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Development of a methodology to assess the footprint of wastes

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ABSTRACT

The ecological footprint (EF) is a widely used indicator to assess the sustainability of people, regions or business activities. Although this metric has grown in interest and popularity over the years, it has also been the subject of criticism and controversy. The advantages of an aggregated indicator are often overshadowed by the shortcomings of its corresponding methodology. One weakness of the EF is that it does not account for toxic or hazardous pollutants and wastes, which cannot be part of a closed biological cycle. The methodology developed in the present work estimates the EF of toxic and hazardous wastes considering a closed cycle modeled through a plasma process; a phenomenon that naturally occurs in stars and volcanoes. Wastes from industry can be treated in a thermal plasma gasification process, and, by developing a methodology to describe this process, the EF of hazardous wastes was calculated. A value of 56.5 gha was obtained, a figure on the same order of magnitude as that obtained in a previous study where a conventional ecological footprint methodology was applied to the same production process.

1. Introduction

The need to report environmental behavior, for both legal and ethical reasons, has led to the proliferation of a wide variety of indicators in recent years. The ecological footprint (EF) is one of the most popular [1] indicators among those that use territorial or natural resource units (namely, ghost acreage, environmental space, ecological rucksack, energy analysis and water footprint). The EF is a sustainability indicator that estimates the amount of bioproductive land required to produce resources and absorb wastes in a given system. In recent years, the EF has been applied in a variety of fields, i.e., policy-making, production processes, environmental evaluations and research projects [2–4]. The European Union (EU) is considering the use of this metric to measure the sustainability of natural resources [5]. However, shortcomings in the methodology behind the EF calculations have been reported, and there is a need for further improvement before the EF can provide a reliable global assessment [6]. Thus, despite its heightened popularity in recent years, the EF has been the subject of criticism and controversy [7–11]. As such, new and alternative EF methodologies continue to be studied by various authors [4,12–14]. These contributions, such as the one proposed here, will help to improve the appraisals obtained by the EF, although it will not perfect them. In the meanwhile, the indicator must be used cautiously; one must remain aware of the limitations implicit in the estimates, but also take advantage of its integrated nature.

1.1. Closed biological cycles in EF calculations

Given that EF calculations only account for materials with an implicit biological productivity (for resources) or absorption rate (for wastes), there are many consumption inputs and pollutant outputs that are excluded from such estimations. This means that, for example, materials, such as plastics, that are neither created by biological processes nor absorbed by biological systems do not have an EF [15]. In some cases, however, there may be a specific assimilation rate, as for acidification emissions [3,16], but including such factors could result in an over-estimation of the EF. Hence, when pollutants are considered to have an insignificant assimilation capacity in the biosphere, they are discarded from the EF calculations [17]. Consequently, the EF should be considered as an indicator of minimum criteria [11], i.e., if the calculated area (assuming and acknowledging underestimation) exceeds the available carrying capacity, then unsustainability is ensured. Otherwise, other factors that can degrade natural resources should be assessed.

Particular analyses must deal with global warming emissions. Generally, only CO_2 emissions are computed in EF estimations. For CO_2 emissions, a sufficiently accurate method is available for calculating the land area required to absorb them, but this is not the case for the other greenhouse gases [5]. Yet, the carbon footprint aggregates various global warming emissions and expresses them as carbon dioxide equivalents; for a full EF calculation, this data is translated into the area required to absorb these carbon emissions in units of global hectares [15]. This approach implies that CO_2 absorption rates are the same as the other greenhouse gases, such as CH_4 or N_2O. Calculating CH_4 emissions based on their global warming potential (GWP) would produce significantly

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different results than if a mass carbon transformation was considered. Hence, methane, which has a GWP factor that is 25 times that of CO_2, does not necessarily require 25 times the land area to sequester its carbon content [18].

Eder and Narodoslawsky [19] proposed an indicator called the dissipation area index (DAI), which was designed as a tool for evaluating the flow of material from the technosphere to the biosphere. Given its strong relation to land occupation, the DAI is considered as a type of ecological footprint; in fact, it is an improvement on the EF methodology [4]. The biosphere can only absorb limited output flows from the technosphere without suffering irreversible damage. Employing this assimilation capacity concept, previous reports calculated the dissipation area from the natural concentration of the substance in soil and the rate of soil replenishment. Thus, a number of dissipation areas are available for chemicals such as nitric oxides and lead in air and nitrates and copper in water [19].

Kitzes and Wackernagel [15] distinguish between the EF of a toxic material and the lifecycle EF stemming of the other biological materials extracted from the biosphere for the toxic material's production, and claim that these two concepts are often confused. Thus, from a lifecycle perspective, apart from the EF associated to the extraction of the original biological materials, other impacts like the carbon fossil emissions released during the production process or the physical area where the plant is built have to be considered. On the other hand, one can also consider the embodied energy, which is the energy used during a product's entire lifecycle in order to manufacture, transport, use and dispose of the product [17]. This concept is used in EF calculations to convert manufactured goods into their energy equivalents, using the best data available on the energy intensity of various goods. This lifecycle-based perspective is used for EF component approaches [20].

The development of new methods to incorporate traditionally excluded issues into EF appraisals is a result of the need to construct a better composite indicator. This means that while it is not plausible to assume the same EF levels for nuclear energy as for fossil fuels, it is also not accurate to exclude nuclear EFs in national footprint accounts, which could lead to the misinterpretation that nuclear powered countries necessarily have a higher ecological performance [5,20]. A proposal to improve the EF of nuclear energy was made by Stoeglehner et al. [21]; from a lifecycle perspective, the authors considered the area associated with uranium mining, nuclear power plant accidents, nuclear transport and nuclear disposal. Even for an underestimation scenario, the footprint per energy was more than five times of that used in the initial EF estimations.

Wastes from industry can be treated in a thermal plasma gasification process, a phenomenon that naturally occurs in stars and volcanoes as well. The methodology developed in the present work estimates the EF of toxic and hazardous wastes by closing their biosphere cycle and considering their transformation in a plasma process.

