collection routes have also been adapted in developed and developing countries, in order to avoid or reduce potential contamination and spread. The Asian development bank has underlined the need for new waste management infrastructures, as landfilling is still one of the most common management options in some countries (Kulkarni, 2020). Developed countries have

| Country          | Location          | Organic | Paper | Plastics | Metal | Glass | Textiles | Wood | Others |
|------------------|-------------------|---------|-------|----------|-------|-------|----------|------|--------|
| Greece           | Attica            | 43.5    | 29.3  | 3.4      | 13.0  | 3.3   | 4.2      | 3.3  | -      |
| Germany          | –                 | 48      | 20    | 8        | 4     | 5     | 6        | –    | -      |
| Italy            | –                 | 30      | 24    | 13       | 1     | 10    | 4        | 18   | -      |
| Singapore        | –                 | 31      | 24    | 11       | 4     | 8     | 5.5      | 16.5 | -      |
| Iraq             | –                 | 44.4    | 28.3  | 11.8     | 4.8   | 4.1   | -        | -    | 12     |
| Tunisia          | –                 | 55      | 7     | 25.2     | 3     | 2.9   | 4.5      | -    | 2.4    |
| Turkey           | Ankara            | 68      | 9     | 11       | 4     | 2     | -        | -    | 6      |
|                 | Bursa             | 55      | 0.57  | 4        | 0.51  | 0.55  | –        | 39.37| -      |
|                  | Eskisehir         | 43      | 7     | 19       | 1     | 4     | –        | -    | 26     |
|                  | Erzurum           | 56.4    | 8.9   | 12       | 1.5   | 9.97  | –        | 3.33 | 7.9    |
|                  | Gaziantep         | 44.45   | 14.81 | 11.48    | 2.6   | 3.7   | –        | -    | 22.96  |
|                  | Sariyer奖项       | 69      | 5.44  | 15.74    | 0.79  | 2.02  | –        | 7.01 | -      |
|                  | Tekirdag          | 55      | 3.8   | 10       | 3.1   | 2.9   | –        | -    | 28.2   |
| India            | –                 | 35      | 3     | 2        | –     | 1     | 6        | –    | 59     |
|                  | –                 | 51      | 7     | 10       | –     | –     | –        | –    | 32     |
|                  | Mavallipura       | –       | 22    | 35       | 17    | –     | –        | –    | 10     |
|                  | Kharagpur         | 80.0    | 7.70  | 8.60     | 0.00  | 0.50  | 3.0      | –    | 0.02   |
|                  | Bangalore         | 84      | 12    | –        | 1     | 1     | –        | –    | 2      |
|                  | –                 | 84      | 12    | 9        | 4     | 1     | –        | –    | 2      |
| Republic of Haitian | Cape Haitian   | 65.6    | 9.0   | 9.2      | 2.6   | 5.8   | –        | 7.9  | -      |
|                  | –                 | 62      | 3     | 2        | –     | 5     | 1        | 3    | –      |
|                  | –                 | 69.3    | 10.3  | 9.8      | 0.8   | 0.6   | 1.3      | 2.7  | –      |
|                  | –                 | 51.83   | 5.43  | 8.59     | 2.29  | 11.6  | 10.55    | –    | –      |
|                  | –                 | 60.97   | 5.39  | 17.54    | 4.31  | 2.43  | 8.36     | –    | –      |
|                  | –                 | 58.19   | 3.68  | 7.63     | 2.23  | 1.20  | 27.07    | –    | –      |
|                  | –                 | 41.97   | 7.96  | 7.46     | 1.21  | 0.45  | 40.95    | –    | –      |
|                  | –                 | 61.67   | 9.43  | 4.1      | 1.06  | 11.43 | 16.41    | –    | –      |
|                  | –                 | 67.60   | 5.30  | 1.4      | 0.60  | 4.00  | 22.50    | –    | –      |
|                  | –                 | 52      | 3.8   | 10       | 3.1   | 2.9   | –        | -    | 28.2   |
|                  | –                 | 53      | 3     | 2        | –     | 1     | 6        | –    | 59     |
|                  | –                 | 51      | 7     | 10       | –     | –     | –        | –    | 32     |
|                  | –                 | 52      | 3.8   | 10       | 3.1   | 2.9   | –        | -    | 28.2   |
| Bangladesh       | Chittagong        | 62      | 3     | 2        | –     | 5     | 1        | 3    | –      |
|                  | –                 | 69.3    | 10.3  | 9.8      | 0.8   | 0.6   | 1.3      | 2.7  | –      |
|                  | –                 | 51.83   | 5.43  | 8.59     | 2.29  | 11.6  | 10.55    | –    | –      |
|                  | –                 | 60.97   | 5.39  | 17.54    | 4.31  | 2.43  | 8.36     | –    | –      |
|                  | –                 | 58.19   | 3.68  | 7.63     | 2.23  | 1.20  | 27.07    | –    | –      |
|                  | –                 | 41.97   | 7.96  | 7.46     | 1.21  | 0.45  | 40.95    | –    | –      |
|                  | –                 | 61.67   | 9.43  | 4.1      | 1.06  | 11.43 | 16.41    | –    | –      |
|                  | –                 | 67.60   | 5.30  | 1.4      | 0.60  | 4.00  | 22.50    | –    | –      |
|                  | –                 | 52      | 3.8   | 10       | 3.1   | 2.9   | –        | -    | 28.2   |

