energies

MDPI

Article

Environmental Analysis of Waste-to-Energy— A Portuguese Case Study

Ana Ramos [1], **Carlos Afonso Teixeira** [2] **and Abel Rouboa** [2,3,*]

[1] INEGI-FEUP, Institute of Science and Innovation in Mechanical and Industrial Engineering, Faculty of Engineering of the University of Porto, 4200-465 Porto, Portugal; aramos@inegi.up.pt
[2] CITAB, Centre for the Research and Technology of Agro-Environmental and Biological Sciences, University of Trás-os-Montes and Alto Douro, 5001-801 Vila Real, Portugal; cafonso@utad.pt
[3] CIENER-INEGI, Centre for Renewable Energy Research, Institute of Science and Innovation in Mechanical and Industrial Engineering, Faculty of Engineering of the University of Porto, 4200-465 Porto, Portugal
* Correspondence: rouboa@utad.pt; Tel.: +351-259-350-317; Fax: +351-259-350-356

Received: 26 January 2018; Accepted: 28 February 2018; Published: 4 March 2018

Abstract: Environmental evaluation of the waste treatment processes for the area of Greater Porto (Portugal) is presented for the year 2015. The raw data for the energy recovery plant (ERP) provided by the waste management entity were modelled into nine environmental impact categories, resorting to a life cycle assessment dedicated software (GaBi) for the treatment of 1 tonne of residues. Also, a sensitivity analysis was conducted for five scenarios in order to verify the assessment quality. Results were compared to two European average situations (typical incineration plant and sanitary landfill with no waste pre-treatment), which showed that these facilities perform better or at the same level as the average European situation, mostly due to the high efficiency observed at the ERP and to the electricity production in the incineration process. A detailed analysis concluded that these helped to mitigate the environmental impacts caused by some of the processes involved in the waste-to-energy technology (landfill showing the harder impacts), by saving material resources as well as avoiding emissions to fresh water and air. The overall performance of the energy recovery plant was relevant, 1 tonne of waste saving up to 1.3 million kg of resources and materials. Regarding the environmental indicators, enhanced results were achieved especially for the global warming potential (-171 $\text{kg}_{\text{CO}_2\text{-eq.}}$), eutrophication potential (-39×10^{-3} $\text{kg}_{\text{PO}_4\text{-eq.}}$) and terrestrial ecotoxicity potential (-59×10^{-3} $\text{kg}_{\text{DCB-eq.}}$) categories. This work was the first to characterize this Portuguese incineration plant according to the used methodology, supporting the necessary follow-up required by legal frameworks proposed by European Union (EU), once this facility serves a wide populational zone and therefore is representative of the current waste management tendency in the country. LCA (life cycle assessment) was confirmed as a suitable and reliable approach to evaluate the environmental impacts of the waste management scenarios, acting as a functional tool that helps decision-makers to proceed accordingly.

Keywords: waste to energy; LCA; sustainability; waste; incineration

1. Introduction

Waste management is currently a global concern in view of an exponential population growth accompanied by lifestyle improvements and their consequences, such as higher demand for plastic products and packaging, evidenced by the steadily growing number of field-related published literature. Chen et al. [1] performed a bibliometric analysis of the research concerning municipal solid wastes from 1997 to 2014 and concluded that this type of publications has progressively increased, especially at the beginning of the 21st century. Recently, Eriksson [2] has also published a special issue on energy and waste management, compiling more than 20 works which cover the technical aspects as well as some future perspectives on the energy systems. Zhang et al. [3] reported on the key challenges and opportunities on the waste-to-energy (WtE) in China, referring some hints of the economic and social benefits related to the implementation of standardized and regulated waste management processes. Environmental regulations and directives seek sustainable solutions to this problem, regarding the implementation of new technologies as well as using the existing ones, to assure environmental quality and aiding to meet the set goals [4–8]. The European Union has established well-defined waste management policies, preconizing preventive measures and promoting reducing ones, with the aim to take control over the progressively increasing amounts of solid residues produced nowadays [9].

Cucchiella et al. [10] studied the sustainability of Italian waste-to-energy (WtE) plants according to environmental, financial, economic and social interpretations. A remarkable conclusion of their work was that WtE processes are effective in combating climate change arising from global warming potential causes, once it is possible to generate renewable energy, reducing carbon emissions. This is corroborated by a myriad of studies compiled some years ago by Cherubini and Stromman [11]. Also, as waste is combusted instead of disposed of, these techniques reduce the amount of methane released by landfills. The authors found an interesting solution to balance the need to manage waste with a safe and controlled release of pollutant emissions through the use of mixed waste strategies, therefore promoting sustainability as well as complying with waste legislations. For a deeper understanding of waste management evolution, a thorough review on this topic was published by Brunner and Rechberger [12], where incineration is highlighted as a featured WtE technique. This technology was also pointed as more environment-friendly when compared to others such as sanitary landfill and mechanical-biological treatment [13] or even recycling in specific cases [14]. There are even published works on the waste management balance between some techniques, showing that as landfilling is reduced and other options such as incineration raise, more easily attainable are the EU goals, while high efficiency rates are reached [4]. While the first incinerators were built only for hygienic and waste volume reduction purposes, with no interest in energy recovery, nowadays besides environmental protection, modern WtE plants show significant contributions to the so-claimed resource conservation once some of their by-products may substitute primary resources [3,4]. In countries where waste streams are already seen as important assets for energy production, WtE outcomes are intensively scrutinized in order to determine the overall amount of biogenic CO_2 emissions, as in the case of Austria [15], and also to interpret the effect of changing waste fractions by adding different types of residues, recalling a recent work published for Norway [16].

Portugal also struggles to reach the so desired environmental sustainability, hence progresses have been made in the last years. Back in 2006, Magrinho et al. [17] published a review on the municipal waste disposal, reporting on the waste management practices at that time. Main findings were that since 1998 separate collection of residues was growing as the most common way of disposal, until 2002 when WtE plants became the most important disposal means. In 2009, Ferreira et al. [18] conducted an overview of the bioenergy production highlighting that, although by that time the country was the fourth-largest share of renewable electricity generation in Europe, bioenergy production was not at the desired level. The authors suggested that the energy from animal origin had high potential but was still not well developed. Regarding biomass, it was and still is a highly available resource, enabling the use of several technologies for power production. More recently, Margallo et al. [19] assessed incineration in Iberian Peninsula, so that the overall process was better known and discussed, in order to understand the influence of some critical factors such as waste composition, moisture and heating value on the environmental burdens associated with each fraction. The trigger for this conscious behaviour towards environment and public health protection as well as materials and energy return was given by the settlement of PERSU I (strategic plan dealing with municipal solid waste management between 1996 and 2006, establishing major goals such as ending up waste discharges in Nature, creating waste recovery plants and sanitary landfills, among others), followed by PERSU II (proceeding with municipal solid waste management between 2007 and 2016 and rectifying possible flaws from the previous plan) [17]. Nowadays the prevailing plan is PERSU 2020, which constitutes an improvement of PERSU II for the period between 2014 and 2020 aiming at specific targets like reducing waste deposition from 63% to 35% of the reference values for 1995, raising the reuse and recycling rates from 24% to 50% and also ensuring levels of selective waste collection of 47 kg/inhabitant/year [20].

The waste management entity for the area of Greater Porto (the most densely populated district on the north of the country), LIPOR, holds responsibility for the management, recovery and treatment of municipal wastes from eight associated municipalities, produced by 1 million inhabitants at a 500,000 t/year rate. Its integrated waste management system (IWMS) includes separated units for waste valorisation, incineration, recovery, composting of the organic residue and landfilling of a small pre-treated fraction (Table 1). Despite recyclables may be seen as treasured resources due to their origin and heating value (enhancing the capacity of the plant to produce renewable energy), the company makes the effort of instilling the idea that these items can be transformed in better assets through the sorting plant than sending them to energy valorisation process, according to the waste management hierarchy.

Table 1. Waste streams separation considered for this study by final destination, for 2015.

Waste Final Destination	Weight %
Sorting Plant	9.12
Composting Plant	9.79
Energy Recovery Plant	81.08
Landfill	0.01

A life cycle assessment (LCA) approach is a very useful tool in the evaluation of the contribution of each of the processes to the overall efficiency picture of the disposal options. Arena et al. [21] and Tarantini et al. [22] compared the performance of alternative solid waste management in Italy quantifying the relative advantages and disadvantages for several options, while Liu et al. [23] evaluated the urban solid waste handling options in China and Menikpura et al. [24] assessed the sustainability of an integrated waste management system in Thailand, all of them using LCA as a decision-support tool. Although this is a very powerful mean, aspects such as the lack of transparency or wrong methodology assumptions may lead to difficult comparisons or even deficient interpretation of the results as reviewed for municipal solid waste by Cleary [25]. A summary of the methodology for correctly applying LCA was reported by Clift et al. [26], special attention being paid to the system definition and to the environmental credits achieved from materials or energy recovery. A detailed discussion on the importance of a complete life cycle inventory may be accomplished elsewhere [27]. System boundaries are also a crucial element to be clearly defined, once they have a direct effect on the magnitude of the inputs, accounting for totally different outputs and consequently distinct LCA features [25,28], along with other technical issues [26,29]. LCA may also be seen as a tool that provides decision makers with key information that can help them plan and opt between different waste management scenarios [6,23,24,30,31]. Astrup et al. [32] published a recent review including major recommendations to perform a correct LCA study for WtE technologies. Parkes et al. [33] assessed three different scenarios of waste generation (mixed residential/commercial, mainly residential or mainly commercial/industrial), thus generating diverse streams. The authors found that advanced thermal treatments depicted lower global warming potential than landfill process. Toniolo et al. [34] conducted an environmental assessment on the design phase and on the operational phase of a municipal solid waste (MSW) incineration plant. Results showed that some of the impact categories were underestimated during the design phase stressing the role of the assumptions made during this stage, which might have compromised the reliability of the operational results. Morselli et al. [35] also showed that updated technologies promote lower environmental impacts, matching the needs of modern legislation. Boer et al. [36] developed a decision-support tool for the waste management system assessment. This tool allowed to create and compare planning scenarios for the urban waste management systems, taking into account the design and analysis options.

Herva et al. [37] performed complementary investigations regarding the same IWMS for the data between 2007 and 2011, but using two different methodologies—Energy and Material Flow Analysis (EMFA) and Ecological Footprint (EF). Although this study allowed the delineation of an efficient management strategy, some drawbacks were identified namely the non-assessment of the gaseous emissions from the ERP, which were not included in the chosen indicators. Therefore, concerns such as the yields of dioxins, furans and other toxic substances were not quantified, raising the need for a different approach to be undertaken once they are extremely important due to public health issues, especially for the neighbouring population.

This study assesses the environmental impact of the energy valorisation process of an integrated waste management system during 2015, using a LCA methodology in order to evaluate the performance of each participating facility and their contribution on the total weighted impact. To the best of the author's knowledge, this is the first time this type of study is performed for a waste management institution in this area hence, awareness of the assessed outputs achieved with the actual practices may help to understand results in other business dimensions (like financial, social or technical) and serve as foundations for the development of efforts in finding better management solutions. In regards to the EU legislation, the results from this work were also compared to European average situations in order to understand the trends and evolution of the Portuguese situation in the waste management segment, supporting a follow-up for the EU-proposed frameworks, in order to monitor the progress of this topic within the participating countries.

2. Methods

In this section, the integrated waste management system description and waste characterization will be elucidated. Also, boundaries, functional unit and life cycle inventory for the evaluated system will be defined as well as the LCA scenarios described.

2.1. Integrated Waste Management System for the Portuguese Case Study

Regarding the integrated management system, four main stages are considered from the residues generation until its final valorisation, as can be seen in Figure 1. Stage I refers to the waste creation whether it occurs in homes, small businesses and enterprises or public institutions. Then municipalities have a key role in stage II, providing the necessary containers and differentiated vessels for each kind of waste, as well as taking care of its collection and transport to LIPOR facilities, where stage III takes place in sub-processes like energy, organic and multi-material valorisation. Actually, the three central waste management systems in the IWMS include the sorting plant (SP, where materials from eco-points are received and an additional separation is performed according to their nature—metal, plastic, glass, paper and cardboard), the composting plant (CP, where the organic fraction of the collected waste like tree branches, bushes and grass is composted) and the energy recovery plant (ERP, where the waste incineration occurs). Besides, there is a landfill where by-products from the ERP such as slag (previously separated from the ferrous fraction by magnetic segregation), inert ashes and also raw waste that does not comply with any of the treatment processes offered by this unit are disposed. Finally, stage IV corresponds to the obtainment and commercialisation of the valuable products that result from the previous steps, like electricity, compost and fertilizers [38].

For the reference case (scenario 0), the life cycle assessment of the energy recovery plant (stage III of the Figure 1) was performed, within the conditions defined in Section 2.2. The ERP works in continuous operation treating around 1,100 t of waste per day and producing about 170,000 MWh of electricity per year, from which an average of 90% is supplied to the national electric grid. Waste is discharged in a closed depressurized building, where claws and hoppers move residues to the combustion grids. Here, the waste is decomposed at temperatures between 1000 °C and 1200 °C, generating flue gases which are released at 950 °C and also bottom ash. Before its release into the atmosphere, the gaseous fraction is cleaned passing through scrubbers and filters, hazardous substances being removed and some even converted into marketable products. Bottom ash is collected and landfilled and heat is used in a boiler, where steam is produced and then sent to a turbine to generate electricity [38].