1.2. Thermal plasma technology fundamentals

Thermal plasma technology, which emerged in the Nineties, has received a great deal of interest for its ability to treat mixed forms of waste. It can be applied to solids, liquids or gases. Because high temperatures can be reached, it can be used for different applications, such as the destruction of organics or the vitrification of hazardous waste [22]. Thus, plasma treatment is ideally suited for toxic wastes and complex waste streams that have recoverable energy content. The high temperature of the plasma arc greatly reduces the amount of undesirable by-products that are generated [23].

A simultaneous dual reaction process takes place in a plasma reactor: the organic compounds are thermally decomposed into their constituent elements (syngas with more complete and advantageous conversion of carbon into gas than in incinerators), while the inorganic materials are melted and converted into a dense, inert and nonleachable vitrified slag, which does not require controlled disposal (Fig. 1). Therefore, it can be viewed as a totally closed treatment system [24].

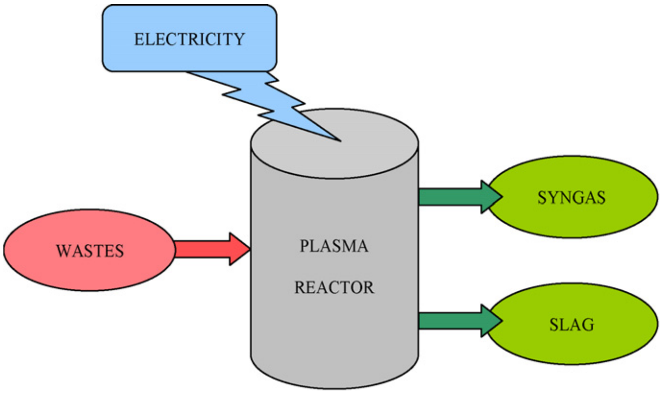

Fig. 1. A simplified scheme of the plasma technology process, indicating the main inputs and outputs.

Syngas (mainly composed of CO and H_2) can be used to generate electrical power and produce valuable hydro-carbonic acids. Vitrification is the result of the interaction between the plasma and inorganic materials. Because the inert fraction is vitrified and harmful substances can barely leach from the lava, this product can be used for road construction or as a building material [24]. In addition, plasma can induce the thermal decomposition of toxic molecules into simpler ones that are benign (e.g., the CN molecule can be broken down into the elements C and N).

The application of this kind of technology to the treatment of hazardous wastes has been explored by different authors, and prior research includes studies on steel plant dust [25], nuclear waste [26], hazardous medical waste [22,27], tannery waste [28] and organic wastes [29].

1.3. Aim of the present study

A closed cycle, generated by the application of thermal plasma technology into the biological cycle, was proposed so that the requirements for EF conversion could be accomplished. Thus, a methodology to assess the EF of wastes, including both hazardous and non-hazardous wastes, was developed on this premise. Nonetheless, this does not mean that plasma treatment was considered as a panacea to deal with waste management problems; however, it was employed as a closed cycle model for methodological purposes.

2. Methodology

2.1. The application of plasma technology as a closed cycle model for calculating the EF of wastes

It was assumed that, in a simplified approach, the thermal plasma process closes the waste cycle in the biosphere due to the fact that the combusted syngas returns to the biosphere via CO_2 absorption in forests and oceans, and the vitrified material returns to the production cycle as new input material. Hence, three main factors were computed in the estimates (Fig. 2):

- The balance between the electricity consumed by the process (waste pre-treatment, plasma torching and syngas cleaning) and the energy generated in the combined cycle.

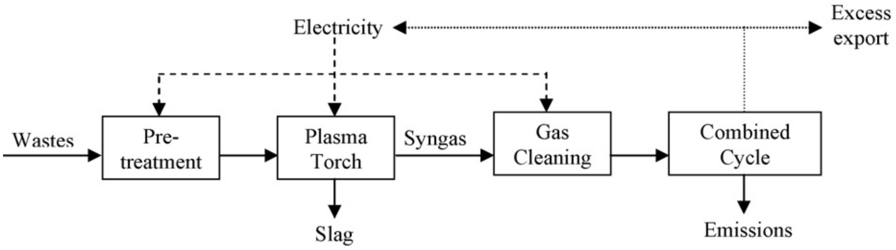

Fig. 2. The operational units used in the thermal plasma process and their implications for the EF estimate.

- Carbon emissions in the combined cycle, which are a result of the syngas combustion.
- The counter-footprint associated with the recovery of inorganic material in the slag, avoiding the extraction and manufacture of new raw materials.

In addition, the area occupied by the process itself was considered to be built land. However, due to the scarcity of data found in the literature on this topic, this term was not included, avoiding a major level of uncertainty in the calculations. The possible contribution of this factor is discussed below.

2.2. Correlations

Using data from the literature about input and output flows in thermal plasma treatments of different kinds of wastes, correlation functions were established between the consumption and generation flows of the process and the carbon-content percentage, which was selected as characteristic parameter of the waste. SPSS Statistics 17.0® software was used for this purpose, as well as for conducting a statistical analysis of the correlations obtained to explore their significance and reliability.

The electricity consumed by the plasma torch and the auxiliary units used in the process were directly found in the literature for different kind of wastes; then, the carbon content was estimated and correlations were established. The literature provided data on the electricity generated in the combined cycle, but in some cases, it was necessary to estimate the electricity generated by syngas heating considering the efficiency of conversion in the combined cycle power plant.

The net electricity balance can be expressed as follows:

$$E_N = E_P + E_A - E_C \tag{1}$$

where E_N is the net external electricity demand (from a power supplier); E_P is the electricity consumed by the plasma torch; E_A is the electricity consumed by the auxiliary operational units; and E_C is the electricity generated in the combined cycle. All of these terms are expressed in relative units, that is, the energy per unit mass of waste treated. According to Eq. (1), if the electricity consumed by the plasma torch and the auxiliary units exceeds the electricity generation in the combined cycle, then a positive balance is obtained and external demand from a power supplier is required. Otherwise, for high energetic wastes, this balance may result in a negative net value, which indicates that a surplus of energy is generated and it can be exported (as contemplated in Fig. 2) [30].

