Solutions for the treatment of undifferentiated fraction of municipal solid waste in Portugal: a life cycle perspective

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Abstract**—** Even though landfilling of waste is the less preferred option in waste management hierarchy, more than half of Portugal's waste is directed to landfills. This hinders actions to achieve landfills disposal target of 10% established by the EU landfill directive 2018/850. By means of a life cycle analysis, this study aims to compare the environmental performance of three waste management scenarios. Environmental performance was measured for global warming potential using CO_2 equivalent for a time horizon of 100 years. Scenario 1 was based on the recovery scheme operated at Valorsul, where municipal solid waste (MSW) without pretreatment is incinerated to produce electricity through a steam turbine. Scenario 2 consisted of a MSW mechanical treatment, including the separation of the organic waste fraction, to obtain a higher quality fuel with lower organic content – refuse derived fuel RDF, which is then gasified. Syngas obtained is then burned and cleaned following same steps as scenario 1. Scenario 3 is similar to scenario 2, however, in this case the organic waste fraction is not separated during pre-treatment, therefore RDF obtained has higher organic fraction. Based on energy and mass balance simulated through Aspen Plus V11 for all scenarios, it was possible to evidence that by having a high quality fuel it is possible to improve environmental impacts (less impact in scenarios 2 and 3 than scenario 1) and that gasification has approximately 70% less CO_2 equivalent emissions than combustion. Although the promising results of gasification regarding its global warming potential, an analysis of the technology status indicates that it doesn't have enough maturity to be a short- or medium-term solution, requiring further investigation and testing.

Keywords: Gasification, Refuse Derived Fuel, Mechanical-Biological Treatment, Combustion, Life Cycle Analysis, Waste to Energy.

I. INTRODUCTION

Municipal solid waste (MSW) constituted a sub-category of total waste generation that is a leading component of human health problems and environmental degradation. MSW consists of non-hazardous products that are discarded every day from households and commercial activities including schools and businesses.

In 2021, Portugal's production of MSW was 5'311,000 tons, corresponding to 513 kg per capita [1]. For the same year, the average value of the European union was 530 kg per capita, therefore Portugal's per capita production is a value slightly below the European average but far from the 2020 target of 410 kg per capita [2]. Statistics shows that Portugal has been increasing its waste production and has gone from being a country with a low waste production to reach the average of the European union with projection to continue growing and contributing to the waste problem.

In Portugal, solid waste management starts with the collection of the 2 main groups into which its collection is divided: undifferentiated waste collection and selective multi-material waste collection. Selective materials correspond to waste that is separated at source, for Portugal this category is glass, plastic/metals and paper/cardboard. In 2021, 78% of the waste generated corresponded to undifferentiated waste collection, 21% to selective collection and 1% to other MSW producers [1].

In terms of waste destination and treatment, there are 2 distinctions: its direct destination and its final destination. The direct destination is the first step after sorting, it's the treatment that is given to the waste that is usable. After their direct destination, the remaining waste is taken to its final destination, where it ends its chain within waste management cycle. For waste that is not usable by any means (neither recycling nor any type of recovery), its direct destination is the same as its final destination: incineration or landfills.

In 2021, according to the Portuguese environmental agency APA, 51% of MSW in mainland Portugal had direct destination without any prior treatment, 31% was directed to landfills and 20% was sent to energetic valorisation by means of mass incineration without previous treatment. The remaining 49% had as direct destination mechanical treatment (6%), mechanical-biological treatment (27%), organic valorisation (2%) and material valorisation (13%) [1].

In 2021, MSW final destination considering all rejected and residual material from direct destination processes was: 55.7% to landfills, 18.8% to energetic valorisation, 7.2% to composing/anaerobic digestion, 14% to recycling and 1.7% other valorisations [1]. This information allows to estimate the real situation of the country, which sends more than half of their waste to landfills. Landfills also receive refuses and rejected materials from treatment processes, explaining the increase in percentage of waste disposed in landfills from direct and final destination (31% vs 55.7%).