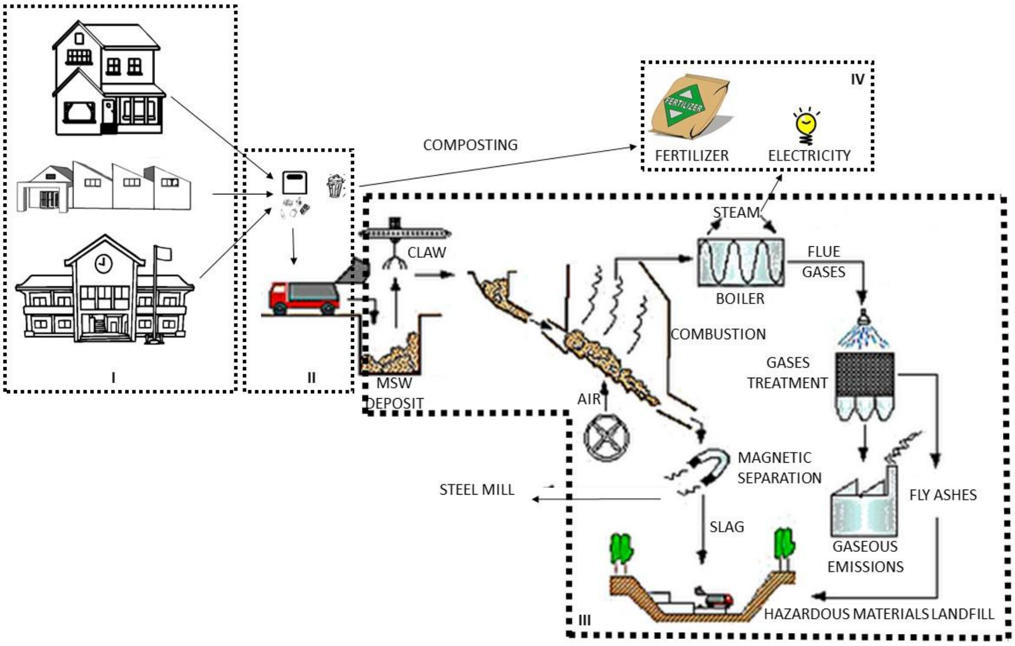

Figure 1. Integrated waste management system operated at the Greater Porto area. ■ ■ ■ ■ ■ (bold dashed lines) representing the chosen boundary for this study.

The waste partition for the collected residues at the referred waste management plant in 2015 is shown in Table 1. As far as the energy recovery plant is concerned, approximately 81% of all the received debris are conveyed towards incineration, which corresponds to roughly 405,000 t/year. From these, the major materials are bio-waste, followed by plastics and health care textiles, as represented in Table 2 [39].

Table 2. Characterization of the material received in the energy recovery plant, in 2015.

Waste Type	Weight %
Bio-waste	37.57
Plastics	12.10
Health care textiles	8.72
Textiles	7.74
Waste < 20 mm	7.59
Composites	6.39
Paper	6.16
Glass	5.53
Cardboard	4.31
Metals	2.45
Others	1.44

2.2. LCA Methodology

2.2.1. Reference Case (Scenario 0)

The scenario depicted in Figure 2 was modelled, taking into account the type of incineration in practice, the landfill usage and also the electricity production. Only major flows are highlighted, the remaining inputs and outputs being reported in a dedicated table (Table 3).

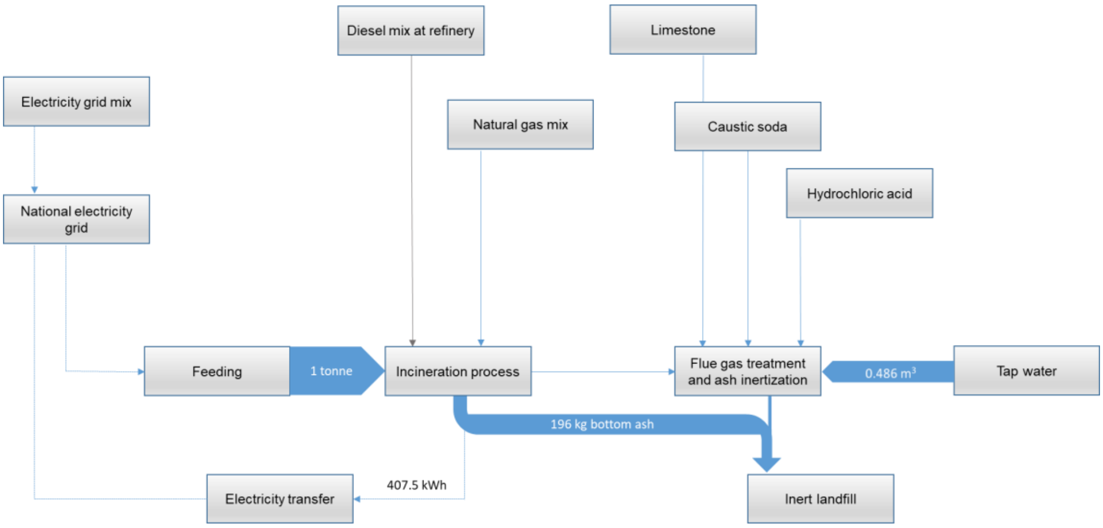

Figure 2. GaBi plan for the reference case (scenario 0)—Portuguese case study.

Table 3. Main lifecycle inventory for the studied ERP (annual data referred for 2015).

Inputs and Outputs	
Waste for incineration, t	407,053
Lower Heating Value, kJ/t	7700
Water, m^3	197,785
Diesel, m^3	1.45
Natural gas, Nm^3	12,556
Auxiliary Materials	
Tripolyphosphate, t	1.06
NaOH, t	16.8
Limestone, t	4703.6
HCl, t	28.8
Activated charcoal, t	202.2
Urea, t	1412.3
Produced steam, t	567
Used in the turbine, t (%)	878,237 (96.9)
Produced electricity, MWh	193,068
Self-consumption, MWh (%)	27,180 (14.1)
Exported to the National grid, MWh (%)	165,888 (85.9)
Exported to the National grid, kWh/t	407.5
Emissions	
HCl, mg/Nm^3	4.8
NOx, mg/Nm^3	164.8
NH_3, mg/Nm^3	7.2
HF, mg/Nm^3	0.1
SO_2, mg/Nm^3	8.3
Total Organic Carbon, mg/Nm^3	0.4
Particulate matter, mg/Nm^3	0.8
CO, mg/Nm^3	4.0
O_2, %	8.8
Hg, µg/Nm^3	0.3
Neutralized ashes, t	32,427
Removed scraps, t	5646
Removed slags, t	79,627

In this case, the utilised landfill was a process that includes only inert material (neutralized residues as well as other non-hazardous substances), standard end-of-life treatment service for specific waste being considered, landfill gas collection and leachate treatment being excluded (for more details, please see the Supplementary Material section). The electricity production was considered taking into account the self-consumption of the plant and the surplus distribution to the national grid. Therefore, the environmental results of this setup can be taken as the most representative for this case study during the year of 2015, constituting scenario 0. Electricity grid mix refers to the electrical input available at Porto region, mainly composed of renewable energies as described elsewhere [40]. Electricity transfer is a GaBi internal process that grants the outputs related to the production of electricity to be taken into account in the overall sustainability analysis.

2.2.2. Scope, System Limits and Functional Unit

Scenario 0 focused on the waste energy valorisation, other stages and activities (as administrative services or hazardous wastes delivery to other entities, such as ferrous scraps which are sent to a national steel managing entity) being left aside. All the inventory data used and the technical explanations about the operation circuits were provided by the waste management entity through the website [38], oral information during guided tours and internal data described by email and in published reports [39]. System boundaries were established according to the data provided by the company, which led to the omission of some processes, namely regarding waste collection and transportation to the treatment facilities (fulfilled by the associated municipalities), as well as the process of wastewater treatment (currently taken care by the municipal wastewater treatment plant).

Most of the information is given on a yearly basis (in this case referring specifically to the year 2015), all the quantities being then normalized to 1 tonne of residues treated in the ERP, which constitutes the functional unit (fu) employed in the LCA software GaBi, used in this study.

Concerning all the steps involved in MSW incineration, the flowchart depicted in Figure 3 was set according to the stipulated limits for the attributional LCA study performed, where slashed lines indicate the boundaries and boxes represent the processes, which are connected by flows (arrows).

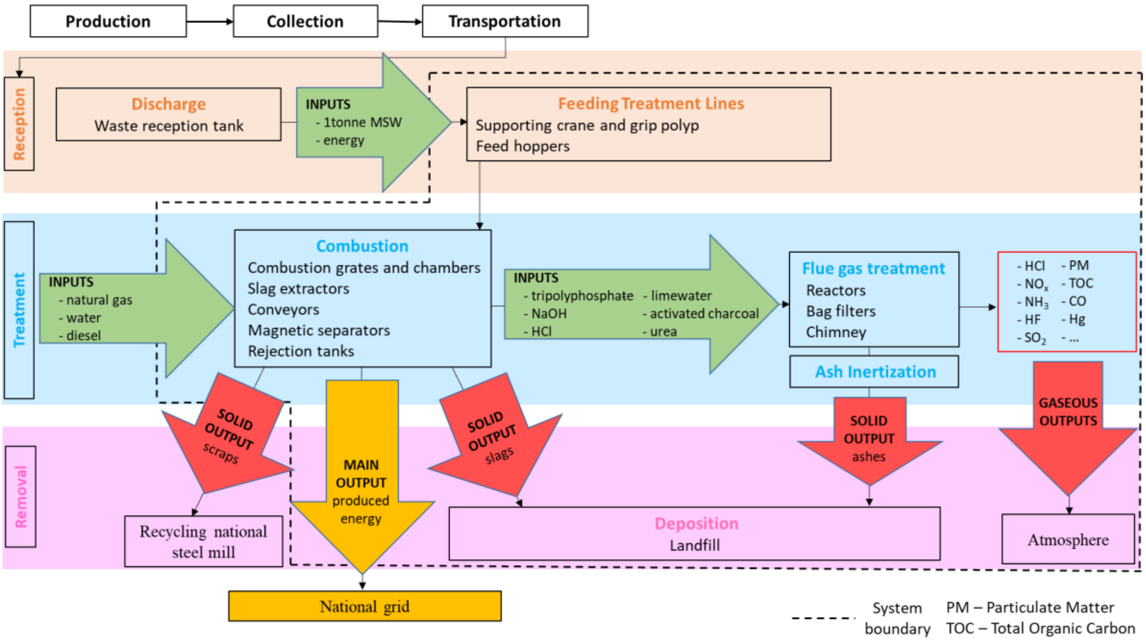

Figure 3. Flowchart of the present LCA study, with defined boundary, inputs and outputs.

2.3. European Average Scenarios

The selected options were a European average incineration (EAI) scenario and a European average landfill (EAL) scenario. The first consists in a plan created on GaBi software (PE International, Stuttgart, Germany) [41] with well-established and documented European processes from the database, simulating the incineration of 1 tonne of residues with average characteristics, inputs and outputs. The former corresponds to the plain situation where waste is sent to landfill, with no previous thermal treatment, once again making use of processes described in the software database [41], adequately standardized for the usual landfill of 1 tonne of municipal solid waste in Europe (for further details please refer to the Supplementary Material section).

2.4. Sensitivity Analysis

Within the energy valorisation of the eligible waste fraction, three main processes occur as can be seen in Figure 2. These are the incineration itself, the flue gas treatment and the neutralization of ashes. Each of these processes has its own inputs and outputs and when differently combined or linked through the available flows, they result in distinct overall impacts. Based on the reference case presented above, four different scenarios were tested to verify the potential effects caused by distinct conditions.

Scenario 1 (Sc1): inclusion of plant construction and waste transportation to the treatment facilities within the system boundaries. This plant was built with the expected duration of 50 years. In this hypothesis, the inputs and outputs related to its construction were taken into account. Regarding waste transportation after collection, the average travel distance to reach the treatment facility is 25 km.

Scenario 2 (Sc2): inclusion of plant construction and wastewater treatment facilities within the system boundaries. Opposite to what happens actually at the evaluated facilities (Sc0), in this scenario the operating process consumes nearly 95% of the produced electricity, only 5% being directed to the national grid.

Scenario 3 (Sc3): using a typical European landfill. The only difference from this scenario to the reference case is the landfill process. In order to better understand the environmental profit of having a restricted type of landfill, a typical landfill for this kind of waste treatment was used in this scenario, representing a solution proposed from the average European situation, several plants being studied to accomplish the net performance of their landfills. This type of disposal includes landfill gas collection, leachate treatment, sludge treatment and deposition (for further details please refer to the Supplementary Material section).