The carbon emissions from the combined cycle depend on the composition of the syngas obtained in the plasma process. Generally, the predominant components are CO and H_2, but in some cases, the syngas can contain small quantities of CH_4. Thus, to calculate the total carbon emissions, three components were taken into account:

- The CO_2 produced via CO oxidation.
- The CO_2 produced via CH_4 oxidation.
- The CO_2 initially present in the syngas.

For the first two terms, a general oxidation factor of 0.995 for the gaseous fuels was used [31]. This means that the effect of the technology employed was also considered, apart from the carbon content in wastes.

Additionally, a correlation was obtained to express the slag production (per unit mass of waste treated) as a function of the carbon content of the wastes. This slag generated was directly reported in the literature for different kinds of wastes fed into the thermal plasma process.

2.3. EF estimation

Plasma technology allows for the recuperation of the energy contained in wastes. This is represented by a counter-footprint term in the electricity balance equation. The amount of energy consumed by the conversion process should also be taken into account. Hence, the first term of the EF estimation considered the transformation of the net electricity balance into units of area. In this case, the average electricity breakdown for Spain was considered (Fig. 3).

Even though the combustion of the syngas in the combined cycle implies external electricity demand savings, it also means that CO_2 emissions are released by the plant itself. The associated EF was measured by considering the area needed for the absorption of these emissions. An absorption rate of 1 tC/(ha yr) was used according to the Living Planet Reports. For the vitrified slag, the counter-footprint was calculated on the basis of the energy (fossil) saved, because there was no need to manufacture new raw materials (i.e., inert construction materials). This assumption implies that all the slag generated will be reused, and that, consequently, no surplus slag will be stored. However, this may be over-estimation of the counter-footprint assigned to this material given that the market may not absorb all of it. The conversion of all of these terms into EF units was carried out using a spreadsheet (Microsoft Excel®), in a manner similar to the method employed in a previous work [3].

The final EF of the wastes was calculated using the following equation:

$$EF_{wastes} = EF_{electricity} + EF_{carbon\_emissions} - CF_{slag} \tag{2}$$

where EF_{wastes} is the total EF estimated for the wastes; $EF_{electricity}$ is the contribution from the net electricity balance, which may result in a positive or negative term; $EF_{carbon\_emissions}$ is the area required to absorb the CO_2 released in the combined cycle; and CF_{slag} is the counter-footprint associated with the slag production.

3. Results and discussion

First, correlations among the parameters used in the EF calculation were determined using data from the literature. Once these equations were obtained, the final model of the EF estimation of wastes was constructed using Eq. (2).

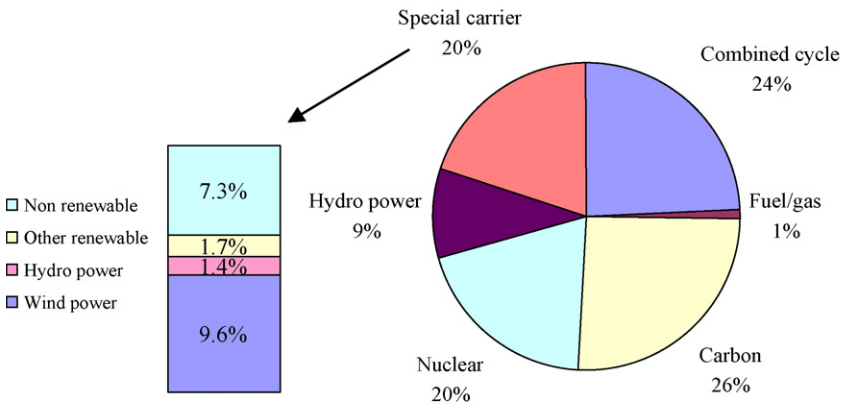

Fig. 3. Coverage of electricity demand in Spain in year 2007 [32].

3.1. Correlations

The correlations based on data found in the literature are presented in this section, which discusses the electricity consumption by the plasma torch, electricity generated by the combined cycle, carbon emissions and slag production. It was not possible to establish a correlation for the electricity consumption in the auxiliary operations because of a lack of data, which will be explained later. The wastes considered in this study were characterized by their carbon content, as presented in Table 1. In fact, higher carbon content means that more energy will be provided by the combined cycle power plant [33].

3.1.1. Electricity consumption by the plasma torch

To relate the electricity consumption to the carbon content, the data sets presented in Tables 1 and 2 were employed. This data were then converted into homogeneous units, which are shown in Fig. 4.

In Fig. 4, there is a data point that clearly does not follow the general trend. This data point corresponds to a series of industrial source data [43]; actually, for the same waste type (Refuse Derived Fuel – RDF), another industrial calculation [44] indicated a much smaller energy consumption. The other industrial values are found at the bottom of the figure and displaced from the general data trend as well. However, for the pilot plant series, a more homogeneous trend was observed; thus, it was decided to construct the correlation only using this data, which showed a good correspondence with the values from a theoretical simulation. Given the variability of data points, different types of functions were tested to obtain the most suitable correlation to fit the experimental data. After conducting a statistical analysis (see Section 3.1.6), an exponential correlation was preferred and Eq. (3) was obtained, which relates the electricity consumption per ton of waste treated to the carbon content of the wastes:

$$E_P = e^{0.026C} \tag{3}$$

where E_P is the electricity consumed by the plasma torch in units of GJ/t feed, and C is the carbon content of the wastes expressed as a percentage.

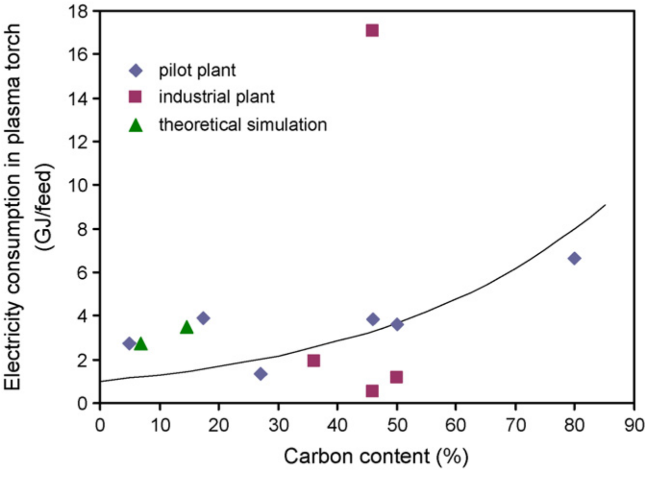

Fig. 4. Electricity consumption in the plasma torch as a function of carbon content in wastes.