Table 1 Municipal solid waste composition in selected global locations.
adopted different strategies, for instance the UK now prioritizes the collection of selected waste categories (DEFRA, 2020), some cities in the USA have stopped recycling programmes (Zambrano-Monserrate et al., 2020), while Singapore has reduced the frequency of recyclables’ collection (Singapore, N.E.A., 2020). In these cases, thermal treatments could also provide benefits whereas in developing countries these are rarely applied (Mayer et al., 2019).

1.2. Energy production and urban patterns of utilization

"Urban metabolism" is a concept that first appeared in 1965 (Wolman, 1965), and has received increasing attention up to the present (Zhang et al., 2015b; Pincetl et al., 2012). It may be defined as a tool to analyse the city functionalities, assessing its environmental impacts while depicting the mutual influences among urban and rural areas (Minx et al., 2011). The environmental aspects of urban metabolism are assessed by means of different tools as LCA (Braulio-Gonzalo et al., 2015; Zhang, 2013; Baynes and Wiedmann, 2012; Ascione et al., 2008), directly contributing to the "urban quality" (Garau and Pavan, 2018).

According to the International Energy Agency (Agency, I.E., 2015), roughly 80% of world’s total primary energy supply originates from fossil fuels, with high CO₂ emissions (Agency, I.E., 2015). Together with the fact that renewable sources still make only a small contribution in energy production, there is an urgent need to develop alternative WtE techniques. Fig. 1 presents world energy data (Agency, I.E, 2015) and energy generating capacity from MSW over the last decades (OECD/IEA, 2018).

Considering MSW to be included in the ‘other’ share, it is clear that its use in the energy production sector is still low (< 6% share). Nevertheless, the total share of electricity produced from MSW has grown more than 200% since 2000 (OECD/IEA, 2018). This is probably due to the increased number of thermalisation plants implemented over time and to the higher synthetic fraction gradually seen on waste, namely plastics, artificial fabrics and complex polymer mixtures typically characterizing urban MSW. Also, the fact that population characterizes urban MSW. Also, the fact that population efficiency (Ciuta et al., 2015; Vehlow, 2007; Ascione et al., 2009).

Countries such as China (Zheng et al., 2014) and the USA (Park and Lah, 2018; Hoornweg and Bhada-Tata, 2012) that were responsible for a large share of MSW generation, energy consumption and CO₂ emissions, accounted for half the increase in renewable-based electricity production, while the EU, Japan and India represent a combined growth of 20% (OECD/IEA, 2018). Data in Fig. 2 presents the global contribution of each sector to the energy consumption.

The chief sectors for energy consumption are transport, manufacturing, residential uses and services (Dor and Kissinger, 2017). The USA leads the transport sector due to its massive dependence on private motor vehicles and domestic air travel, as compared to more efficient modes of travelling such as buses and trains used in most of the European countries. The manufacturing sector is mostly dependent on the major types of industries but overall, the energy consumption intensity decreased around 40% since 2000. This is due to the increased operational efficiency of major industrial facilities and to the use of low carbon energy options.