Scenario 4 (Sc4): neglecting electricity production from waste incineration. A virtual plan was created simulating the waste incineration with no electricity production, where electricity production from waste incineration is not accounted neither used to feed the system. For this purpose, electricity production was disregarded, hence self-consumption was admittedly neglected, forcing the system to consider all the energy inputs as if they provided from the national electric grid. This strategy aimed at demonstrating evidence for the chief importance of taking advantage of the waste incineration to produce energy, a highly-demanded asset nowadays.

2.5. Environmental Indicators and Life Cycle Inventory Data

The environmental evaluation methodology chosen within this study was CML 2001, which consists in a database that contains characterisation factors for life cycle impact assessment, such as global warming potential (GWP), acidification potential (AP), human toxicity potential (HTP), abiotic depletion potential (ADP), eutrophication potential (EP) among several others that can be more or less adequate for each assessment, according to the modelled data. These impact categories were evaluated through the use of the product sustainability software GaBi (database version 4.131 distributed by PE International, Stuttgart, Germany), which enabled data modelling and environmental performance estimation rendered by the suitable indicators calculation. These calculations are based on plans, processes, inputs and outputs for the studied system, specific balances being elaborated for each case based on the main operational data, as the life cycle inventory reported in Table 3. For the inventory data of further scenarios, please refer to the Supplementary Material section.

This life cycle inventory enabled the appraisal of the environmental indicators used to assess the energy recovery plant. Table 4 lists the impact categories evaluated, as well as their correspondent units and the applied methodology.

Table 4. Environmental indicators, units and assessment methodology.

Impact Indicator	Units	Assessment Methodology
Abiotic Depletion Potential (ADP)	$kg_{Sb\text{-}eq.}$; MJ	CML 2001
Acidification Potential (AP)	$kg_{SO2\text{-}eq.}$	CML 2001
Eutrophication Potential (EP)	$kg_{PO4\text{-}eq.}$	CML 2001
Global Warming Potential (GWP)	$kg_{CO_2\text{-}eq.}$	CML 2001
Freshwater Aquatic Ecotoxicity Potential (FAETP)	$kg_{DCB\text{-}eq.}$	CML 2001
Human Toxicity Potential (HTP)	$kg_{DCB\text{-}eq.}$	CML 2001
Marine Aquatic Ecotoxicity Potential (MAETP)	$kg_{DCB\text{-}eq.}$	CML 2001
Terrestric Ecotoxicity Potential (TETP)	$kg_{DCB\text{-}eq.}$	CML 2001

As stated in Section 2.2, the functional unit was chosen on a convenient way for the kind of research this study reports: 1 tonne of wastes treated at the energy recovery plant. Therefore, each contributing step was compared on the same basis, making it easier to take conclusions and understand how each of them affects the global results individually.

3. Results and Discussion

Considering the available data collected, all the quantities and flows were normalized according to the chosen functional unit and LCA plan. Resourcing to the software calculation tools, the LCA study was performed and the waste management system was assessed with the environmental indicators shown in Table 4.

A comparison between the environmental impacts originated by each of the settled situations is herein discussed, as well as the establishment of the individual roles of the main processes is specified for the reference case. A contextualization among reported works was attempted where possible, although it was arduous to accomplish due to the myriad of different boundaries, functional units, utilised software, methodologies and also diverse ways to present the results.

3.1. Portuguese Case Study among the European Scenarios

Each impact category was quantified according to CML 2001 methodology for the reference case (Sc0) as well as for the European average scenarios. This way, results from the reference case may be understood under a range of two extreme possibilities: a typical IWMS and a regular sanitary landfill, both for EU-27 region. Results for environmental impact categories are shown in Table 5. A weak point analysis performed with the software (not shown here) helped to construct a better interpretation of the results.

As can be seen from Table 5, in the European average incineration scenario almost all the impact categories have negative values with higher avoided burdens. In fact, exploring the net LCA results in the software, the most impacting category is GWP (approximately 504 $kg_{CO_2\text{-}eq.}$), due to the main output of this scenario: carbon dioxide emissions to air. This has already been observed by other authors for similar studies, values varying between 674 $kg_{CO_2\text{-}eq.}$ and 1490 $kg_{CO_2\text{-}eq.}$ [34], 637 $kg_{CO_2\text{-}eq.}$ and 736 $kg_{CO_2\text{-}eq.}$ [42], 58 $kg_{CO_2\text{-}eq.}$ and 496 $kg_{CO_2\text{-}eq.}$ [43]. In the case of TETP, the positive value achieved is a reflection of the heavy metals released into the atmosphere, namely arsenic (+V), chromium, mercury (+II) and vanadium (+III).

Table 5. Comparison of the environmental impacts for the Portuguese incineration plant and the European standards for incineration and landfill.

Impact Categories	EAI	Sc0	EAL
GWP ($kg_{CO_2\text{-eq.}}$)	503.76	−170.9	655.1
AP ($kg_{SO2\text{-eq.}}$)	−2.426	-242×10^{-3}	167×10^{-3}
EP ($kg_{PO4\text{-eq.}}$)	-38.9×10^{-3}	-38.6×10^{-3}	847×10^{-3}
$ADP_{elem.}$ ($kg_{Sb\text{-eq.}}$)	-8×10^{-3}	-50.1×10^{-6}	9.24×10^{-6}
ADP_{fossil} (MJ)	-4.622×10^{3}	-2.00×10^{3}	550.9
FAETP ($kg_{DCB\text{-eq.}}$)	−1.716	-267×10^{-3}	534×10^{-3}
HTP ($kg_{DCB\text{-eq.}}$)	−125.647	−7.45	1.786
MAETP ($kg_{DCB\text{-eq.}}$)	-340×10^{3}	-26.3×10^{3}	5.30×10^{3}
TETP ($kg_{DCB\text{-eq.}}$)	133×10^{-3}	-59×10^{-3}	1.687

When comparing EAI to Sc0 (reference case), albeit EP results are similar in both cases most of the other categories are at least one order of magnitude less impacting in Sc0. The key factors in this plan are the GWP and TETP outputs, due to the reduction of greenhouse gases from the more effective type of landfill. In the reference case, every impact category depicted negative values which means alleviation of the environmental burdens most probably due to the energy recovery held at the IWMS [44], meaning environment is less jeopardised than if no energetic valorisation was achieved. Other studies also confirm that electricity generation in waste treatment facilities is a key advantage in what concerns environmental impacts, once it saves major quantities of natural resources that would be necessary to assure the equivalent amount of energy, as can be seen by the significant value achieved for the abiotic depletion category. Back in 2005, Morselli et al. [45] assessed a municipal solid waste incinerator in Italy with daily waste capacity less than half of the herein reported input. Although several other stages within the applied boundaries were included (such as plant construction/demolition, waste transportation and waste water treatment), the authors concluded that 7 out of 10 impact categories presented avoided impacts, majorly due to the energy recovery step. More recently, Passarini et al. [46] compared the environmental impact of another Italian incineration plant before and after structural upgrades. Enhanced results were achieved after the revamping operations mostly due to the implementation of new procedures related to flue gas treatment, which reduced air emissions. Nevertheless, the authors guarantee that putting the same type of efforts in the energy recovery process would afford even better outcomes, raising plant sustainability. However, due to the national Italian grid mix evolution along the years and to the actual national energy policies, this valuable impact would represent lower net avoided burdens than the new gas treatment techniques. This paradigm highlights the influence of the current transition from fossil to renewable fuels. With these regards, Burnley et al. [47] also studied the factors influencing the burdens associated to energy recovery from municipal wastes namely metal and aggregate recovery, thermal efficiency and the displacement of fossil electricity by the power generated within incineration. Electricity from waste impact has shown to be highly dependent on the type of fuel to be displaced, coal-based electricity affording maximized benefits, and natural gas replacement performing poorly.

In an attempt to briefly compare the achieved results for the reference case (Sc0) with literature, an interesting work by Hong et al. [44] reports a sensitivity analysis using two different calculation methods from which related categories may be compared. In relation to the herein obtained results, improved values for GWP and ADP fossil (non-renewable energy) were presented when IMPACT 2002+ methodology was used, and for GWP, HTP, FAETP when Recipe methodology was used. In this last case, EP depicted similar values to the ones achieved in this work, TETP and MAETP performing poorly than the current study. A possible explanation for the differences encountered may lie in the distinct boundaries applied once Hong et al. included infrastructure construction, leachate treatment and material recovery in their study [44].

In relation to the European average landfill scenario, this undoubtedly constitutes the poorest option, as may be seen by the positive values for all the impact categories, which means grieving of the natural resources. A work conducted by Liamsanguan and Gheewala [42] compares landfilling and incineration in Thailand. The authors found that, for the specific conditions used in the study, landfill only performed better than incineration in regards to the energy recovery impacts achieved in both scenarios, if landfill gas was recovered for electricity production. This is in line with the results of the present work, once the studied ERP does not pursuit electricity produced through biogas exhaled by the landfill. Other authors also stress that improving landfill gas collection would raise the overall incineration efficiency [48]. Likewise, Jeswani and Azapagic [43] compared incineration to biogas recovery from landfill but under two different perspectives: the disposal of 1 tonne of municipal residues and the generation of 1 KWh of electricity. All the environmental categories assessed (except HTP) depicted lower impacts in the case of incineration for both functional units. Improved results were expected if instead of replacing a natural gas-based electricity grid, heavy fuel oil or coal dependent grid was displaced as stated elsewhere [47,49,50]. A more detailed description of what happens in each of the cases in Table 5 will be performed next.

3.2. Environmental Performance of the Reference Case

3.2.1. Global Warming Potential

GWP is assigned to the effect of greenhouse gases (CO_2, CH_4, N_2O, CO, CFCs, HCFC's, HFC's) which are able to absorb heat radiation, increasing atmospheric temperature [51]. All the contributing substances can be modelled and quantified for different time horizons and, in CML 2001, the utilized parameter is GWP for 100 years. Figure 4 shows a detailed balance of the emissions contributing to GWP and, as can be seen, Sc0 constitutes the most sustainable option, preventing more environmental injury.

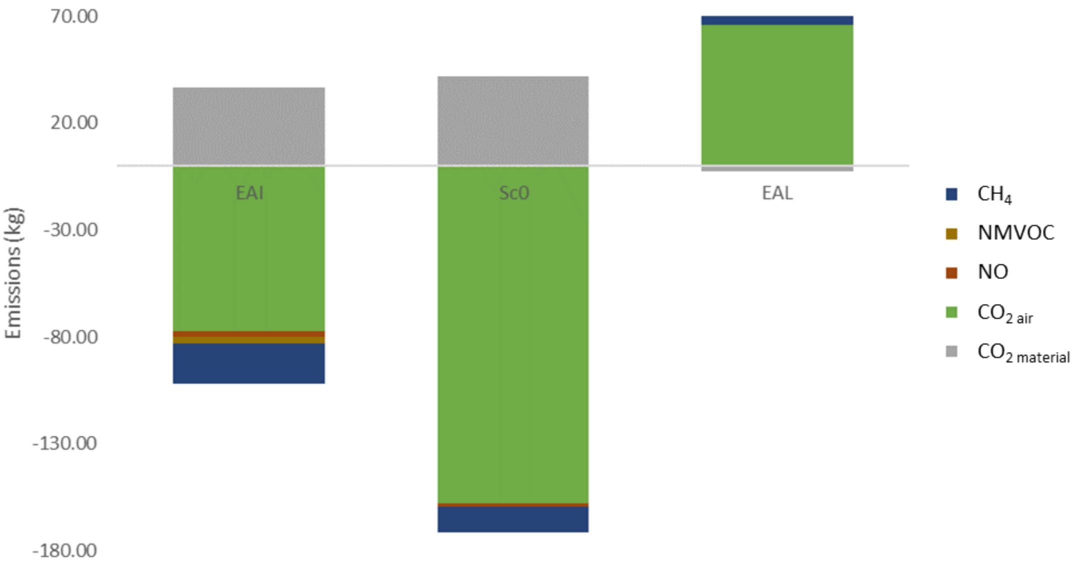

Figure 4. Global warming potential comparison for the reference case (Sc0) among average European scenarios. Results refer to one tonne of treated residues.

This situation is explained through the avoided emissions of CO_2 (-158 $kg_{CO_2\text{-eq.}}$/fu) and CH_4 (-12 $kg_{CO_2\text{-eq.}}$/fu) from the landfill, as reported in another work [52]. Other authors attribute this effect to the CO_2 released from the flue gas to the atmosphere, similar values for the total contribution of Sc0 to GWP being also reported [53]. As shown in Table 2, plastics are the second major type of residues in ERP which constitutes a high calorific value asset contributing to a superior amount of recovered energy from incineration process, explaining the more negative values obtained for Sc0 rather than EAI. In this last scenario, the most problematic contribution to GWP is the CO_2 devastation as material resource (36.7 $kg_{CO_2\text{-eq.}}$/fu). GWP result is in the same order of magnitude as reported by other authors [52,54,55], situations where waste collection and transport to the incineration facilities depicted significantly different values [56] although CO_2 is still the major contribution. It must be stressed that the results on biotic CO_2 in all scenarios were not accounted once they are considered part of the carbon cycle, its effect on the GWP being inconsequential [29,57]. This explains the relatively low contribution shown by the incineration process to GWP, Hong et al. [44] obtaining a result similar to Sc0 in this category (−254 $kg_{CO_2\text{-eq.}}$/fu). CO_2 emission savings are attained with EAI and Sc0. EAL shows a situation in which there is an overbalance of roughly 70 $kg_{CO_2\text{-eq.}}$/fu. This effect was also described in other assessments, Fernández-Nava et al. [52] stating that landfill is the most unfavourable waste management option with even higher CO_2 emissions than this work, and Bezama et al. [58] suggesting upgraded landfill options to reduce this value. Concerning CH_4 emissions, EAL shows that there is only a partial capture, some of it being released to the atmosphere, contrarily to what happens in EAI and Sc0. This was also reported in other cases [50,59].