3.1.2. Electricity consumption by the auxiliary operations

It was particularly difficult to find data on the consumption of electricity by the auxiliary operations (i.e., waste pre-treatment, which occurs before the wastes enter the plasma reactor and syngas cleaning). In fact, direct values for the plasma process were only available for two industrial scale applications; these values were 0.78 GJ/t feed [43] and 0.54 GJ/t feed [44].

Given the difference between these applications, the consistency of the data was verified using a comparison with an equivalent incineration process. The ancillary operations considered here include those required for waste pre-treatment processes, which were mainly size homogenization and water content conditioning as well as gas cleaning prior to combustion. Therefore, this part of the process was expected to be comparable for both of the thermal treatment processes. In the work by Grieco and Poggio [45], a power requirement of 2.45 MW for ancillary units was reported for a waste flow of 4.28 kg/s, which yielded an electricity consumption of 0.57 GJ/t. Meanwhile, the electricity necessary for RDF sorting was 0.051 MJ/t waste, according to Arena et al. [46]. Adding these values, the total electricity consumption is 0.621 GJ/t feed, which is on the same order of magnitude as plasma processes. Thus, an average value of 0.65 GJ/t feed was used in the spreadsheet.

3.1.3. Electricity generated by the combined cycle

In most reports in the literature, the syngas heating value and flow rates were indicated, while in a few references the direct value of the electricity generation was provided. All of the data that was collected is summarized in Table 3. The electricity values were converted into syngas heating values using the efficiency of conversion in the combined cycle power plant to represent these values in a homogeneous manner. Some references provided specific efficiency values of 26% [29], 34% [35], 40% [43], and 42% [44]. When a particular efficiency was not specified a value of 40% was assumed because this is an average value of efficiency for combined

Table 1
Data used for the estimation of carbon content in wastes.

Waste type	Description	Carbon content (%)	Source
Fly ash (1)	Fly ash from bark boiler	27.00	[33]
Fly ash (2)	Fly ash from coal fired power boilers	5.00	[33]
EAF dusts (1)	Electric-arc furnace dusts from metallurgical industry with additional carbon content of 75 kg per ton of dust.	6.98[a]	[25]
EAF dusts (2)	Electric-arc furnace dusts from metallurgical industry with additional carbon content of 170 kg per ton of dust.	14.53[a]	[25]
Alloy-steel dust	Alloy-steel dust from electric-arc furnace with additional anthracite (77.4% C) in a rate of 290 kg per ton of dust.	17.40[a]	[25]
RDF (1)	Refuse Derived Fuel (common)	45.90	[34]
RDF (2)	Refuse Derived Fuel (known composition)	36.10	[35]
Wood (1)	Common wood	50.00	[36]
TDF	Tyre Derived Fuel	79.87	[37]
Rubber		79.87	[37]
Carpet waste		*52.17*	*Weighted average*
Carpet fiber	2/3	59.10	[38]
Carpet fines	1/3	38.30	[38]
USAF BEAR waste	United States Air Force Basic Expeditionary Airfield Resources Base waste	*52.25*	*Weighted average*
Non-durable paper	31.0%	46.00	[36]
Cardboard	22.5%	46.00	[36]
Non-durable plastics	14.5%	75.00	[36]
Durable plastics	11.0%	75.00	[36]
Rubber	2.0%	75.00	[36]
Textiles	3.5%	50.00	[36]
Glass	2.0%	0.00	[36]
Metal	4.0%	0.00	[36]
Wood (1)	3.0%	50.00	[36]
Vinyl and styrofoam	3.5%	75.00	[36]
Food	3.0%	38.00	[36]
Tannery waste	Considering the carbon content for leather	54.90	[39]
Fly ash (3)	Fly ash with a carbon content of 1.7% treated in an oxidizing atmosphere	1.70	[40]
Fly ash (4)	Fly ash with a carbon content of 3.1% treated in an oxidizing atmosphere	3.10	[40]
Polypropylene		86.10	[34]
Wood (2)	Wood with known composition	44.38	[41]
Medical waste		51.10	[42]

[a] Calculated for the final mixture fed to the plasma reactor.

Table 2
Electricity consumed by the plasma gasification process.

Waste type	Electricity consumption in plasma torch		Electricity consumption in auxiliary units		Source	Scale[a]
	Value	Units	Value	Units		
EAF dusts (1)	816	kWh/t EAF dusts			[25]	S
EAF dusts (2)	1130	kWh/t EAF dusts			[25]	S
Alloy-steel dust	1.08	MWh/t feed			[25]	P
Fly ash (1)	367	kWh/t fly ash			[33]	P
Fly ash (2)	766	kWh/t fly ash			[33]	P
RDF (1)	3.82	MJ/kg feed			[24]	P
RDF (2)	530	kWh/t RDF			[35]	I
Wood (1)	3.6	MJ/kg feed			[24]	P
Wood (1)	325	kWh/t wood			[35]	I
TDF	6.66	MJ/kg feed			[24]	P
RDF (1)	4930	kWh/t RDF	217.8	kWh/t waste	[43]	I
RDF (1)	150.0	kWh/t waste	150.0	kWh/t waste	[44]	I

[a] Scale of application of the study — P: Pilot; I: Industrial; and S: theoretical simulation.

Table 3
Electricity generated in the combined cycle in the plasma gasification process for different wastes.