In the residential utilization, heating ranks first, followed by lighting and electrical appliances. Countries such as the Netherlands, Portugal, Germany and Ireland show consumption drops of over 35% since 2000, once they have adopted the heating requirements and incorporated building features consistent with desired comfort levels and efficiency (OECD/IEA, 2018). A recent publication on the environmental performance of the urban territory for a Portuguese city identified similar sectors as hotspots in terms of climate change and fossil fuels depletion (Dias et al., 2018). The authors report a total input of almost 50.000 ton/capita/year (82% referring to water, 12% to construction materials, 3% to energy, 2% to eating habits and 1% to other products). These inputs generated outputs of the order of roughly 35.000 ton/capita/year of wastewater and 750 kg/capita/year of solid waste. Results show more than 8.400 ton/capita/year of CO₂-equivalent for climate change and almost 2.400 toe/capita/year for fossil fuels depletion (Dias et al., 2018), in agreement with other European countries/cities (Ciuta et al., 2015; Vehlow, 2007; Ascione et al., 2009).

2. Material and methods

In order to assess the environmental impacts displayed by MSW treatment under the three WtE techniques considered in the present study, a life cycle inventory (LCI) for each of them was developed. Data modelling was achieved with product sustainability software GaBi (database version 4.131 distributed by PE International) (Stuttgart, 1992–2016), the environmental performance being evaluated through the calculation of eleven different impact categories using CML 2001 methodology and according to ISO 14040:2006 (ISO, 2006). The characterization factors for CML 2001 are the most utilized for the considered impact categories, as reported elsewhere (Chevalier et al., 2011; Rosado et al., 2019). The MSW sample for this case study was provided by an industrial partner, within the framework of a joint work towards the development of new strategies for the company.

2.1. Scope, system boundaries and functional unit

The scope of the present study was the analysis of the environmental impacts caused by incineration, regular gasification and plasma gasification of MSW. Fig. 3 describes the limits of each system, dashed blue lines indicating the boundaries. Coloured boxes represent the processes, connected by flows (arrows). MSW was considered an input as received.
at the plant, its origin, collection and transport to the thermal treatment facilities being excluded from the boundaries of the system. Also excluded were metallic scrap regeneration (in the case of incineration and gasification) and the vitrified sub-product (in the case of plasma gasification). The power generated from each WtE replaced the electricity from the grid, in an auto-consumption mode, this indicated by the green route (electricity flow). The slashed green arrows stand for the seldom occasions where electricity from the grid is used to start the system, after maintenance or shut down periods. For the gasification schemes, decomposition was performed using a bubbling fluidised bed in the presence of oxidizing agents (oxygen and steam).

The functional unit (fu) was defined as the thermal treatment of 1 t of MSW, its characterization being shown in Table 2. Further information on the experimental conditions is described in (Ramos et al., 2018b; Ramos et al., 2018c; Ramos et al., 2019b).
2.2. Life cycle inventory

Data such as material flows, energy requirements and emissions for each process within the system boundaries are compiled and then adapted and dimensioned to the functional unit. LCI enables the calculation of balances between specific inputs and outputs, based on the main operational data for each technique (ISO, 2006).

As seen from Fig. 3, major processes may be considered for each of the WtE methodologies, namely the purple, golden and orange boxes for incineration, gasification and plasma gasification, respectively, and also the landfill process (common to all). These are focal stages where inputs and outputs need to be carefully accounted to assure robust environmental results. All the methodologies utilize auxiliary materials, the complete LCI being available in the Supplementary Material.

3. Results and discussion

3.1. Environmental impacts

Table 3 shows the environmental results for the impact categories. Positive values mean harmful impacts (grieving natural resources or emission of contaminants), while negative values represent environmental savings concerning the emission of heavy metals are also achieved by the two-stage plasma process. In the case of MAETP, the most prevented hazard is the emission of inorganic substances such as HF, both in incineration and plasma gasification, due to electricity production and flue gas treatment, corroborated by (Passarini et al., 2014). Incineration results for MAETP are superior to those reported elsewhere (Toniolo et al., 2014). Referring to TETP, a contribution of approximately 60% from incineration and nearly 30% from plasma gasification is seen. Regarding incineration, the avoided heavy metals in agricultural soil is the most featured impact, although literature reports lower efficiencies (Liamsanguan and Gheewala, 2008).