3.2.2. Acidification Potential

AP is assigned to the release of hydrogen ions into the environment by acidifying substances (SO_2, NO_x, HCl, NH_3), SO_2 being the basis for the determination of this impact. Acid gases that are released into the air or resulting from the reaction of non-acid components of the emissions are taken up by atmospheric precipitations forming "acid rain", which has widespread noxious effects [51]. Figure 5 depicts the contributions of each scenario to this category and it can be seen that the prevailing harmful substances are sulphur dioxide and nitrogen oxides, mainly related to the flue gas treatment process.

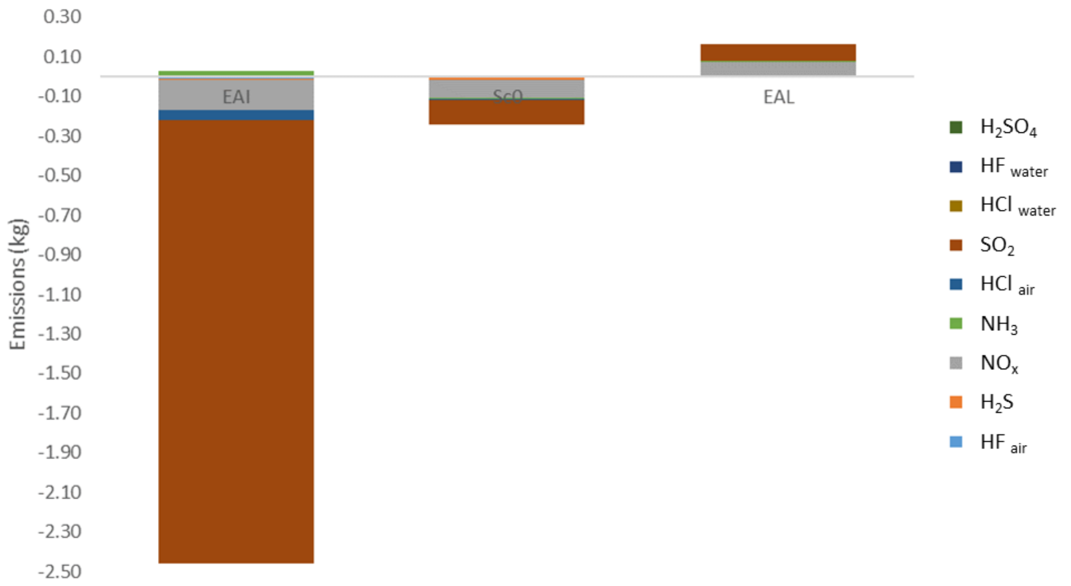

Figure 5. Acidification potential comparison for the reference case (Sc0) among average European scenarios. Results refer to one tonne of treated residues.

In this category EAI portrays the ideal situation, once it keeps back more than 2 $kg_{SO_2\text{-eq.}}$/fu, while Sc0 retains only 0.1 $kg_{SO_2\text{-eq.}}$/fu, showing also NO_x savings one order of magnitude lower than EAI. Nitrogen oxides are mainly released from the landfill process in the reference case, while sulphur dioxide is mostly emitted during flue gas treatment, although being in compliance to the European guidelines. Regarding EAL, this scenario displays positive values for AP, revealing a heft for the environment, probably due to the absorption of these compounds by plants, soil and surface waters leading to leaf damage and super-acidity of the soil, which in turn affects the solubility and hence the availability of plant nutrients, negatively affecting the ecosystems. This trend is also verified by other authors [46], Mendes et al. [59] confirming NO_2 as the most warning emission from incineration, assuring compliant gas treatment systems that effectively abate other emissions. The production of electric power seems to reduce the positive AP impact as also reported in literature [53], some authors also showing that when the energy recovery doubles, AP will no longer be a hazard, becoming an environmental credit [46]. Meanwhile, Banar et al. [56] conclude that stages such as waste collection and transport afford positive AP values, constituting an environmental burden.

3.2.3. Eutrophication Potential

EP comprises all the potential impacts with high environmental levels of macronutrients (nitrogen and phosphorus) causing increased production of aquatic plants, reducing water quality and oxygen depletion in the bottom layers. In the case of incineration, one of the most worrisome substances is NO_x [51] but there are others as can be seen for Sc0, shown in Figure 6.

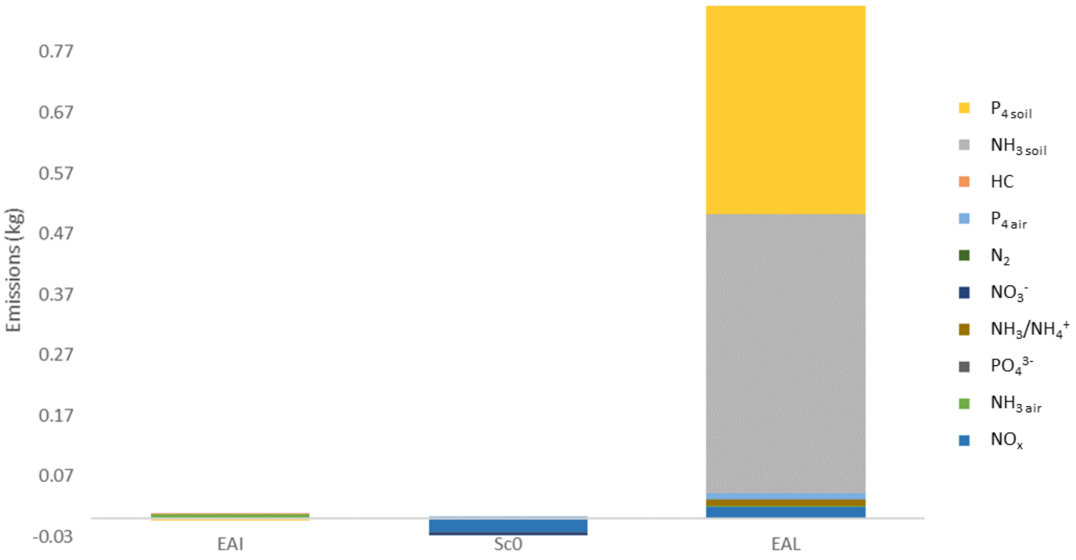

Figure 6. Eutrophication potential comparison for the reference case (Sc0) among average European scenarios. Results refer to one tonne of treated residues.

In the case of EAI the most impacting substance is ammonia (5.98×10^{-3} $kg_{PO_4\text{-eq.}}/fu$), enhanced results being achieved for Sc0 (9.95×10^{-4} $kg_{PO_4\text{-eq.}}/fu$), mostly due to the landfill process. Regarding NO_x, Sc0 depicts negative values caused by the electricity generation. Mendes et al. [59] use "nutrient enrichment potential" to assess what we designate by eutrophication potential, also concluding that nitrogen compounds are the major contributors to this category though the highest level of nitrogen compounds was released to the water. Although the electricity production abates the emission of NO_x, P_4 and NH_3 are the major emissions to the soil, especially in the case of EAL which corresponds to a plan with less restrictive landfilling, permitting the accumulation of these substances also in the soil. The total contribution of this environmental category is somehow comparable to the values found in other reports, Gunamantha and Sarto [60] achieving an EP value double than the Sc0 (-7.87×10^{-2} and -3.86×10^{-2} $kg_{PO_4\text{-eq.}}/fu$, respectively), but far more disruptive in cases where waste collection and transport are considered [56].

3.2.4. Abiotic Depletion Potential

ADP represents the reduction of the total amount of non-renewable natural resources being divided in two sub-categories: elements and fossil resources [28]. This category might be regarded as an indicator of the primary energy usage, to evaluate the efficiency of these resources on the overall system. Figure 7 shows detailed balance for the two ADP categories. In both cases, EAI is the most environmental friendly option, Sc0 showing negative values for all the contributions to ADP while EAL performs poorly.

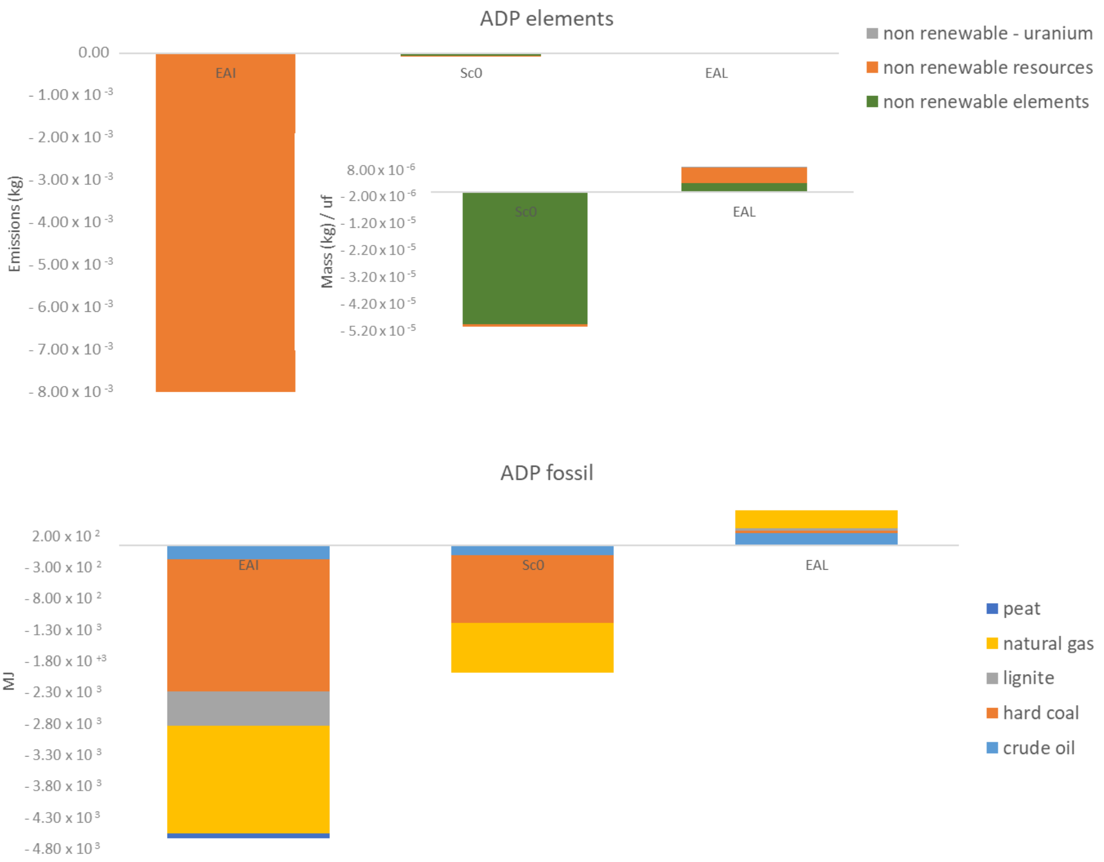

Figure 7. Abiotic depletion potential comparison for the reference case (Sc0) among average European scenarios. **Top**—abiotic depletion of elements, insights for Sc0 and EAL scenarios; **bottom**—abiotic depletion of fossil resources. Results refer to one tonne of treated residues.

Regarding abiotic depletion of elements, EAI contributes to the reconstruction of non-renewable resources like copper, gold, silver, molybdenum, lead and zinc ores (total amount of $-7.92 \times 10^{-3}\ \mathrm{kg_{Sb\text{-}eq.}}/\mathrm{fu}$), while Sc0 subscribe mostly to non-renewable elements copper, gold, lead and molibdenum (total amounts of $-4.98 \times 10^{-5}\ \mathrm{kg_{Sb\text{-}eq.}}/\mathrm{fu}$), due to the electricity production process. Mineral resources had been reported to be enhanced by the production of electric energy elsewhere [46]. EAL shows positive impacts for ADP elements when compared to scenarios that have a previous waste treatment, as reported in another work [52]. The most contributing process for these results is the landfill itself.