Waste type	Syngas heating value (units)	Electricity generated (units)	Source	Scale[a]
Fly ash (1)	1785 (kWh/t fly ash)	–	[33]	P
Fly ash (2)	766 (kWh/t fly ash)	–	[33]	P
RDF (1)	5.88 (MJ/m^3 with gas yield 2.46 m^3/kg waste)	–	[24]	I
RDF (2)	–	900 (kWh/t waste)	[35]	P
Carpet waste	23.5–33.6 kW (waste feed rate 23.1 kg/h)	–	[23]	P
Wood (1)	6.16 (MJ/m^3 with gas yield 2.48 m^3/kg)	–	[24]	P
Wood (1)	–	930 (kWh/t waste)	[35]	I
USAF BEAR waste	27.5–41 kW (waste feed rate 10.7 kg/h)	–	[23]	P
Tannery waste	–	415 (kW from 560 kg/h waste feed)	[28]	I
Rubber	9 (MJ/Nm^3 with gas yield 3 Nm^3/kg rubber)	–	[29]	P/L
TDF	5.89 (MJ/m^3 with gas yield 5.03 m^3/kg waste)	–	[24]	P
RDF (1)	4106 (kWh/t waste)	2328 (kWh/t waste)	[43]	I
RDF (1)		1150 (kWh/t waste)	[44]	I

[a] Scale of application of the study — L: Laboratory; P: Pilot; and I: Industrial.

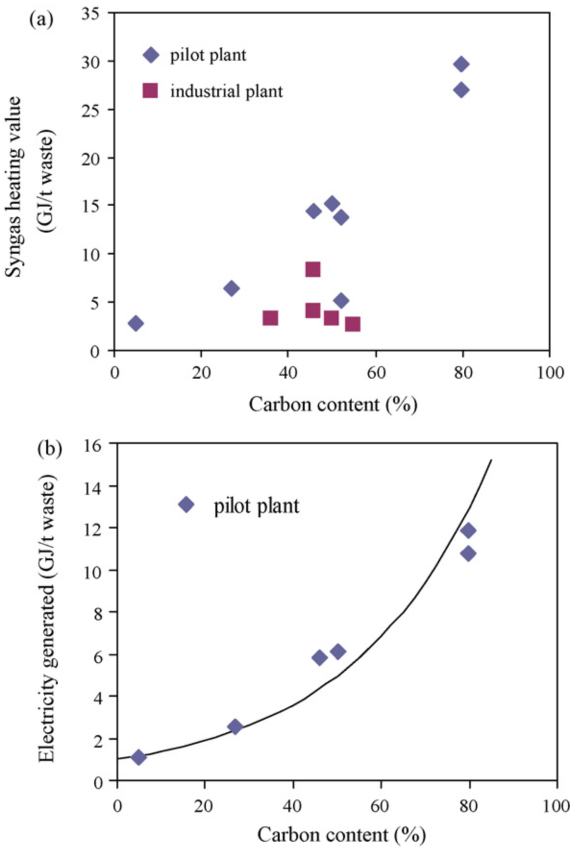

Fig. 5. Electricity generation in the combined cycle as a function of carbon content in wastes. (a) All available data is expressed in terms of syngas heating values; (b) data from pilot plant studies expressed in terms of the electricity generated per ton of waste fed to the treatment system.

cycles, leading to lower EF values for wastes (the minimum criteria principle).

Given that the majority of the available data were expressed in terms of the syngas heating, the electricity values were converted so that all of the data could be presented in a homogeneous way (Fig. 5a). An increase in the electricity generated as the percentage of carbon content in the wastes increased for the pilot plant data was noted; however, the industrial data did not show any clear behavior. For the electricity consumption by the plasma torch, the values from industrial installations did not follow any discernable trend. In particular, the data from Moraga [43] were regarded as anomalous and were not used in the correlation. Moreover, for the case of tannery waste, there was uncertainty in the estimation of the carbon content as the value for leather was adopted; however, tannery waste consists of organic substances that are removed from hides and skins, which are composed of tissue and fat mixed with the chemicals used in the tanning process [28].

Consequently, only the values from studies on a pilot scale were considered in this work (Fig. 5b). However, there was a discordant value within the pilot series, which corresponds to carpet waste. The operational conditions of this study [23] were quite particular, as wastes were introduced in aluminum cans and fed into the furnace in batches of three every 2 min. For this reason, it was decided to not include the two data points from reference [23] in Fig. 5b.

The data points in Fig. 5b show a very homogeneous tendency that could be adjusted either to a linear, a quadratic or an exponential correlation. Among these options, the most significant model was calculated based on an exponential function that allows for a residual electricity generation (from H_2) when the carbon content in wastes is zero. Thus, Eq. (4) was used to calculate the electricity generated by the combined cycle as a function of the carbon content of the wastes fed to the plasma treatment process:

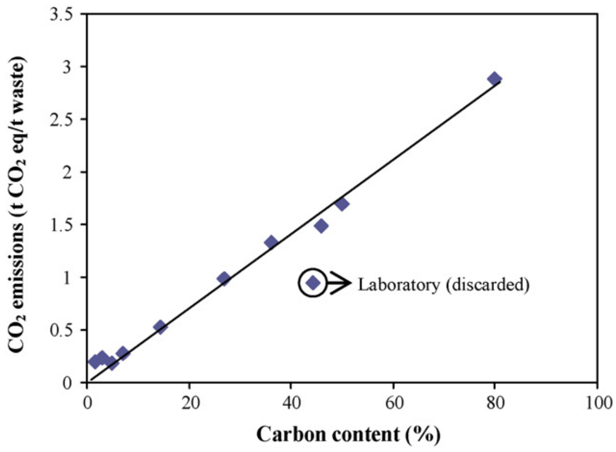

Fig. 6. CO_2 released in the combined cycle as a function of the carbon content in wastes.

$$E_C = e^{0.032C} \tag{4}$$

where E_C is the electricity generated expressed in GJ/t feed, and C is the carbon content in the wastes expressed as a percentage.

3.1.4. Carbon emissions in the combined cycle

The data used to estimate the carbon emissions released in the combined cycle is shown in Table 4. Given that 100% oxidation was not assumed, CO and CH_4 could have been present in the exhaust gas. Thus, these emissions were accounted for based on their carbon content and future transformation into CO_2 rather than considering their global warming potential factors. Nonetheless, their contribution in this particular case was practically negligible (<0.3%).