In two-stage plasma gasification, electricity production is the major contributor to the overall results as seen in (Evangelisti et al., 2015b), 382 MJ being produced per functional unit. ADPelements generates a 65% contribution from incineration and only 20% from plasma gasification. Incineration produces savings in resources such as copper, gold, lead and molybdenum due to the electricity production (Passarini et al., 2014), while plasma gasification results in the saving of mineral salts such as sodium chloride. FAETP shows 80% contribution from incineration and roughly 20% share from plasma. This is attributed to the avoided emission of heavy metals into freshwater and air as a result of landfill process in incineration and plasma stage in plasma gasification. Both incineration and two-stage plasma gasification depict enhanced results when compared to literature (Evangelisti et al., 2015a; Toniolo et al., 2014), respectively. Regarding TETP, a contribution of approximately 60% from incineration and nearly 30% from plasma gasification is seen. Regarding incineration, the avoided heavy metals in agricultural soil is the most featured impact, although literature reports lower efficiencies (Toniolo et al., 2014). Besides agricultural soil, major environmental savings concerning the emission of heavy metals are also achieved by the two-stage plasma process. In the case of MAETP, the most prevented hazard is the emission of inorganic substances such as HF, both in incineration and plasma gasification, due to electricity production and flue gas treatment, corroborated by (Passarini et al., 2014).
3.2. Environmental performance

Fig. 5 provides a comparison between the assessed WtE with respect to resources and emissions. As an overall observation, it may be said that material resources, energy resources and emissions to fresh water are the major outcomes from the assessed WtE techniques, especially from incineration and two-stage plasma gasification.

As mentioned previously, regular gasification globally depicts a hazardous environmental profile (saving more than 240 t of emissions per tonne of treated waste), only minor credits being shown related to the emissions to industrial soil (saving nearly 1 kg of emissions per functional unit). Both incineration and plasma gasification constitute more sustainable options, saving up more than 500 t of resources and emissions per functional unit. Incineration saves 295 t of material resources and 291 t of emissions to fresh water, while two-stage plasma gasification saves up to 264 t of energy resources, 130 t of material resources and similar amount of emissions to fresh water as main flows.

Evangelisti et al. (Evangelisti et al., 2015b) also report on the overall excellent performance of a two-stage plasma gasification treatment for MSW, considered an improved environmental solution when compared to other available technologies. The authors argued that the electricity produced in a two-stage plasma gasification facility is generated from the combustion of a high-quality syngas which affords a high temperature gas which then supplies a gas engine, whereas the flue gas resulting from the combustion process in incineration generates steam, which is afterwards employed in a steam turbine to produce electricity, with lower levels of efficiency (Rutberg, 2011). Another possible reason accounting for the upgraded environmental performance of two-stage plasma gasification may be the lower air pollution emissions and even less landfill requirements result from lower levels of gas produced.

Moreover, plasma gasification occurs in a sub-stoichiometric oxygen atmosphere resulting in lower CO₂ emissions than for incineration (Zaman, 2013). This oxygen-starved situation promotes lower gas yields than incineration, which maximizes the cleaning process (Helsen and Bosmans, 2010). Furthermore, less off-gas emissions and even less landfill requirements result from lower levels of gas produced.

3.3. Waste generated vs electrical demand

Our current understanding of the possible waste management scenarios available at urban, regional or even national scales has increased social awareness of the importance of renewable energy technologies (Wüstenhagen et al., 2007). A compilation of surveys relating to the social acceptance of low carbon energy and associated infrastructures was reported by Batel et al. (Batel et al., 2013), noting the importance of public responses towards the development of the relationship between the communities and the new treatment facilities, their operation and the decision-making process, as discussed in (Harris and Spickett, 2011; Weibler et al., 1995). In order to attract the interest and acceptance of large audiences, apart from the environmental arguments, even more convincing facts must be used, a worthwhile approach relating the amount of energy used and the yield of waste produced per capita.
Considering the average yield of waste and electric consumption per capita, it is possible to estimate the share of energy potentially produced from the waste generated per person. As there are few LCIs available for MSW samples and for the assessed techniques, an extrapolation of the electricity produced from the MSW amount generated in several parts of the world was conducted using the characterization in Table 2. This is a feasible approach as the MSW sample resembles the average global composition (Hoornweg and Bhada-Tata, 2012). Table 4 depicts the results achieved applying the WtE electrical efficiencies (further details may be found in Supplementary Material) with respect to different geographical regions.

Table 4 suggests that, assuming no losses in conversion efficiency and no significant changes in MSW composition, if the MSW generated by each person was thermally converted into energy and afterwards used as electricity, a high proportion of the daily electrical consumption per capita would be achieved. Depending on the world region and its “urban metabolism”, the thermal treatment of the daily waste produced by a citizen could afford 4% to 41% of the electricity consumed daily by that same citizen. In fact, two-stage plasma gasification enables higher electricity production, followed by the regular gasification and incineration. This is in line with the expected based on the efficiency comparison depicted in Supplementary Material.