Relative to fossil abiotic depletion, EAI shows a better performance again, sharing negative values for major contributions like hard coal, natural gas and lignite. Hard coal and natural gas lead the avoided burdens as a consequence of the landfill process unit, environmental credits being also achieved by the electricity production. This general avoided consumption of fossil sources was also reported by other authors [42,44], although the present study reveals better efficiency once it utilises only 240 MJ/fu and recovers ca. 2000 MJ/fu (similar to a reported study for a Spanish plant [52]). Chaya and Gheewala [61] performed a similar assessment for an incineration plant treating half the daily waste quantity as compared to the reference case in this study and achieved a total energy resource saving of only (−)563 MJ, most of which comes from the effect of electricity production. Menikpura et al. [54] reported a specific case were incineration promoted a reduction of 190% on net resource consumption. Concerning EAL, positive impacts were achieved as stated in literature [58] especially for crude oil and lignite.

3.2.5. Ecotoxicity

Ecotoxicity may be seen as the effect of the chemical substances in environment. Therefore FAETP, MAETP and TETP define the ecotoxicity in freshwater, marine and terrestrial compartments respectively. The substances contributing to these categories are numerous and difficult to point out even if grouped, their biodegradability, bioaccumulation and distribution being modelled. Figures 8–10 show the results obtained for the three sub-categories.

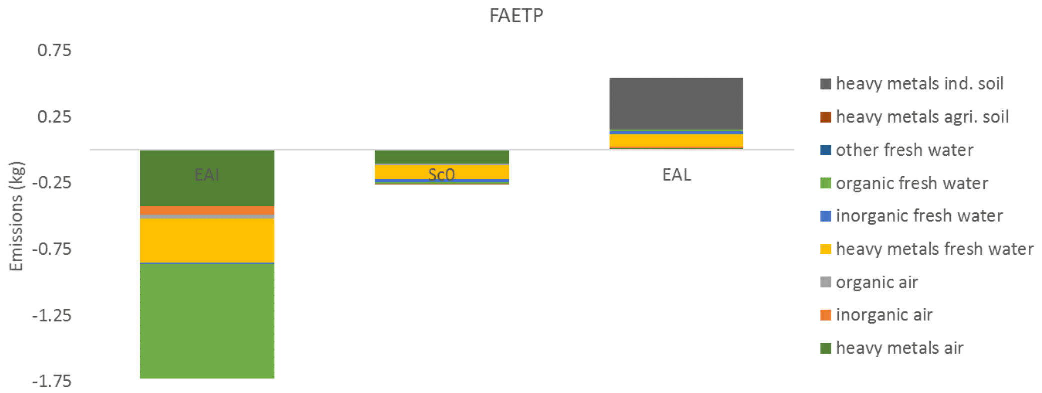

Figure 8. Freshwater ecotoxicity comparison for the reference case (Sc0) among average European scenarios. Results refer to one tonne of treated residues.

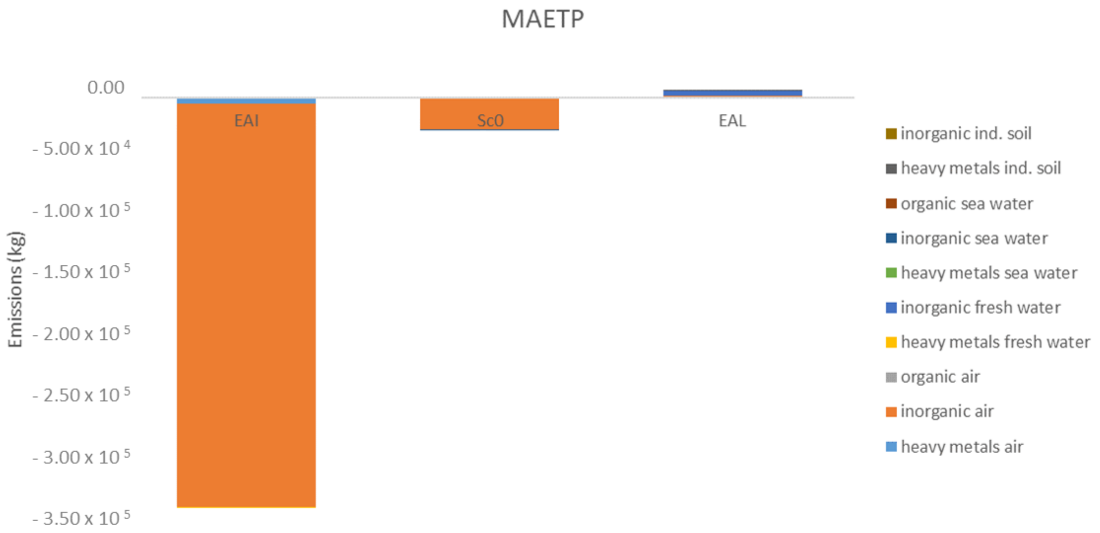

Figure 9. Marine water ecotoxicity comparison for the reference case (Sc0) among average scenarios. Results refer to one tonne of treated residues.

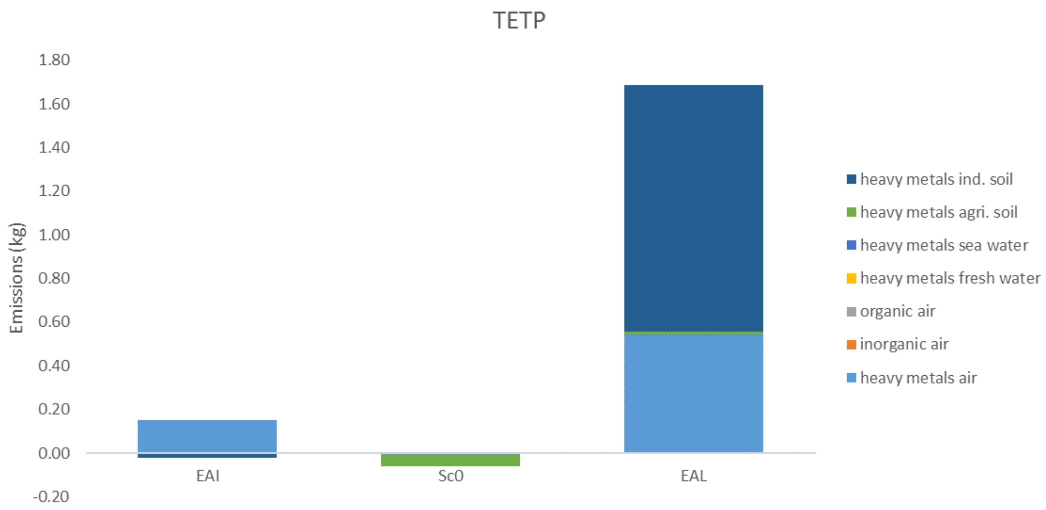

Figure 10. Terrestric ecotoxicity comparison for the reference case (Sc0) among average European scenarios. Results refer to one tonne of treated residues.

In the case of FAETP, EAI shows the best output alleviating fresh water from (−)0.862 $\text{kg}_{\text{DCB-eq.}}$/fu due to organic emissions and (−)0.333 $\text{kg}_{\text{DCB-eq.}}$/fu from heavy metals, and also avoiding the emission of (−)0.424 $\text{kg}_{\text{DCB-eq.}}$/fu from heavy metals to the atmosphere. Sc0 is the second most compliant scenario, with major contributions of −0.105 $\text{kg}_{\text{DCB-eq.}}$/fu and −0.101 $\text{kg}_{\text{DCB-eq.}}$/fu from heavy metals to freshwater and air, respectively. These savings can be attributed to the electricity production, and somehow counterbalanced by the landfill process. Both EAI and Sc0 performed better than reported by Toniolo et al. [34], who attained values between 3.09 and 7.27 $\text{kg}_{\text{DCB-eq.}}$/fu, thus meaning environmental burdens. For MAETP, EAI has the most environmental friendly results again crediting (−)3.35 × 10^5 $\text{kg}_{\text{DCB-eq.}}$/fu of inorganic emissions to the air, Sc0 playing less extensive outputs (−2.55 × 10^4 $\text{kg}_{\text{DCB-eq.}}$/fu). The contributing processes to these results are the production of electricity and the flue gas treatment as corroborated by other studies [46], while landfill reduces these achiements showing positive impacts. Once more, when compared to published literature [34] EAI and Sc0 depicted enhanced results (literature values ranging from 0.79 $\text{kg}_{\text{DCB-eq.}}$/fu to 4.79 $\text{kg}_{\text{DCB-eq.}}$/fu).

As referred earlier, TETP was one of the categories where Sc0 performed better than EAI and this can be proved observing the avoided heavy metals in agricultural soil (−0.0485 $\text{kg}_{\text{DCB-eq.}}$/fu) for the first and the contribution of heavy metals to air for the second (0.153 $\text{kg}_{\text{DCB-eq.}}$/fu). The release of heavy metals in industrial soil is magnified in the case of EAL (1.13 $\text{kg}_{\text{DCB-eq.}}$/fu) due to the landfill process. Other authors confirm the release of heavy metals from the landfill [43] (which are reduced when electricity production is considered) or from the incineration process [22] as the major impact for this category. When compared to published works [34], Sc0 assured a good result for this category of impact (literature values ranging from -7.64×10^{-3} $\text{kg}_{\text{DCB-eq.}}$/fu to 5.77×10^{-2} $\text{kg}_{\text{DCB-eq.}}$/fu).

3.2.6. Human Toxicity Potential

HTP is related to the negative effects of toxic substances (e.g., volatile organic compounds, particulate matter, heavy metals, NO_x, SO_2) on human health. These can be irritative, corrosive, allergenic, irreversible, carcinogenic among others, always excluding indoor exposure [51]. Figure 11 depicts the results of this category in the evaluated scenarios.

In this category, EAI still depicts the best environmental performance when compared to the other scenarios with organic, inorganic and heavy metals emissions to air as well as organic emissions to freshwater being the most pronounced avoided burdens (accounting for a total of nearly −125 $\text{kg}_{\text{DCB-eq.}}$/fu). Sc0 follows the trend but with less visible results (total amount of −7.45 $\text{kg}_{\text{DCB-eq.}}$/fu), a little under other findings: Toniolo et al. [34] reported values between

-62.9 $kg_{DCB\text{-}eq.}$/fu and 156 $kg_{DCB\text{-}eq.}$/fu and Banar et al. [56] values ranging from -182 $kg_{DCB\text{-}eq.}$/fu to 92 $kg_{DCB\text{-}eq.}$/fu. Nevertheless, these are valuable results, consequence of the flue gas treatment and the landfill processes [62]. Comparable conclusions on the scenarios performance were drawn by others [22,52].

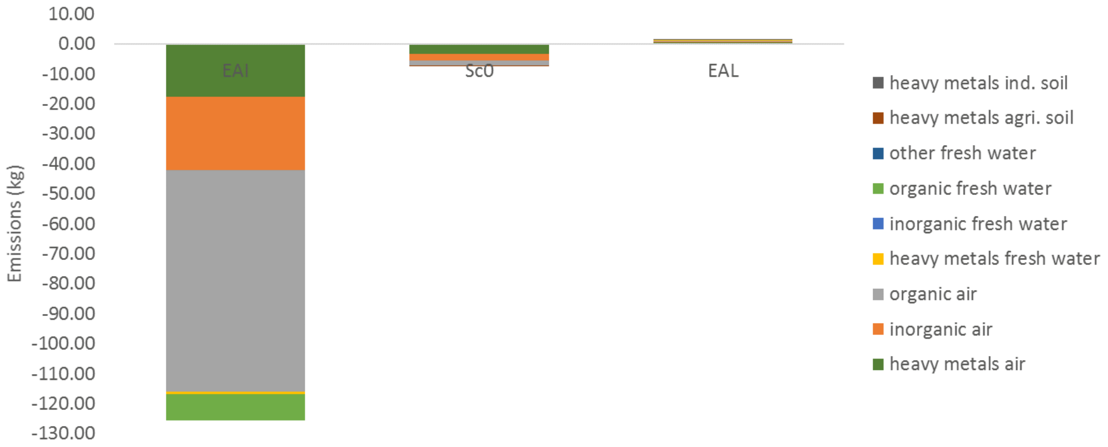

Figure 11. Human toxicity comparison for the reference case (Sc0) among average European scenarios. Results refer to one tonne of treated residues.

3.3. Sensitivity Analysis

After concluding that the actual practices in the ERP give rise to sustainable results, it is interesting to run a sensitivity analysis in order to understand the effect that some methodological changes depict on the environmental impacts. Therefore, the described reference case was compared to four other scenarios and the main results are shown in Table 6. As it is difficult to compare so many different ranges of values, within nine impact categories and five distinct scenarios, a correlation of scenarios 1–4 to the real ERP results is presented in Figure 12. It reports the correlation coefficient between each scenario and the reference case (Sc0), through the comparison of a set of properties. Each scenario is regarded as an environmental matrix composed by the related results for the impact categories and the relationship among the compared scenarios is determined by the differences in their standard deviations.

Table 6. Results for the evaluated scenarios in the sensitivity analysis.