The total emissions are shown in Fig. 6, which allows for an examination of a relationship with the carbon content in wastes. As expected, an increasing linear relationship was observed for these parameters. The correlation, given below in Eq. (5), was calculated such that the origin condition was fulfilled. When this condition was not established, a constant was determined for the model, but it was statistically not significant (even for a confidence level of 90%). This is reasonable because if no carbon is present in the residues, then no CO_2 can be expected to form. Moreover, the data point from Wood (2) was discarded as it was an outlier (it corresponded to the only laboratory study considered for this calculation).

$$Carbon\_emissions = 0.035C \tag{5}$$

Here, the *Carbon_emissions* are the CO_2 emissions released (expressed in tons per ton of waste treated), and C is the carbon content in the wastes expressed as a percentage.

3.1.5. Slag production

To correlate slag production with the carbon content of the wastes, the data corresponding to different processes reported in the literature are shown in Table 5. Unlike previously reported correlations, in this case, the quantity of slag obtained decreased as the carbon content increased (Fig. 7). This was because the slag was mainly composed of the vitrified inorganic compounds present in the wastes treated in the plasma process. Furthermore, the trend was asymptotic with respect to the x axis. Therefore, the data were fitted to an exponential correlation by discarding the values from the study by Vaidyanathan et al. [23], which are represented in red dots in Fig. 7 and did not follow the general tendencies of the other data. These two values were also excluded when calculating

Table 4
Data used for the estimation of CO_2 emissions released in the combined cycle.

Waste type	Waste input flow		Syngas flow		Syngas composition[a]			Source	t CO_2eq/t waste
					CO	CO_2	CH_4		
Fly ash (1)	1000	kg	1843	kg	–	–	–	[33]	0.99
Fly ash (2)	1000	kg	341	kg	–	–	–	[33]	0.18
Fly ash (3)	726	kg	38.7	kg C	–	–	–	[40]	0.19
Fly ash (4)	810	kg	52.7	kg C	–	–	–	[40]	0.24
EAF dusts (1)	1075	kg/h	508	kg/h	33.1[b]	5.1[b]	–	[25]	0.27
EAF dusts (2)	1170	kg/h	441	kg/h	88.2[b]	–	–	[25]	0.52
RDF (1)	1	kg	2.46	m^3	27.5[c]	3.2[c]	–	[24]	1.48
RDF (2)	10000	lb/h	11067	lb/h	49.0[b]	30.6[b]	4.4[b]	[34]	1.33
Wood (1)	1	kg	2.48	m^3	31.4[c]	3.5[c]	–	[24]	1.70
Wood (2)	2.22	g/s	–		53.33[d]	2.95[d]	2.68[d]	[41]	0.95
TDF	1	kg	5.03	m^3	24[c]	5.2[c]	–	[24]	2.88

[a] Only those compounds implied in the estimation of CO_2 emissions are indicated.
[b] Percentage on weight basis.
[c] Percentage on volume basis.
[d] Percentage on weight basis and referred to the waste input flow.

Table 5
Slag production in the plasma gasification process for different wastes.

Waste type	Slag production	Source
Fly ash (1)	730 kg slag/1000 kg ash	[33]
Fly ash (2)	950 kg slag/1000 kg ash	[33]
Fly ash (3)	439 kg slag/726 kg ash	[40]
Fly ash (4)	490 kg slag/810 kg ash	[40]
RDF (2)	600 (kg/h)/10000 (kg/h)	[40]
Carpet waste	30.8–42.7 mass% of total input	[23]
Medical waste	0.11 kg/kg waste	[27]
USAF BEAR waste	9.95–22.9 mass% of total input	[23]
Polypropylene	2% weight	[29]
RDF (1)	6944.7 t/75707.3 t feed	[43]
RDF (1)	150 kg/t waste	[44]

the correlation to estimate the electricity generated in the combined cycle (Section 3.1.3), given the particular conditions of the mentioned study.

To estimate the slag production as a function of the carbon content in wastes, the following equation was used:

$$Slag = e^{-0.047C} \tag{6}$$

where *Slag* is the fraction of waste treated that is converted in vitrified material in tons of slag per ton of waste treated, and *C* is the carbon content in wastes expressed as a percentage.

3.1.6. Statistical analysis of the correlations

The reliability and the significance of the correlations obtained were analyzed according to the statistical information provided by the SPSS 17.0 software. The information was summarized in Table 6, including the standard error and *p*-value for coefficients, standard error for the estimation and the R^2 value for the correlation.

It can be seen that the R^2 values indicate that good correlations were obtained in all cases. Moreover, the significance of the coefficients in the equations was ensured by the low *p*-values obtained. Actually, this was a criterion taken into account during the selection of the function type for the correlations. In all cases, better significance was obtained when no constant was included in the model. Further reasoning to justify the correlations selected to model the electricity consumption in the plasma torch, and the electricity generated in the combined cycle is explained below (this is not done for carbon emissions and slag as the tendency of data in these cases was clear enough to avoid any doubt).

In the case of electricity consumption in the plasma torch, the major variability in data points pointed towards checking different likely function types. A quadratic correlation was discarded as no significance was obtained. Meanwhile, when a linear model without a constant was selected, a significant model with a good R^2 (0.869) was calculated; however, this would mean that no electricity is consumed when the carbon percentage is zero (the slag formation also requires energy). As a consequence, the exponential model was selected as the statistic parameters were also good. This model allowed the consideration of residual electricity consumption for null carbon content, and this kind of function fitted better to data points in Fig. 4. Nonetheless, this is statistically the weaker of the functions calculated, and the availability of more data points would be desirable. The variability observed could be explained by the fact that the influence of water content was not considered, which can affect electricity consumption in the plasma torch [24]. In most of the experimental studies used in Fig. 4 to obtain the correlation [24,25,33], additional vapor (in different quantities in each case) was supplied to the reactor, apart from the water embodied in the residues. The dependence of power consumption and plasma enthalpy on water content like that indicated in [24] was explored, but without obtaining significant results. For that reason, the influence of this parameter was excluded from the final model.