The highest contribution to the electricity replacement is seen for Sub-Saharan Africa, where despite the fact that both the electricity consumption and the waste production are reduced compared to all evaluated geographic regions, the ratio between these two parameters is the lowest. Conversely, in Europe and Central Asia both the electricity consumption and the average waste production are very high but the ratio between them is not so favourable: 1.1 kg of waste is produced per capita and almost 15 kWh are required to fulfill the electrical demand. This promotes the lowest contribution to the electrical demand per capita (3% to 6%).

From the regions assessed, OECD countries are the ones where more MSW is produced per capita and more electricity is required to maintain the standard way of living. Compared to the world average situation, OECD produces one additional kg of MSW and requires almost 2.5 times the electricity per capita, and only 5% to 8% of the electrical needs are covered using the MSW generated. The Middle East and North Africa regions are closest to the world average in terms of waste generation and electrical demand, a contribution of 6% to 12% being achieved for the electricity production.

Fig. 6 presents the relation between the electricity use and the waste production for the same regions. Socio-economic correlations may be potentially inferred for the diverse world areas, regarding population habits and regional trends. Therefore, the relation between the electricity consumed and the waste produced may be suggested as a possible approach for evaluating the level of development of a country/community/society. Higher income countries are seen to produce more waste and to require more energy on a daily basis, which is consistent with a society with superior economies and standards of living, while for lower income countries the electrical requirements are more easily achieved and the level of waste production is significantly lower (Hoornweg and Bhada-Tata, 2012). As most of the nowadays’ commodities depend on electric power, the social welfare is herein implied and an indicator such as the ratio of electricity consumed per waste generated might serve as a basis for strategic development of waste management options or electrical grid planning.

### 3.4. Life cycle cost assessment

Table 5 depicts the operational costs associated with the main allocations for each waste treatment technique, per functional unit. The results presented are dependent on the economic panorama and the renewable energy sector data among others (Ouda et al., 2016;...
Martinez-Sanchez et al., 2017), once the buoyancy of some related factors such as currency valorisation, bioenergy market share and inflation rate, dramatically affect the electricity production and the final revenue (Leme et al., 2014; Li et al., 2016).

As may be seen from Table 5, both incineration and plasma gasification present positive net results, meaning that the treatment of the urban residues leads to profits. In fact, although the waste management costs are significantly higher in the case of incineration (representing more than 58% of the total costs) when compared to regular gasification, the later shows maintenance costs 7.5 times higher (accounting for 90% of the total costs) than the previous. Literature on waste management LCC has previously shown that operation and management costs are usually accounted as one of the chief costs in the process (Leme et al., 2014). The economy of scale is also a factor to take into account when performing the LCC of a defined WtE technique, improved economic performance being seen for incinerators serving wider populations (Leme et al., 2014). Also, both regular and plasma gasification present high revenues when compared to incineration. Nevertheless, the cost differences among these two options reveal major profits for two-stage plasma gasification.

Due to the scarcity of LCC assessments for waste management techniques, as well as to the distinct scopes, functional units and system boundaries reported, only approximate comparisons of the results achieved in this study to literature data are accomplished. Nevertheless, taking into account the respective currency exchange, the costs herein presented for plasma gasification are lower than reported for a similar plant scale, and the revenues achieved are higher than expected (Ramos and Rouboa, 2018; Ducharme, 2010). Plasma gasification has been previously reported as a promising WtE with the possibility to maximise its economic benefits if by-products such as the vitrified slag are also commercialized (Danthurebandara et al., 2015). As far as regular gasification is concerned, although the net result in the present study is negative (meaning no profit) the revenues afforded are 3.5 times higher than reported elsewhere (Cardoso et al., 2019). This means that if costs are optimized (especially the operation and management expenses) and the whole system is suitably managed, regular gasification may potentially become an economically feasible treatment technique. Regarding incineration, the net results are positive which means it is profitable, although in a lesser extension than plasma gasification. Nevertheless, when compared to other waste management techniques more widely used in developing economies, incineration within a properly designed integrated system is suggested as an advanced option assuring enhanced results (Menikpura et al., 2016).

In a broader sense, considering also other social aspects that are difficult to include in LCC such as the cost of human health damage or community discomfort, the herein presented approach should be mainly viewed as a comparative tool. In other words, the LCC conducted in this study should serve only as an indicator of damage costs and not as a definitive estimate.