Impact Categories	Sc0	Sc1	Sc2	Sc3	Sc4
GWP ($kg_{CO_2\text{-}eq.}$)	-170.9	58	940	49	39.06
AP ($kg_{SO2\text{-}eq.}$)	-242×10^{-3}	-7.75×10^{-1}	-2.19	-2.04×10^{-1}	1.50×10^{-2}
EP ($kg_{PO4\text{-}eq.}$)	-38.6×10^{-3}	-4.60×10^{-2}	-4.25×10^{-2}	1.84×10^{-1}	1.20×10^{-2}
$ADP_{elem.}$ ($kg_{Sb\text{-}eq.}$)	-50.1×10^{-6}	-4.00×10^{-5}	- - -	-4.87×10^{-5}	1.24×10^{-5}
ADP_{fossil} (MJ)	-2.00×10^{3}	-4.88×10^{3}	- - -	-1.84×10^{3}	464.6
FAETP ($kg_{DCB\text{-}eq.}$)	-267×10^{-3}	-17	3.09	-1.34×10^{-1}	8.00×10^{-2}
HTP ($kg_{DCB\text{-}eq.}$)	-7.45	46	-62.9	-7.161	2.93
MAETP ($kg_{DCB\text{-}eq.}$)	-26.3×10^{3}	-2.16×10^{5}	7.94×10^{-1}	-2.57×10^{4}	2.19×10^{4}
TETP ($kg_{DCB\text{-}eq.}$)	-59×10^{-3}	-3.00×10^{-1}	-7.64×10^{-3}	2.12×10^{-1}	1.42×10^{-1}

- - - Values below the methodology error.

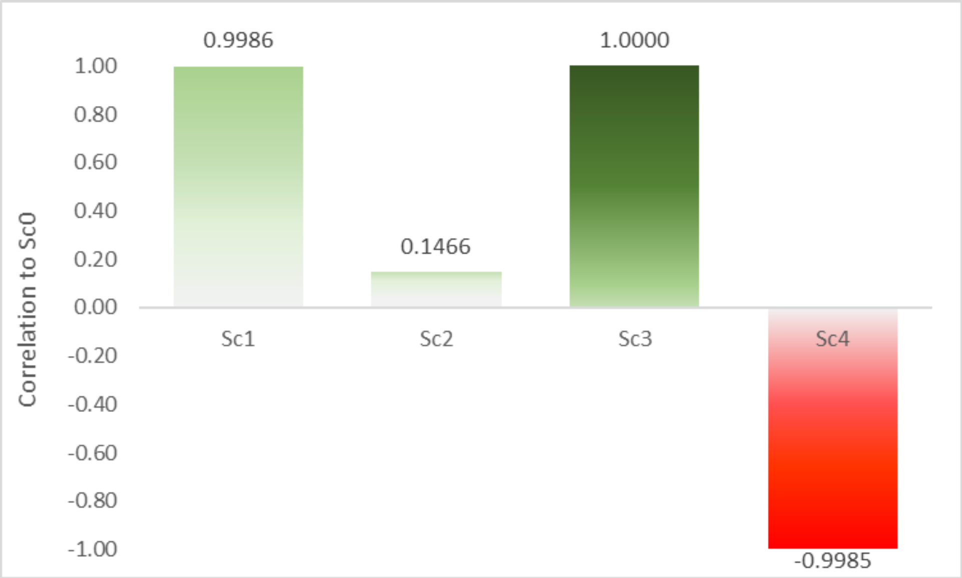

Figure 12. Correlation of different scenarios to the reference case.

Concerning the main differences encountered between Sc0 and Sc1, GWP discrepancy is possibly due to the inclusion of plant construction, waste transport to the incinerator and also bottom ashes processing. Sc1 presented higher CO_2 values (452 kg/t) and higher emissions (600 $g_{DCB\text{-}eq.}$/t of NO_x and 75 $g_{DCB\text{-}eq.}$/t of SO_2 to air) which contributed to GWP and HTP respectively, contrasting to the values achieved for Sc0 (158 kg/t; −217 $g_{DCB\text{-}eq.}$/t of NO_x and −9.92 $g_{DCB\text{-}eq.}$/t of SO_2 respectively). An increase in GWP results when plant construction and/or waste collection and transportation are as also shown by other authors. In a thorough LCA work comparing different waste management scenarios in Macau, Song et al. reported waste transportation as one of the most impacting activities, especially when regarding resources depletion [63], contributing to oil consumption as well as NO_x production. This was recently corroborated in studies conducted to assess different possible municipal solid waste management scenarios for the island of Mauritius [64] and also for selected areas in China and Finland [65]. Observing Figure 12 it may be seen that these different boundaries do not interfere significantly in the correlation between both scenarios, meaning that the global performance of the incineration plant is not affected by these modifications.

Sc2 depicts positive impacts for GWP, FAETP and MAETP especially due to stack emissions of CO_2, NO_x and SO_2 whereas Sc0 depicts negative results for these impact categories. This might probably be explained by the study boundaries that include the construction of the plant facilities (accounting for heavier effects on GWP) as well as the wastewater treatment plant [66] (influencing FAETP and MAETP), which are not within the system herein presented for Sc0. Observing Figure 12 these individual differences between impact categories in each case seem to influence the overall performance of the incineration plant, once the correlation coefficient achieved for Sc0 and Sc2 is very low. As both Sc1 and Sc2 comprehend plant construction, comparing their results allows to see that the waste transportation (Sc1) is a more sustainable option than the inclusion of the wastewater treatment facility (Sc2). This may be observed namely for GWP, FAETP, MAETP and TETP which depict lower harmful effects or even avoided burdens for Sc1 rather than Sc2. As a benefit, Sc2 presents a more sustained option in the case of AP and HTP. This is due to the wastewater treatment facility, which reduces the release of acidic and toxic effluents.

Sc3 shows worse results than Sc0 only for GWP, EP and TETP while AP, $ADP_{elements}$ and FAETP are improved and MAETP, HTP and ADP_{fossil} present similar values to the reference case. This seems to create a balance between all the impact categories, and that is why landfill type does not seem to affect the plant performance as may be confirmed by the high correlation coefficient to Sc0 seen in

Figure 12. Liikanen et al. [65] reported the major contribution of landfill to the increase of EP impact due to NO_x emissions, as well as GWP worsening in the absence of landfill gas collection.

Regarding Sc4, all the impact categories show inferior results to the reference case, owing the environmental burdens to the plant energy requirements, once electricity self-consumption will not occur. Other authors had already reported on the importance of recovering energy through incineration concluding that lower carbon footprints and higher electricity savings are attained [55,64,65].

As Figure 12 shows, two of the suggested scenarios are highly correlated to the reference case, Sc1 presenting a correlation coefficient of 0.999 and Sc3 perfectly matching the global environmental results achieved by Sc0. This means that the changes imposed by these scenarios do not change the final environmental performance of the incineration held under the conditions of this study. Therefore, it is possible to say that the life cycle assessment herein conducted for this IWMS is a robust and reliable evaluation as well as the ERP maintains its environmental sustainability even considering the inclusion of the plant construction plus the waste transport to the treatment facilities and the less restricted type of landfill.

Regarding the inclusion of the wastewater treatment facilities, this will have a visible effect on the plant performance, supported by the low correlation coefficient achieved for Sc2. The possible causes for this may rely on the fact that the wastewater treatment affords sludges, which require processes such as water removal, pathogen destruction and digestion before being disposed. This is in accordance to the fact that this scenario consumes much more energy than the reference one, 95% of the generated energy being reused to operate the plant itself. Relative to Sc4, the result was somehow expected not to correlate so well with the reference case once electricity production is one of the major advantages of the incineration plants, as aforementioned [55]. Therefore, when considering only waste treatment, incineration may be viewed as an unsustainable technique, jeopardizing the environment instead of contributing to its maintenance and equilibrium. This is better explained in the Section 3.4, where a hot-spot analysis allows a more detailed discussion.

In a comprehensive evaluation, Figure 13 shows a comparison of the main resource and emissions for scenario 0 and scenarios 3 and 4 (the strongest and the weakest correlations to Sc0), presented in kg of emissions (or materials) per tonne of treated waste. In the case of Sc0 or Sc3, the waste treatments result in severe avoided impacts for the environment, the most spared segments being material resources, fresh water and air.

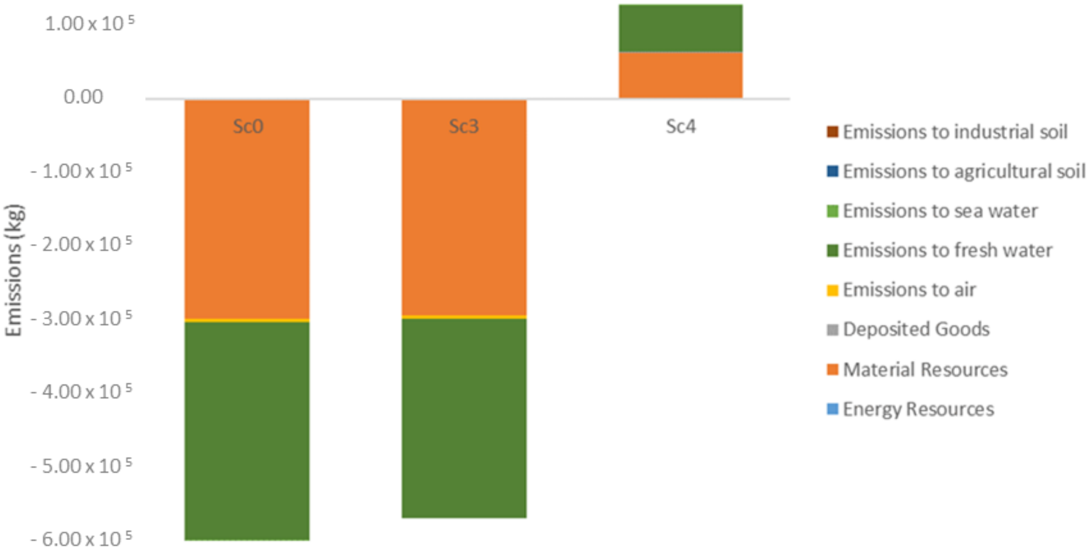

Figure 13. Balance comparison between the reference case (Sc0) and two other alternatives (Sc3 and Sc4). Results refer to one tonne of treated residues.

Figure 13 also shows the added value given by energy production through the incineration process, Sc4 constituting the option with worse results due to this absence: 1 tonne of municipal waste affects more than 120 tonnes of resources available in nature. The production of electrical energy had already been reported as the massive cause for the good performance of incineration plants with this facility, in several impact categories [44,67]. This indicates that using incineration solely as a waste disposal practice would be clearly unsustainable, raising serious environmental issues.

3.4. Hot-Spot Analysis

After a general interpretation of the scenarios with extreme behaviour for the incineration of this waste stream (Sc0 against Sc3 and Sc4), it is interesting to understand what are the main consequences of the type of landfill or the electricity production and reuse within the system for each of the assessed environmental categories, and not only in a global view. For this purpose, a hot-spot analysis was set, Figures 14 and 15 portraying the influence of each of the tested situations.

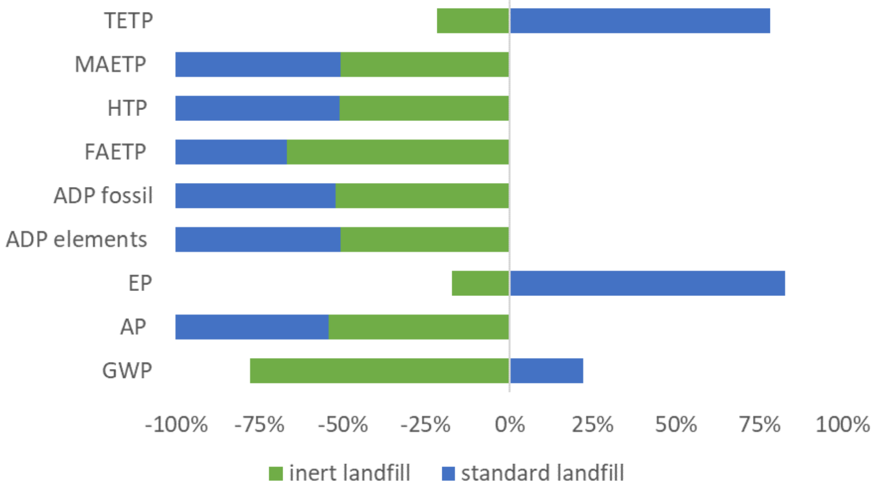

Figure 14. Landfill type effect on the environmental impact categories.

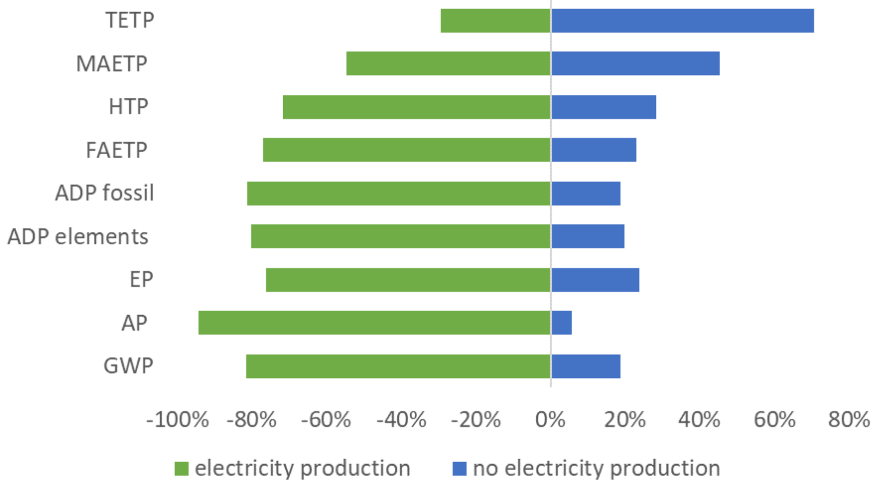

Figure 15. Electricity production and self-consumption effect on the environmental impact categories.