Regarding the electricity generated by the combined cycle, the linear and quadratic functions were significant only when no constant was included in the model. This meant that no electricity would be generated if the carbon percentage was zero; however, a certain amount of electricity can be generated in the combined cycle from H_2 and, therefore, this model would not properly represent the reality in the plasma process. Therefore, an exponential function was preferred that fit well with the data points in Fig. 5b. In addition, this model allowed the contemplation of residual electricity generation when the carbon content in wastes was zero.

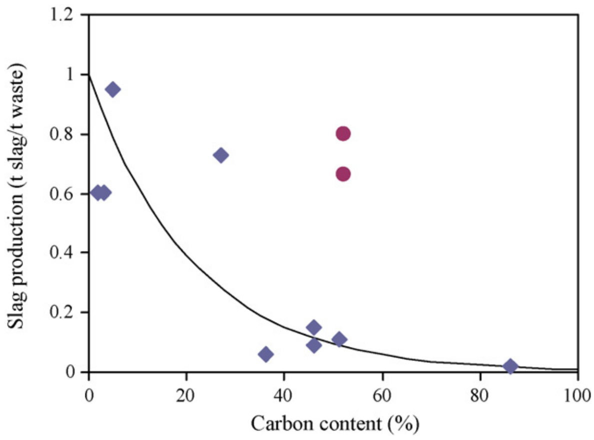

Fig. 7. Slag production in the plasma reactor as a function of the carbon content of wastes.

Table 6
Summary of statistics for the correlations.

No. Eq.	Estimated parameter	Function type	Coefficient B			Standard error for the estimation	R^2
			Coefficient value	Standard error	p		
(3)	E_P	$y = e^{Bx}$	0.026	0.006	0.005	0.606	0.816
(4)	E_C	$y = e^{Bx}$	0.032	0.001	<0.001	0.186	0.991
(5)	*Carbon_emissions*	$y = Bx$	0.035	0.001	<0.001	0.086	0.996
(6)	*Slag*	$y = e^{Bx}$	−0.047	0.005	<0.001	0.578	0.930

Table 7
Carbon content of textile process wastes used for the EF estimate.

Waste type	Comments	Carbon content (%)	Source
Non-hazardous wastes			
Textile		50	[36]
Paper and cardboard		46	[36]
Plastic		75	[36]
Hazardous wastes			
Batteries	Associated to the casing (plastic)	4.5	[36,49]
Computers waste	Calculated as an average for motherboard, keyboard and casing.	47.64	[50]
Fluorescent light		n.a.	
Oil filter		45.05	[51,52]
Used mineral absorbent	0.7–0.9 kg liquid/kg absorbent	34.32	[51,53]
Paint	455 g/l VOC's and 0.9 kg/l specific weight	50.55	[54]
Polluted containers	Considering plastic	75	[36]

n.a.: not available.

Further analysis with respect to the behavior of the correlations in the boundaries of the study is provided in Section 3.4.

3.2. Final model for the EF of wastes

Once the correlations were developed, they were inputted into a spreadsheet (Microsoft Excel®) together with the factors required to convert into units of area for the three main terms, i.e., net electricity balance, carbon emissions and slag. Thus, to estimate the EF of a given waste, it is necessary to account for the carbon content and the amount of waste generated. The used conversion factors for the calculations were equivalence factors [17], energy conversion factors [47,48] and slag embodied energy [47].

3.3. Case study: textile process wastes

To test the proposed method, the wastes generated in a textile process were evaluated. The data was extracted from a previous work [3] where the contribution of hazardous wastes to the total EF of a tailoring process remained unevaluated due to the lack of an appropriate methodology. Non-hazardous wastes were also assessed using the approach proposed in the present work and the results were compared to those obtained using conventional EF methodology. Thus, it was necessary to estimate the carbon content for the different kinds of wastes considered (Table 7).

The carbon content of batteries was associated with their casings, which, according to Ascent [49], represents 6% of the total weight. The casings were assumed to be made of plastic and had a carbon content of 75% [35]. In the case of the oil filter, the carbon content of the waste was calculated considering the residual oil because the casing was usually made of metal. According to the commercial enterprise SAIC Lubrication [52], after filter compaction, 53% of the total weight recovered is oil. Considering that the carbon content in waste lubricant oil is 85.35% [51], the carbon content of the oil filter was estimated to be 45.05%. In a similar way, if oil is considered to be absorbed by the mineral absorbent and assuming an absorption capacity of 0.7–0.9 kg liquid/kg absorbent [53], then the percentage of carbon is 34.32%. Finally, for the paint, the percentage of carbon was calculated on the basis of the concentration of the VOCs [54].

The proposed tool was applied to the flows of wastes generated during the year 2005 [3], and the results are shown in Table 8 and indicate the contribution from each term in Eq. (2). The results calculated here for non-hazardous wastes have the same order of

Table 8
Results of the application of the developed methodology to the textile process wastes and comparison with previous estimates for the year 2005 [3].

Waste type	EF previous estimate			EF new approach				
	Recycling	No recycling	Units	Elect.[a]	CO_2[b]	CF[c]	Total[d]	Units
Non-hazardous wastes	*25.1*	*91.3*	*gha*				*56.52*	*gha*
Textile	22.4	83.5	gha	−3.29	56.83	0.32	53.21	gha
Paper and cardboard	2.5	7.3	gha	−0.19	3.15	0.03	2.93	gha
Plastic	0.2	0.5	gha	−0.15	0.53	<0.01	0.38	gha
Hazardous wastes							4.3×10^{-2}	*gha*
Batteries	–	–		8.5×10^{-5}	1.0×10^{-4}	7.6×10^{-5}	1.1×10^{-4}	gha
Computers waste	–	–		-2.9×10^{-3}	4.2×10^{-2}	3.9×10^{-4}	3.9×10^{-2}	gha
Fluorescent light	–	–		–	–	–	–	gha
Oil filter	–	–		-1.1×10^{-4}	2.0×10^{-3}	2.3×10^{-5}	1.9×10^{-3}	gha
Used mineral absorbent	–	–		0	0	0	0	gha
Paint	–	–		-5.0×10^{-5}	5.7×10^{-4}	4.3×10^{-6}	5.2×10^{-4}	gha
Polluted containers	–	–		-6.4×10^{-4}	2.3×10^{-3}	3.7×10^{-6}	1.6×10^{-3}	gha