This value of waste finally disposed in landfills is high compared to the 23%, the average value for the European union between 1995 and 2021 [3]. This indicates Portugal's challenging situation to meet environmental targets proposed by the Portuguese Strategic Plan for Urban Waste 2030 (PERSU 2030) and the EU landfill directive 2018/850. By 2035, according to both regulations, only 10% of waste could be disposed in landfills [4] and PERSU 2030 established a recycling target of 65% for the same year [5].

Even if targets were met, there is a proportion of unsorted and unrecycled waste (25%) that needs to be managed through the best technical and environmental viable solution. Current thesis is motivated by this challenge of Portugal's waste disposal methods and the national waste management future vision and structure. In particular, the objective is to solve the main research question: What is the best strategy in terms of technology to treat and take advantage of this residual and undifferentiated fraction?

II. BASIC CONCEPTS AND STATE OF THE ART

Currently, incineration is the most mature and implemented waste to energy technology with more than 2,000 plants around the world [6]. However, recent year's trends indicated that waste management sector is trying to develop new solutions to replace incineration. In this sense, advanced thermal conversion technologies, including gasification, are increasingly being tested.

A. Gasification

Thermal gasification can be defined as the process where a carbonaceous solid feedstock is partially oxidized and converted into a mixture of gases called syngas and a solid residue material (char) that remains after light gases and tar have been driven out. Syngas is mainly composed by methane CH_4, carbon dioxide CO_2, carbon monoxide CO, hydrogen H_2 and condensable short-branched hydrocarbon gases (tars). Syngas is a stepping for further processing and production of biochemical and biofuels as well as heat and power [7].

Most of the reactions involved in gasification are endothermic, requiring energy to proceed. Depending on the energy source there are 2 types of gasification: autothermal and allothermal.

It is called autothermal or direct gasification when the required heat is generated directly by carbonaceous feedstock partial oxidation inside the gasifier with the gasification agent. Allothermal systems are heated by external sources such as heat exchangers, plasma gasification or heat carriers as circulated hot bed material or high temperature steam [7].

The relation between oxidizing supplied to oxidizing required for the stoichiometric reaction, called equivalent ratio (ER), should be less than 1 in gasification and could varies between 0.2-0.4 4 [8]. Oxidizing agent could be air, pure oxygen, carbon dioxide CO_2 or high pressure steam. Regarding gasifier configuration, they typically fall into 5 main categories: fixed-bed (updraft and downdraft), fluidized bed (bubbling and circulating), entrained fluidized bed, rotatory kiln and plasma reactors [4].

B. Gasification Projects

Gasification is already a commercialized and mature technology for fossil fuels feedstock, mainly coal. Although in recent years this technology has received increasing attention to treat biomass and municipal solid waste, the share is still low. In 2020, gasification market was led by coal representing approximately 62% of global gasification market, followed by natural gas with approximately 7%, and biomass and waste with less than 5% in total [4].

There are a variety of licensed technologies and processes associated with gasification. Table I summarised some examples of mature technologies widely implemented in commercial gasification plants, along with feedstock type, final product and status up to 2023.

TABLE I. COMMERCIAL GASIFICATION PROJECTS AROUND THE WORLD. STATUS (C) CLOSED, (O) OPERATIONAL, (D) DEMONSTRATION, (S) SHUTDOWN, (A) ABANDONED, (M) MOTHBALLED. [4]

Location	**Feedstock**	**Status**	**Product**	**Technology**
Denmark	Wood chips	O	Electricity	Babcock & Wilcox Volund (Fixed bed)
China	Hazardous Waste	D	Electricity	Alter NRG Westinghouse Plasma (Fluidized bed and Plasma)
UK	RDF	A	Electricity	
UK	RDF	S	Electricity	Biomass Power Limited (Moving grate)
UK	RDF	O	Electricity	
Norway	MSW	O	Electricity	Energos (Moving grate)
UK	RDF	M	Electricity	
Finland	RDF	O	Electricity	Valmet (Circulating fluidized bed)
Japan	MSW	O	Electricity	Kobelco Eco solutions (Bubbling fluidized bed)
UK	RDF	O	Electricity	Outotec Energy Products (Bubbling fluidized bed)
USA	Wood waste	O	Electricity	
Canada	MSW	O	Biomethanol and bioethanol	Enerkem (Bubbling fluidized bed)
Sweden	Woodchips, forest	M	Biomethane	GoBiGas (Dual fluidized bed gasifier,