As can be seen from Figure 14, although the correlation coefficient between Sc3 and Sc0 is 1, inert landfill (Sc0) favours a more environment-friendly approach than the typical one (Sc3), all the categories showing negative values for the environmental impacts. This is even more significant in the case of TETP, EP and GWP which, when evaluated under a standard landfill scenario exhibit the opposite behaviour, meaning high environmental damage. MAETP, HTP, ADP (both genres) and AP share relative quotas between the two landfill types, which indicates that they are not influenced by this variable, depicting similar results in both cases, whereas FAETP renders a pronounced effect of approximately 80% towards the inert landfill.

It is relevant to state that in the case of energy recovery held under the conditions presented for Sc0, the inert landfill really is a good asset once it is dedicated to a definite sort of residues, stating a remarkable difference in categories that span from soil, to aquatic and gaseous compartments. Policy makers should be in possession of this kind of information, granting noxious impact remission at the source, instead of having to consider extra means of technical confinement.

In the case of electricity generation within the incineration system (Sc0), Figure 15 shows unquestionable gains for all the assessed categories, TETP and MAETP suffering higher repercussions if energy production is neglected and all the electric inputs have to be supplied by the national grid (Sc4). Regarding the incineration plant herein evaluated, it is not a surprise that it contributes greatly to more sustainable performances, since the plant conversion efficiency is high, with more than 85% of the produced electricity in 2015 being sold to the grid. This benefit has also been reported by Eriksson and Finnveden [49] in recent paper about the key parameters in WtE systems. To enhance this feature, a possible mechanism to be used is the production of electricity from the landfill gas, which can be taken into account in a further stage of development of the facilities, as recommended by other authors [44,48].

3.5. Life Cycle Impact Analysis

After comparing the created scenarios and then their performance in each impact category, the environmental evaluation of the ERP main facilities (Sc0) was done process by process so that weak points were noticed and possibly corrected in the future, if necessary. Figure 16 describes this assessment with an insight for better perception on the flue gas treatment and ash inertization profile, as well as for landfill profile. These results were achieved summing all the contributing inputs and outputs for each of the three main processes presented, as featured by the used software GaBi. For further details, please refer to the Supplementary Material section.

As already commented, the evaluated IWMS is very effective and environmentally sustained, as confirmed here. Furthermore, there are no reports on public health issues related to this facility neither environment emissions above the legal limits. Highlights must be given to the massive avoided burdens in the incineration process unit, mostly due to the electricity production and also to the utilisation of waste as fuel, since this represents a noxious asset for nature and, this way, it is converted into a useful feedstock instead of deposited. In what concerns the electricity production, it must be stressed that this contribution is an approach, once this is not an established process in the plan, rather constituting an output of the incineration process. Hence, the balance was achieved subtracting Sc4 from Sc0, since the electricity production is the only difference between these two scenarios [42], more than 700 $t_{emissions}/fu$ being mitigated. The most protected sections are natural resources (saved by incineration in comparison to their grieving if the waste was landfilled), fresh water and minorly air (through the avoided emissions to these environmental compartments when regularly producing electricity from fossil fuels), meaning an overall avoidance of 1300 $t_{emissions}/fu$.

The electric power generation revealed very prone to the success of the incineration facilities (as in general in EU-27 region) and also in other reported studies [45,46,65], but this is not always true. Depending on the type of resources utilized to compose the grid mix electricity available for the consumer, the avoided impacts generated by the electricity provided from incineration will be different and sometimes not so significant [59].

The flue gas treatment and ash inertization process apports resources consumption and emissions to fresh water (summing nearly 1 $t_{emissions}/fu$) and landfill raises this impact to 7.2 $t_{emissions}/fu$, with the contribution of the deposited products and also non-neglegible emissions to the air. These two processes have harmful impacts on environmental compartments, but landfill is the one presenting worse results as reported elsewhere too [59,68].

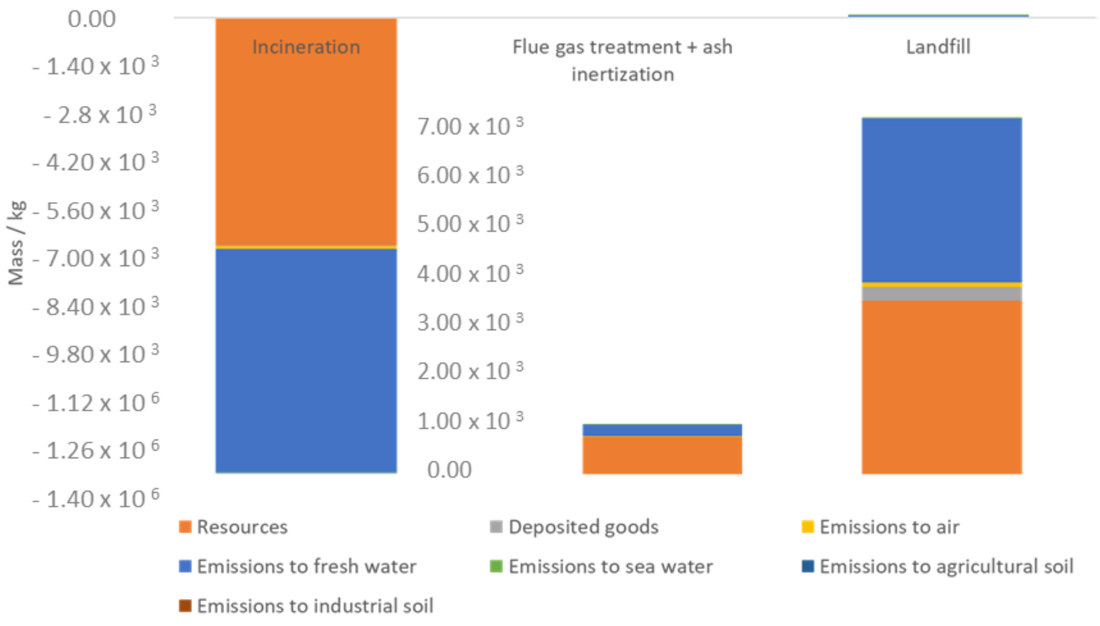

Figure 16. Environmental impact of the incineration processes in the Portuguese case study. Results refer to one tonne of treated residues.

4. Conclusions

A life cycle analysis of an energy recovery plant at the biggest northern city of Portugal was performed for the year 2015. The assessed environmental impacts were compared to European average scenarios in an attempt to position the IWMS amongst a broader panorama, in accordance to all the efforts that are being made worldwide to reduce waste production, to establish new routes for the reuse of everyday products and to embrace several multipurpose opportunities of converting these into more valuable goods. This study aimed at understanding the specific results of this plant, and their effects on the surrounding area and populations, which is a subject that depicts lack of relevant literature. For the majority of the categories, the incineration plant results were within the two European situations ranged, enhanced results being achieved in the case of GWP ($-171\ \mathrm{kg}_{\mathrm{CO_2\text{-}eq.}}$), EP ($-39 \times 10^{-3}\ \mathrm{kg}_{\mathrm{PO_4\text{-}eq.}}$) and TETP ($-59 \times 10^{-3}\ \mathrm{kg}_{\mathrm{DCB\text{-}eq.}}$), due to the landfill restrictions posed by this facility which reduce noxious emissions to environmental compartments, as confirmed by a hot-spot analysis. This analysis also gave insights that may help policy makers when considering landfill types and, most importantly, energy recovery options for similar WtE facilities.

One of the most resource-demanding process is the requirement for electricity, as it depletes natural reservoirs but, within the scope of the assessed ERP, the incineration plan benefits from energy production, which enables a self-consumption situation, the surplus being sent to the national electrical grid, thus generating revenue and avoiding the grieve of environmental deposits. This is the main factor contributing to the absolute sustainable situation provided by the waste incineration, this waste-to-energy technology saving material resources as well as avoiding emissions to fresh water and air. In fact, 1 tonne of energetically valorised waste saves approximately 1.3 million kg of resources and materials, landfill being established as the weak point of the whole system.

When a comparison of the attained outcomes to recently published literature is made, this plant shows a truly favourable environmental profile, holding a solid position amongst the concurrent results. This validates the LCA approach methodology as a favourable and reproducible procedure to take into account when environmental evaluation of the waste management scenarios is on focus.

Another important conclusion to take from this assessment is that the inclusion of the wastewater treatment facility negatively affects the global incineration plant performance, while including the waste transportation to the incineration facilities as well as using a less restrictive landfill do not influence significantly the outcome.

Supplementary Materials: The following are available online at www.mdpi.com/1996-1073/11/3/548/s1. For further details on the different landfill scenarios, please check the Section Supplementary Information 1. For further details on the European average scenarios, please check the Section Supplementary Information 2. For further details on the life cycle inventory for the sensitivity analysis scenarios, please check Section Supplementary Information 3. For further details on the contributions of each main process to the total mass flows, please check the Section Supplementary Information 4.

Acknowledgments: The authors would like to acknowledge LIPOR for providing the necessary data and information, enabling the LCA study in this work. Funding: This work was supported by the Portuguese Foundation for Science and Technology [grant number SFRH/BD/110787/2015].

Author Contributions: Ana Ramos conceived, designed and performed the experimental work, analysed the data and wrote the paper. Carlos Afonso Teixeira enabled and mentored the use of the LCA software. Abel Rouboa supervised the whole work.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

CP	composting plant
EAI	European average incineration
EAL	European average landfill
EF	Ecological Footprint
EMFA	Energy and Material Flow Analysis
ERP	energy recovery plant
HC	hydrocarbons
IWMS	integrated waste management system
LCA	life cycle assessment
NMVOC	non-methane volatile organic compounds
PERSU	*Plano Estratégico para Resíduos Urbanos* (strategic plan for urban residues, in English)
SP	sorting plant
WtE	Waste-to-Energy

References

1. Chen, H.; Jiang, W.; Yang, Y.; Man, X. Global trends of municipal solid waste research from 1997 to 2014 using bibliometric analysis. *J. Air Waste Manag. Assoc.* **2015**, *65*, 1161–1170. [CrossRef] [PubMed]
2. Eriksson, O. *Energy and Waste Management*; Multidisciplinary Digital Publishing Institute: Basel, Switzerland, 2017.
3. Zhang, D.; Huang, G.; Xu, Y.; Gong, Q. Waste-to-energy in China: Key challenges and opportunities. *Energies* **2015**, *8*, 14182–14196. [CrossRef]
4. Ryu, C.; Shin, D. Combined heat and power from municipal solid waste: Current status and issues in South Korea. *Energies* **2012**, *6*, 45–57. [CrossRef]
5. Wagner, T.; Arnold, P. A new model for solid waste management: An analysis of the Nova Scotia MSW strategy. *J. Clean. Prod.* **2008**, *16*, 410–421. [CrossRef]
6. Pires, A.; Martinho, G.; Chang, N.-B. Solid waste management in European countries: A review of systems analysis techniques. *J. Environ. Manag.* **2011**, *92*, 1033–1050. [CrossRef] [PubMed]
7. Ruj, B.; Ghosh, S. Technological aspects for thermal plasma treatment of municipal solid waste-A review. *Fuel Process. Technol.* **2014**, *126*, 298–308. [CrossRef]
8. Inoue, K.; Yasuda, K.; Kawamoto, K. Report: Atmospheric pollutants discharged from municipal solid waste incineration and gasification-melting facilities in Japan. *Waste Manag. Res.* **2009**, *27*, 617–622. [CrossRef] [PubMed]
9. Brems, A.; Baeyens, J.; Dewil, R. Recycling and recovery of post-consumer plastic solid waste in a European context. *Therm. Sci.* **2012**, *16*, 669–685. [CrossRef]