Terms in Eq. (2): [a]$EF_{electricity}$; [b]$EF_{carbon\_emissions}$; [c]CF_{slag}; and [d]EF_{wastes}.

magnitude as those previously reported. Hence, for the plasma-based methodology, a total contribution of 56.5 gha was estimated for these wastes, which was 91.3 gha (or 25.1 gha when 100% waste recycling was considered) using conventional EF methodology. Meanwhile, the EF calculated for the hazardous wastes was 4.3×10^{-2} gha, which represented 0.08% of the total waste. This result means that negligible errors were assumed in the previous work [3] when considering the EF of this kind of waste, which was the situation here because very low quantities of hazardous wastes were generated (mainly during maintenance operations). Specifically, hazardous wastes represented only 0.25%. However, other kinds of industries or activities that involve higher quantities of hazardous substances should produce wastes that are a major contribution to the total EF. Consequently, the availability of a methodology to assess their footprint and thus provide a more comprehensive and realistic measure of the total environmental impact of the process is essential.

Only two values were found in the literature that can be associated with the plasma treatment process for built land EF; these were 2 ha for a treatment capacity of 30,000 t/yr [44] and 0.067 ha for a capacity of 1.1 million kg/yr [55]. Both values yield a similar ratio for the area required per ton of waste treated (6.7×10^{-5} ha/t in the first case and 6.1×10^{-5} ha/t in the second). Even after multiplying this result for the corresponding 2.21 equivalence factor for built land [17], the contribution of this land type compared with the total EF estimated for wastes could be considered negligible.

The influence of the consumption of electricity by auxiliary units was also determined to be negligible. Thus, the uncertainty due to the lack of data regarding this factor did not significantly influence the final results.

Furthermore, it was observed that, for the materials that were tested in the case study, the contribution of the counter-footprint calculated for the slag generated does not exceed a 1.4% contribution to the total EF, except for the particular case of the batteries (notice that the carbon-content estimation in this case was not very accurate, as explained above). This means that the error assumed when considering that all the inert material generated in the plasma process could find a market application does not significantly alter the final results.

3.4. Limitations of the developed methodology

Even though plasma is a state of matter that, under appropriate conditions, can be induced for any type of waste, thermal plasma technology has only been developed for the treatment of hazardous wastes. As a result, the data available in the literature allows for evaluations of only certain kinds of wastes (Table 1). Thus, the usefulness of the developed methodology is more relevant for industrial activities where these wastes are generated, rather than for municipal policy makers.

The correlations obtained within this range were good, which shows that the carbon content acted as a characteristic parameter. However, inconsistent data points were observed at the boundaries of the study, especially for lower values of carbon percentage (i.e., lower organic matter content), as seen in Section 3.1.6. Actually, the plasma process is particularly recommended for residues containing organic matter, thus allowing for energy recovery [24]. This means that not even a zero carbon-content waste could ever be treated by this technology. If this was the case, the evaluation of Eq. (6) would lead to calculate a generation of 1 t slag/t waste treated, i.e., because no organic matter is present the entire waste is converted into a slag. Therefore, from a cautious approach, the proposed methodology should presently be restricted to wastes within the studied range of carbon content. Moreover, the assumption of expressing the correlations as a function only of the carbon percentage could be considered very simple, given that different wastes with the same carbon content [56] would lead to the same EF, regardless of their hazardousness. Thus, as for CH_4 emissions, we should ask whether EF accounts weigh the severity of impacts apart from assessing land requirements.

Another aspect that implies a source of error in the methodology is the likely over-estimation of the counter-footprint assigned to the slag. The methodology was constructed on the basis that all of the inert material produced could find an application in market, but whether this is feasible or not is difficult to know. A possible solution to mitigate the effect could be to consider a percentage of slag that could be reused as building material or for road construction, then accounting for it as a counter-footprint (energy savings as new materials production is avoided), while the remaining percentage should be assigned a footprint for its storage. Nonetheless, the uncertainty associated with the selection of this percentage would also be a source of error in the calculations.

As a final remark, the correlations for the estimation of electricity consumption by the plasma torch and electricity generated by the combined cycle were obtained on the basis of pilot plant data. This means that real processes at large scale may differ from the behavior predicted by the model. As more solid and reliable industrial plant data are available, a revision of these correlations should be considered.

4. Conclusions

A minimum criteria indicator, like the Ecological Footprint, may be sufficient for countries interested in knowing the pressure they exert on the environment who only consider whether or not they are exploiting more resources than are available. However, the situation is different at the corporate level, as more comprehensive analyses of all environmental burdens are required. To fulfill this aim, a new technique based on the application of different methodologies, where each methodology deals with different aspects, could be proposed. This would lead to an in-depth, but also laborious analysis. Indeed, handling more detailed information also means that it is more difficult to communicate the results; therefore, it would be useless for enterprises having corporate social responsibilities that need to report their behavior in a synthesized and easily understandable way. Thus, research must be carried out to improve integrated indicators, like the EF, that mostly fulfill the desired characteristics, i.e., an indicator that summarizes in one number a series of environmental impacts while possessing scientific rigor. This figure, expressed as a requirement of bioproductive area, can be interpreted by any stakeholder (policy makers, industry, scientific community or the general public) and compared to the available biocapacity to extract conclusions. Production activities would benefit from the availability of such an indicator to conduct more comprehensive analyses and express their environmental performance in corporate social responsibility reports.

In the present work, a methodology for assessing the footprint of hazardous wastes (which is also suitable for non-hazardous wastes) was developed. The results were on the same order of magnitude of those previously reported using the standard EF methodology. Despite certain limitations, the usefulness of the proposed methodology relies on the availability of a method that accounts for the relative weight of hazardous wastes in the environmental evaluation of an activity, thereby allowing for a synthesized expression in terms of the ecological footprint in units of area. In addition, its application is quite simple and only requires knowing or being able to estimate the carbon content of the wastes considered. That being said, the consistency of the model will be improved as more data from studies on plasma technology become available in the future.

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