Location	Feedstock	Status	Product	Technology
	residues and bark			circulating combustion and bubbling gasifier)

Technologies complied in table I shows a trend between the type of reactor used and material to be treated. Technologies based on fixed bed reactors are more focused on homogenous materials such as wood chips. When treating waste as feedstock, technologies uses fluidizing bed designs. Electricity production remains the most common product of gasification.

Many gasification projects have failed due to technical and commercial reasons, either for not meeting energy generation, revenue or emissions targets [9]. Research on facilities in Europe finds that many facilities have failed due to economic problems, citing inadequate revenues and costs from preparing feedstock [9].

The situation behind this is the lack of maturity of the technologies to work in specific with waste. Technologies are usually demonstrated and tested using biomass with constant characteristics and then the process is extrapolated to solid waste. The common factor among these failed projects is the underestimation of the heterogeneous physical and chemical nature of the solid waste and their impact on the stable requirement thermochemical processes.

C. MSW Pre-treatment

An alternative strategy for technologies such as gasification is to process municipal solid waste first to generate refuse derived fuel RDF. Refuse derived fuel is a term applied to segregated components of waste with high energy density [10].

RDF production is a non-standardized process that spans a very wide range of treatments, therefore its quality and characterization is also variable and intentionally will match with thermochemical processes requirements. Typically, RDF production process chain consist of coarse shredding, sifting, ferrous and non-ferrous metals separation and fine comminution [11].

Mechanical treatment (MT) is the basis and the minimum requirement for the production of RDF. The aim of mechanical treatment is to recover materials to recycle and to have at least a shredding step for size reduction according to EN 15359 standard.

Mechanical-biological treatment (MBT), another strategy for RDF production, comprises a combination of mechanical and biological processes to treat MSW. Possible configurations consist always of several mechanical processes including grinding, shredding, dimensional sorting etc., and a core biological process like bio-stabilization, bio-drying, aerobic digestion (composing) and anaerobic digestion [12].

III. METHODOLOGY AND PERFORMANCE ASSESSMENT

Even though the literature of environmental studies of waste management allowed to conclude that gasification is a promising treatment solution [13], the high specificity and heterogeneity of MSW limits conclusions extrapolation and force the need to perform specific analyses. The main motivation of this study is to fulfil the gap of studies conducted using Portuguese MSW composition and conditions and to propose solutions oriented to entities in charge of waste management, the target audience of the study, like Valorsul.

Valorsul is the company responsible for the treatment and valorisation of approximately 950,000 tons of urban solid residues produced annually in 19 municipalities of Lisbon and its Western region. Valorsul has an integrated municipal waste management system composed by sorting centres, organic's treatment and valorisation plant, slag treatment and valorisation facility, landfills and energetic valorisation plant.

LCA was carried out in agreement with the standards ISO 14040: 2006 and ISO 14044:2006. The goal of the study is to compare the potential environmental impact, focusing on global warming potential (GWP) measured as CO_2 equivalent emissions, of 3 waste management scenarios with electricity generation.

Scenario 1 corresponds to the case of mass incineration followed in Valorsul's energetic valorisation plant without pretreatment, with semi dry cleaning scheme and vapour turbine for electricity production. Scenario 2 corresponds to gasification using bubbling fluidized bed reactor (following Outotec technology scheme) with a pretreatment process where organic fraction is separated and directed to an organic treatment. Gas cleaning and energy production scheme is the same for all scenarios. Scenario 3 corresponds to the same gasification technology as scenario 2 coupled with a mechanical pre-treatment process prior gasification without organic fraction separation.