4. Conclusions

The LCA of one tonne of MSW was conducted for incineration, regular gasification and two-stage plasma gasification. Regular

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**Table 5**

| Costs and revenues | Incineration | Regular gasification | Plasma gasification |
|--------------------|-------------|----------------------|---------------------|
|                    | €/tMSW | % | €/tMSW | % | €/tMSW | % |
| Staff              | 2.30  | 3.3 | 2.30  | 1.7 | 2.30  | 3.9 |
| Energy             | 7.35  | 10.5| 5.84  | 4.2 | 7.79  | 13.3|
| Operation & Maintenance | 19.69 | 28.1| 125.50 | 90.0| 43.18 | 73.7|
| Waste management   | 40.65 | 58.1| 5.78  | 4.1 | 5.35  | 9.1 |
| Total costs        | 69.99 | 100| 139.42 | 100| 58.62 | 100|
| Revenues           | 87.77 | –  | 122.50 | –  | 127.89 | –  |
| Net Result         | 17.78 | –  | – 16.92 | –  | 69.27 | –  |

Lines in bold present the main value the readers will be looking for when observing this table (total costs and net results for each technique).
gasification presented environmental burdens for some impact categories, however yielding excellent results for EP, AP, MAETP and HTTP. Incineration and two-stage plasma gasification presented negative values for all the impact categories, signifying environmental benefits. This represents an increase in the wellbeing of the exposed populations and a higher degree of sustainability.

An estimate of the % of electricity that could be produced from the waste generated per capita in the world was conducted. High contributions were seen for Sub-Saharan Africa and South Asia due to the lower electrical demand, whereas OECD countries were seen to surpass the world average waste production and the electrical requirement per capita. Thus, the renewable energy potentially achieved from the thermal conversion of MSW through the WtE herein studied would enable the reduction of greenhouse gases as well as the fossil fuels-based energy consumption, enhancing society’s life quality. Plasma gasification depicts an outstanding performance both in the environmental assessment as well as in the electricity generation capacity, combining two of the most important aspects for the enforcement of sustainability.

As far as the LCC assessment is concerned, two-stage plasma gasification depicts the best results in terms of revenues, 1 t of MSW delivering a net profit of 69.27 €. Incineration shows significantly lower income, while regular gasification has higher costs than revenues showing a negative net result. This supports plasma gasification as an economically feasible technique for the treatment of urban residues, within the system boundaries utilized in the present study. However, these results should not be taken as strict or immutable, as many factors can contribute to reach different values or conclusions, for instance the time value of money.

The current case study provides a critical analysis of the advantages and disadvantages of three different WtE technologies and thus is able to contribute to the decision process at a regional or national level. Sustainability is made a priority and key perspectives (technical, social and environmental) are seen as critical elements that form a base of integrated knowledge in favor of renewable and sustainable energy solutions with direct benefits to the environment and human health. In the herein reported case study, two-stage plasma gasification affords significantly important results in these three pillars as well as in the economic perspective, therefore representing an interesting option to possibly replace or complement the utilization of fossil fuels.

Nevertheless, some limitations may hinder the results of this study. One is the fact that it is difficult to achieve LCI for different MSW treatment options, especially if they are used in industrial-scale. Therefore, some assumptions had to be used such as extrapolating the electricity produced from the MSW generated per capita in several parts of the world using the MSW sample presented in this study, instead of being able to apply the respective MSW characterization for the defined location. Another limitation concerns the electricity grid which, depending on location, might present different composition in terms of fossil and renewable share of fuels. This will enable distinct results in the electricity production, leading to diverse % of electricity covered by the production from MSW as well as different economic results. In countries where the renewable energy shares are already high, the consequences of producing energy from MSW will be less significant than in places where the fossil fuels are the major source for power production. As future perspectives, these aspects could have a deeper look so as to achieve more precise electrical shares according to the MSW sample thermally treated to produce the energy. At a later stage, accounting for a complete inventory of the capital costs (own investment, borrowed capital, depreciation rate, etc.) as well as considering other externality costs will also aid at performing a more accurate life cycle cost for each of the techniques, complementing the sound LCA conclusions.

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Author statement

Ana Ramos conceived, designed and performed the experimental work, analyzed the data and wrote the paper. Abel Rouboa supervised the whole work.

Conceptualization: Ana Ramos; Methodology: Ana Ramos; Supervision: Abel Rouboa; Writing—original draft: Ana Ramos.

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.

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