10. Cucchiella, F.; D'Adamo, I.; Gastaldi, M. Sustainable management of waste-to-energy facilities. *Renew. Sustain. Energy Rev.* **2014**, *33*, 719–728. [CrossRef]
11. Cherubini, F.; Stromman, A.H. Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresour. Technol.* **2011**, *102*, 437–451. [CrossRef] [PubMed]
12. Brunner, P.H.; Rechberger, H. Waste to energy-key element for sustainable waste management. *Waste Manag.* **2015**, *37*, 3–12. [CrossRef] [PubMed]
13. Hellweg, S.; Doka, G.; Finnveden, G.; Hungerbühler, K. Assessing the Eco-efficiency of End-of-Pipe Technologies with the Environmental Cost Efficiency Indicator. *J. Ind. Ecol.* **2005**, *9*, 189–203. [CrossRef]
14. Xie, M.; Qiao, Q.; Sun, Q.; Zhang, L. Life cycle assessment of composite packaging waste management—A Chinese case study on aseptic packaging. *Int. J. Life Cycle Assess.* **2013**, *18*, 626–635. [CrossRef]
15. Schwarzböck, T.; Rechberger, H.; Cencic, O.; Fellner, J. Determining national greenhouse gas emissions from waste-to-energy using the Balance Method. *Waste Manag.* **2016**, *49*, 263–271. [CrossRef] [PubMed]
16. Lausselet, C.; Cherubini, F.; Del, A.S.G.; Becidan, M.; Strømman, A.H. Life-cycle assessment of a Waste-to-Energy plant in central Norway: Current situation and effects of changes in waste fraction composition. *Waste Manag.* **2016**, *58*, 191–201. [CrossRef] [PubMed]
17. Magrinho, A.; Didelet, F.; Semiao, V. Municipal solid waste disposal in Portugal. *Waste Manag.* **2006**, *26*, 1477–1489. [CrossRef] [PubMed]
18. Ferreira, S.; Moreira, N.A.; Monteiro, E. Bioenergy overview for Portugal. *Biomass Bioenergy* **2009**, *33*, 1567–1576. [CrossRef]
19. Margallo, M.; Aldaco, R.; Irabien, A.; Carrillo, V.; Fischer, M.; Bala, A.; Fullana, P. Life cycle assessment modelling of waste-to-energy incineration in Spain and Portugal. *Waste Manag. Res.* **2014**, *32*, 492–499. [CrossRef] [PubMed]
20. Agência Portuguesa do Ambiente. *PERSU 2020—Plano Estratégico Para os Resíduos Urbanos*; APA: Lisbon, Portugal, 2014; p. 137.
21. Arena, U.; Mastellone, M.L.; Perugini, F. The environmental performance of alternative solid waste management options: A life cycle assessment study. *Chem. Eng. J.* **2003**, *96*, 207–222. [CrossRef]
22. Tarantini, M.; Loprieno, A.D.; Cucchi, E.; Frenquellucci, F. Life Cycle Assessment of waste management systems in Italian industrial areas: Case study of 1st Macrolotto of Prato. *Energy* **2009**, *34*, 613–622. [CrossRef]
23. Liu, G.; Yang, Z.; Chen, B.; Zhang, Y.; Su, M.; Zhang, L. Emergy evaluation of the urban solid waste handling in Liaoning province, China. *Energies* **2013**, *6*, 5486–5506. [CrossRef]
24. Menikpura, S.N.M.; Gheewala, S.H.; Bonnet, S. Framework for life cycle sustainability assessment of municipal solid waste management systems with an application to a case study in Thailand. *Waste Manag. Res.* **2012**, *30*, 708–719. [CrossRef] [PubMed]
25. Cleary, J. Life cycle assessments of municipal solid waste management systems: A comparative analysis of selected peer-reviewed literature. *Environ. Int.* **2009**, *35*, 1256–1266. [CrossRef] [PubMed]
26. Clift, R.; Doig, A.; Finnveden, G. The application of Life Cycle Assessment to Integrated Solid Waste Management—Part 1—Methodology. *Process Saf. Environ. Prot.* **2000**, *78*, 279–287. [CrossRef]
27. McDougall, F.R.; White, P.R.; Dranke, M.; Hindle, P. *Integrated Solid Waste Management: A Life Cycle Inventory*; John Wiley & Sons: New York, NY, USA, 2008.
28. Ghinea, C.; Petraru, M.; Bressers, H.T.A.; Gavrilescu, M. Environmental evaluation of waste management scenarios—Significance of the boundaries. *J. Environ. Eng. Landsc. Manag.* **2012**, *20*, 76–85. [CrossRef]
29. Thomas, B.; McDougall, F. International expert group on life cycle assessment for integrated waste management. *J. Clean. Prod.* **2005**, *13*, 321–326. [CrossRef]
30. Arushanyan, Y.; Björklund, A.; Eriksson, O.; Finnveden, G.; Söderman, M.L.; Sundqvist, J.-O.; Stenmarck, A. Environmental assessment of possible future waste management scenarios. *Energies* **2017**, *10*, 247. [CrossRef]
31. Arafat, H.A.; Jijakli, K.; Ahsan, A. Environmental performance and energy recovery potential of five processes for municipal solid waste treatment. *J. Clean. Prod.* **2015**, *105*, 233–240. [CrossRef]
32. Astrup, T.F.; Tonini, D.; Turconi, R.; Boldrin, A. Life cycle assessment of thermal Waste-to-Energy technologies: Review and recommendations. *Waste Manag.* **2015**, *37*, 104–115. [CrossRef] [PubMed]
33. Parkes, O.; Lettieri, P.; Bogle, I.D.L. Life cycle assessment of integrated waste management systems for alternative legacy scenarios of the London Olympic Park. *Waste Manag.* **2015**, *40*, 157–166. [CrossRef] [PubMed]

34. Toniolo, S.; Mazzi, A.; Garato, V.G.; Aguiari, F.; Scipioni, A. Assessing the "design paradox" with life cycle assessment: A case study of a municipal solid waste incineration plant. *Resour. Conserv. Recycl.* **2014**, *91*, 109–116. [CrossRef]
35. Morselli, L.; Luzi, J.; De Robertis, C.; Vassura, I.; Carrillo, V.; Passarini, F. Assessment and comparison of the environmental performances of a regional incinerator network. *Waste Manag.* **2007**, *27*, S85–S91. [CrossRef] [PubMed]
36. Den Boer, J.; den Boer, E.; Jager, J. LCA-IWM: A decision support tool for sustainability assessment of waste management systems. *Waste Manag.* **2007**, *27*, 1032–1045. [CrossRef] [PubMed]
37. Herva, M.; Neto, B.; Roca, E. Environmental assessment of the integrated municipal solid waste management system in Porto (Portugal). *J. Clean. Prod.* **2014**, *70*, 183–193. [CrossRef]
38. LIPOR. May 2016. Available online: https://www.lipor.pt/en/municipal-solid-waste/energy-recovery/process-description/ (accessed on 1 May 2016).
39. LIPOR. *Sustainability Report*; LIPOR: Porto, Portugal, 2015.
40. Portugal, E.-E.d. EDP. 2009. Available online: https://www.edp.pt/particulares/apoio-cliente/origem-energia/ (accessed on 14 February 2018).
41. Stuttgart, L.-U.O. *GaBi Software—System and Database for Life Cycle Engineering*; Thinkstep AG: Stuttgart, Germany, 2016; pp. 1992–2016.
42. Liamsanguan, C.; Gheewala, S.H. LCA: A decision support tool for environmental assessment of MSW management systems. *J. Environ. Manag.* **2008**, *87*, 132–138. [CrossRef] [PubMed]
43. Jeswani, H.K.; Azapagic, A. Assessing the environmental sustainability of energy recovery from municipal solid waste in the UK. *Waste Manag.* **2016**, *50*, 346–363. [CrossRef] [PubMed]
44. Hong, J.; Li, X.; Zhaojie, C. Life cycle assessment of four municipal solid waste management scenarios in China. *Waste Manag.* **2010**, *30*, 2362–2369. [CrossRef] [PubMed]
45. Morselli, L.; Bartoli, M.; Bertacchini, M.; Brighetti, A.; Luzi, J.; Passarini, F.; Masoni, P. Tools for evaluation of impact associated with MSW incineration: LCA and integrated environmental monitoring system. *Waste Manag.* **2005**, *25*, 191–196. [CrossRef] [PubMed]
46. Passarini, F.; Nicoletti, M.; Ciacci, L.; Vassura, I.; Morselli, L. Environmental impact assessment of a WtE plant after structural upgrade measures. *Waste Manag.* **2014**, *34*, 753–762. [CrossRef] [PubMed]
47. Burnley, S.; Coleman, T.; Peirce, A. Factors influencing the life cycle burdens of the recovery of energy from residual municipal waste. *Waste Manag.* **2015**, *39*, 295–304. [CrossRef] [PubMed]
48. Chi, Y.; Dong, J.; Tang, T.; Huang, Q.; Ni, M. Life cycle assessment of municipal solid waste source-separated collection and integrated waste management systems in Hangzhou, China. *J. Mater. Cycles Waste Manag.* **2015**, *17*, 695–706. [CrossRef]
49. Eriksson, O.; Finnveden, G. Energy Recovery from Waste Incineration—The Importance of Technology Data and System Boundaries on CO_2 Emissions. *Energies* **2017**, *10*, 539. [CrossRef]
50. Tsiliyannis, C. Report: Comparison of environmental impacts from solid waste treatment and disposal facilities. *Waste Manag. Res.* **1999**, *17*, 231–241. [CrossRef]
51. Stranddorf, H.; Hoffmann, L.; Schmidt, A. *Impact Categories, Normalisation and Weighting in LCA (Påvirkningskategories, Normalisering og Vægtning i LCA–in Danish)*; Environmental News No. 78; The Danish Ministry of the Environment. Environmental Protection Agency: Copenhagen, Denmark, 2005.
52. Fernández-Nava, Y.; del Rio, J.; Rodríguez-Iglesias, J.; Castrillón, L.; Marañón, E. Life cycle assessment of different municipal solid waste management options: A case study of Asturias (Spain). *J. Clean. Prod.* **2014**, *81*, 178–189. [CrossRef]
53. Al-Salem, S.M.; Evangelisti, S.; Lettieri, P. Life cycle assessment of alternative technologies for municipal solid waste and plastic solid waste management in the Greater London area. *Chem. Eng. J.* **2014**, *244*, 391–402. [CrossRef]
54. Menikpura, S.N.M.; Sang-Arun, J.; Bengtsson, M. Assessment of environmental and economic performance of Waste-to-Energy facilities in Thai cities. *Renew. Energy* **2016**, *86*, 576–584. [CrossRef]
55. Tabata, T. Waste-to-energy incineration plants as greenhouse gas reducers: A case study of seven Japanese metropolises. *Waste Manag. Res.* **2013**, *31*, 1110–1117. [CrossRef] [PubMed]
56. Banar, M.; Cokaygil, Z.; Ozkan, A. Life cycle assessment of solid waste management options for Eskisehir, Turkey. *Waste Manag.* **2009**, *29*, 54–62. [CrossRef] [PubMed]

57. US EPA, Office of Atmospheric Programs. *Climate Change Division, Accounting Framework for Biogenic CO_2 Emissions from Stationary Source*; US EPA: Washington, DC, USA, 2011; p. 127.
58. Bezama, A.; Douglas, C.; Méndez, J.; Szarka, N.; Muñoz, E.; Navia, R.; Schock, S.; Konrad, O.; Ulloa, C. Life cycle comparison of waste-to-energy alternatives for municipal waste treatment in the Chilean Patagonia. *Waste Manag. Res.* **2013**, *31*, 67–74. [CrossRef] [PubMed]
59. Mendes, M.R.; Aramaki, T.; Hanaki, K. Comparison of the environmental impact of incineration and landfilling in São Paulo City as determined by LCA. *Resour. Conserv. Recycl.* **2004**, *41*, 47–63. [CrossRef]
60. Gunamantha, M.; Sarto. Life cycle assessment of municipal solid waste treatment to energy options: Case study of KARTAMANTUL region, Yogyakarta. *Renew. Energy* **2012**, *41*, 277–284. [CrossRef]
61. Chaya, W.; Gheewala, S.H. Life cycle assessment of MSW-to-energy schemes in Thailand. *J. Clean. Prod.* **2007**, *15*, 1463–1468. [CrossRef]
62. Chen, D.Z.; Christensen, T.H. Life-cycle assessment (EASEWASTE) of two municipal solid waste incineration technologies in China. *Waste Manag. Res.* **2010**, *28*, 508–519. [CrossRef] [PubMed]
63. Song, Q.; Wang, Z.; Li, J. Environmental performance of municipal solid waste strategies based on LCA method: A case study of Macau. *J. Clean. Prod.* **2013**, *57*, 92–100. [CrossRef]
64. Rajcoomar, A.; Ramjeawon, T. Life cycle assessment of municipal solid waste management scenarios on the small island of Mauritius. *Waste Manag. Res.* **2017**, *35*, 313–324. [CrossRef] [PubMed]
65. Liikanen, M.; Havukainen, J.; Hupponen, M.; Horttanainen, M. Influence of different factors in the life cycle assessment of mixed municipal solid waste management systems—A comparison of case studies in Finland and China. *J. Clean. Prod.* **2017**, *154*, 389–400. [CrossRef]
66. O'Connor, M.; Garnier, G.; Batchelor, W. Life cycle assessment comparison of industrial effluent management strategies. *J. Clean. Prod.* **2014**, *79*, 168–181. [CrossRef]
67. Morselli, L.; Luzi, J.; Bartoli, M.; Vassura, I.; Passarini, F. LCA and an Integrated Environmental Monitoring System as joint tools for incinerator environmental impact assessment. *WIT Trans. Ecol. Environ.* **2004**, *78*, 301–309.
68. Pikon, K.; Gaska, K. Greenhouse Gas Emission Mitigation Relevant to Changes in Municipal Solid Waste Management System. *J. Air Waste Manag. Assoc.* **2010**, *60*, 782–788. [CrossRef] [PubMed]