The analysis aims to quantify the contribution from pre-treatment stage, thermochemical transformation and gas cleaning stage of 3 process life cycles based on an average MSW composition managed at Valorsul. The scope of the LCA is a gate-to-gate variation focused on the processes inside Valorsul's energetic valorisation plant: pretreatment, combustion/gasification and gas cleaning.

Functional unit coincides with the service provided by Valorsul, i.e., the thermochemical treatment with electricity generation of 1 ton of undifferentiated municipal solid waste with a composition represented in table III. The 3 scenarios were located in Portugal and the systems boundaries are schematically shown in figure 1, figure 2 and figure 3 with red dotted lines. Waste collection, transportation, solid residues treatment, recycling and final disposal are not included in the boundaries of the study.

Scenario 1 (figure 1) is based on Valorsul's energetic valorisation plant. Waste without pre-treatment is combusted in the mass incineration process. The resulting high temperature flue gas passes through a steam boiler system where it exchanges its heat with water producing superheated steam. Steam passes through a 14-stage condensing steam turbine coupled with an electricity generator. Low temperature flue gas passes through the cleaning system to remove pollutants.

Cleaning system starts with the injection of aqueous ammonia solution in the combustion chamber to remove nitrogen oxides NOx following a non-catalytic reduction scheme. The following step is to remove acid gases, Sulphur compounds SOx and hydrogen chloride HCL, through the injection of limewater with an atomizer. To remove dioxins, furans and heavy metals there is an activated carbon injection in the gaseous flue gas stream. Solid residues, along with unreacted activated carbon and ashes are removed in a bag filter.

Scenario 2 (figure 2) gathers waste pre-treatment, gasification and gas cleaning. Mechanical pre-treatment consists of an initial manual separation to remove bulky waste and an initial size reduction to obtain a particle diameter D_{95} of 150 mm (i.e. 95% of the particles have a diameter less than 150 mm). The shredded waste is separated in a rotatory drum screen into 2 fractions: fine (D_{95} <30 mm) and coarse (D_{95}>30 mm). The fine fraction is the organic waste redirected to biological treatment.

Coarse fraction enters mechanical treatment starting with a magnetic separation system and eddy separator for ferrous and non-ferrous metals separation respectively.

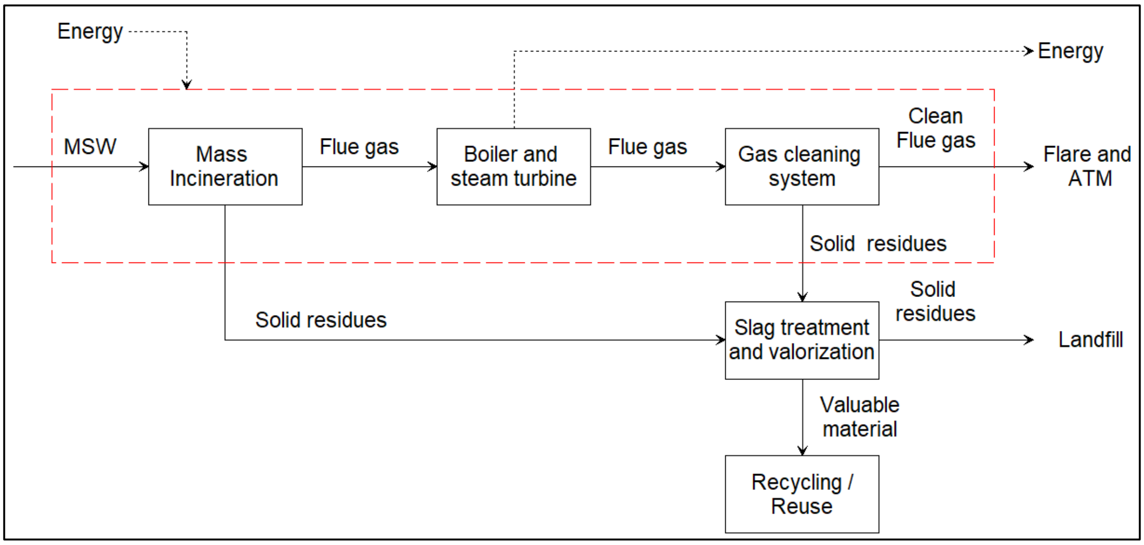


Figure 1. Scenario 1 schematic representation with LCA system boundaries in red dotted lines.

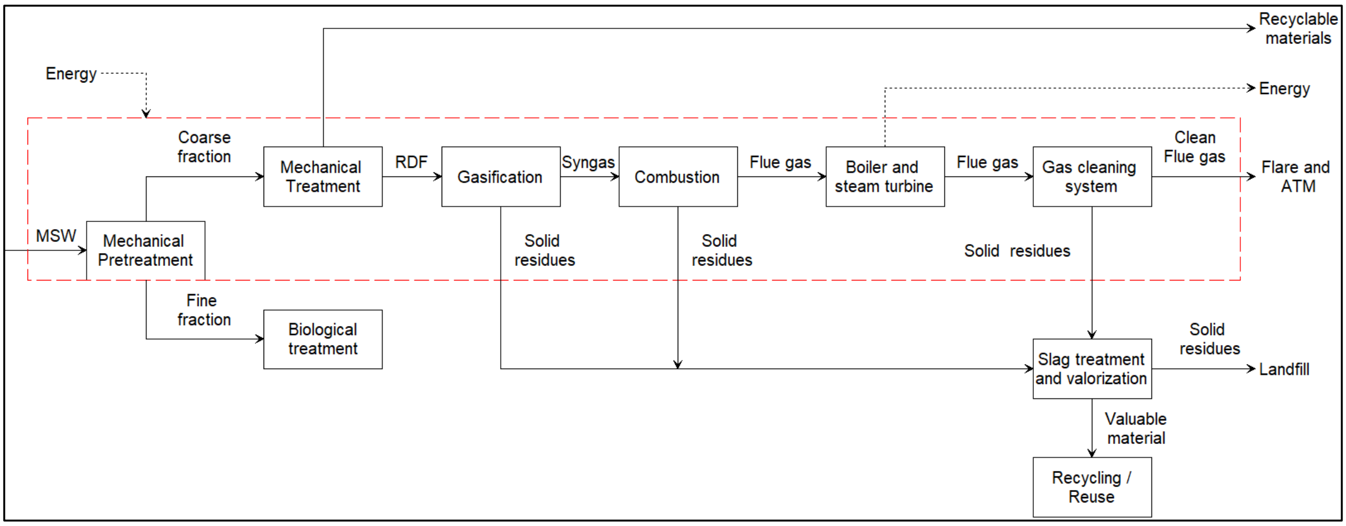


Figure 2. Scenario 2 schematic representation with LCA system boundaries in red dotted lines

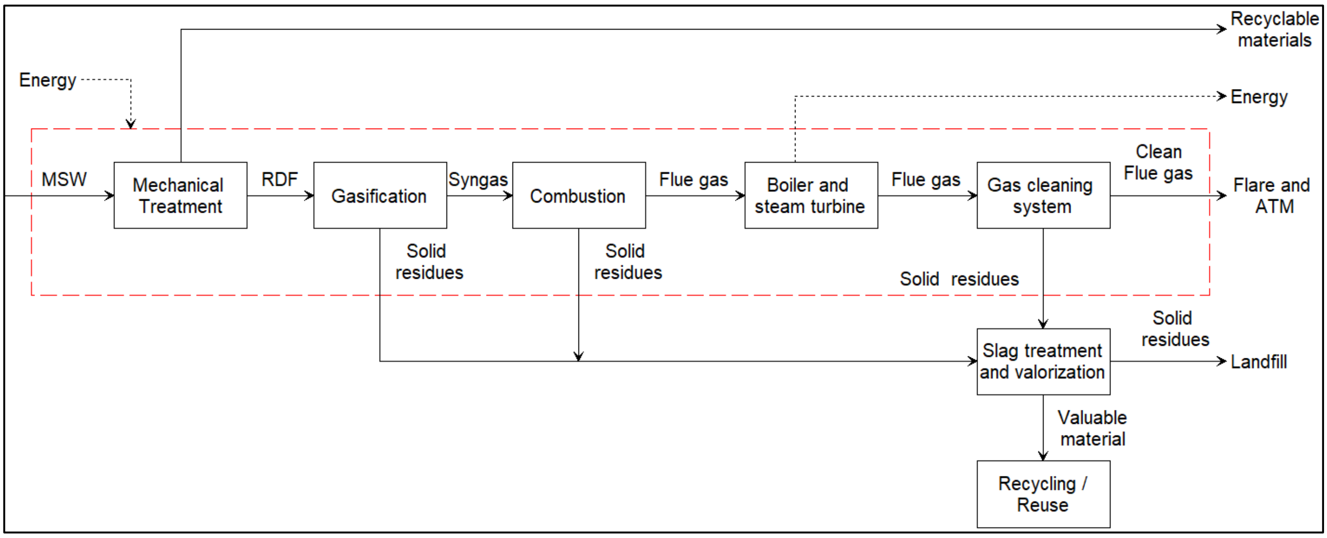


Figure 3. Scenario 3 schematic representation with LCA system boundaries in red dotted lines.

After metal separation for recycling, waste enters an air separation system to separate heavy fraction composed of stones, glass and heavy inert material from light fraction composed by plastic, paper, textiles and others. Light fraction passes a near infrared separation process to separate materials contaminated with chlorine. Finally, waste is subjected to secondary shredding to achieve a particle size of D_{95} 100 mm.

Scenario 2 gasification consist of a bubbling fluidized bed gasifier injected with air as oxidizing agent working under autothermal conditions. Scenario 2 contemplates gasification operating conditions reported for Outotec technology, one of the best consolidated technologies in biomass and waste gasification market [14]. After gasification, produced syngas is taken to a combustion chamber where complete oxidation of the syngas takes place.

Conventional semi dry gas cleaning process is the same in all 3 scenarios and is also implemented by the Outotec technology [14]. The advantage offered by dry cleaning system is to operate below acid and water condensation temperature, avoiding their condensation and reducing corrosion risks [14].

Scenario 3 (figure 3) is a derivation from scenario 2, the only difference is the absence of organic fraction separation in the pre-treatment process. Scenario 3 starts with bulky material separation, initial shredding and whole waste is subjected to the mechanical treatment as scenario 2. The intention of scenario 3 is to evaluate how strict the pre-treatment must be to obtain good performance in gasification.

Although from syngas several products can be obtained, only electricity production was considered since this choice simplifies comparison with existing large-scale incineration waste to energy plant in Valorsul. The examined waste to energy processes allow for material recovery (metals, plastics, inert), following ISO 14044:2006 there is a requirement of allocation to cope with these co-products. The related allocation problem in the LCA modelling was avoided by dividing the unit process to be allocated into sub-processes and colleting the input and output data related to these sub-processes according to ISO 14044:2006 procedure.

Life cycle inventory (LCI) quality of the data is high since the majority of information derive from commercial units. For all scenarios, Portugal's waste management information and Portugal's energy mix characterization was used. The LCA was carried out using Aspen Plus V11 simulations.

Aspen Plus is a process simulation software in the chemical industry with a strong physical and chemical properties database that allows to modeling different industrial unitary operations for both batch and continuous operations. Aspen plus V11, the eleventh version of the software property of Aspen Technology Inc., is a flexible software that integrate process modelling with economic, energy, safety and emissions analysis. [15]

Table II and table III indicate proximate and ultimate analysis in a dry basis (db) for the undifferentiated waste entering the scenarios simulated in Aspen Plus V11 obtained from [16] and [17]. Composition of mixed waste received corresponds to composition received at Valorsul in 2021 according to annual municipal waste report by Portuguese ambient agency [1].

TABLE II. MSW ANALYSED ULTIMATE ANALYSIS IN DRY BASIS. (C) CARBON, (H) HYDROGEN, (O) OXYGEN, (N) NITROGEN AND (S) SULPHUR. [16] [17]

	Ultimate analysis (% db)					
	C	**H**	**O**	**N**	**S**	**Ash**
Plastic	64.8	7.8	24.6	0.0	0.8	2.0
Paper	43.2	5.8	44.2	0.3	0.3	6.1
Glass	-	-	-	-	-	-
Biowaste	61.0	9.6	12.4	0.3	0.1	16.7
Metals	-	-	-	-	-	-
Textiles	45.6	5.5	25.9	3.6	0.0	19.4
Wood	49.4	6.1	43.7	0.1	0.0	0.7
Yard waste	40.3	5.6	38.9	2.0	0.3	12.9
Bulky waste	.	-	-	-	-	-

TABLE III. MSW ANALYSED PROXIMATE ANALYSIS IN DRY BASIS. (FC) FIXED CARBON AND (VM) VOLATILE MATTER [1]

	Proximate analysis (% db)				
	%w MSW	**Moisture**	**FC**	**VM**	**Ash**
Plastic	11.4	0.2	2.0	96.0	2.0
Paper	15.6	10.2	9.4	84.5	6.1
Glass	8.5	-	-	-	-
Biowaste	46.4	70.0	12.0	71.3	16.7
Metals	2.1	-	-	-	-
Textiles	10.4	10.0	7.2	73.3	19.4
Wood	2.5	12.0	14.1	85.2	0.7
Yard waste	1.0	62.0	16.8	70.3	12.9
Bulky waste	2.3	-	-	-	-

Particle size distribution obtained from a study made by the Technical University of Berlin for Germany household waste [18] was used for scenarios simulation. Table IV indicate mass percentage distribution for each size range for MSW constituent.

TABLE IV. MASS PERCENTAGE DISTRIBUTION PER PARTICLE SIZE FOR MSW CONSTITUENT [18]

	Particle size limits in mm			
	10-45	**45-100**	**100-180**	**180-400**
Plastics	5%	25%	30%	40%
Paper	5%	20%	30%	45%
Glass	35%	30%	30%	5%
Biowaste	38%	32%	20%	10%
Yardwaste	38%	32%	20%	10%
Metals	8%	32%	32%	28%
Textiles	2%	11%	27%	60%
Wood	4%	16%	25%	55%

Information gathered to create scenarios was extracted from documents and studies preferably focused on solid waste published less than 5 years. Most of the studies are from 2018 onwards to ensure recent operational values and to capture advances in technologies at commercial level. All the information collected covered the geographical area of Europe, preferably Portugal. Table V summarized scenarios characteristic information

TABLE V. LCA SCENARIOS CHARACTERIZATION

	Scenario 1	**Scenario 2**	**Scenario 3**
Pre-treatment	-	MBT	MT
Technology	Mass incineration	Autothermal bubbling fluidized gasification	
Fuel	MSW	RDF (from MBT)	RDF (from MT)
Pressure	1.013 bar	1.013 bar	
Gasification ER	-	0.4	
Oxidant	Air	Air	
Drying temperature	150°C	150°C	
Pyrolysis temperature	450°C	450°C	
Gasification temperature	-	900°C	
Combustion ER	1.2	1.2	
Combustion temperature	850°C	1000°C	
Flue gas outlet temperature	150°C	140°C	
Superheated vapor condition	420°C and 52.8 bar	400°C and 45 bar	
Steam outlet conditions	55°C and 0.15 bar(a)	55°C and 0.15 bar(a)	
Gas cleaning	Semi dry	Semi dry	
Aqueous ammonia (24% by weight)	785 g / ton MSW incinerated	0.5 mol / mol NO in flue gas	
Activated carbon	460 g / ton MSW incinerated	0.5 kg / ton feedstock	
Hydrated lime	8 kg / ton MSW incinerated	6.5 kg /ton feedstock	
Baghouse filter efficiency	99.9%	95.5%	

The percentages of material recovery in MSW pretreatment, indicated in table VI, were selected as an average value of 6 material recovery facilities in Europe with schemes similar as the pre-treatment for scenarios 2 and 3 [19].

TABLE VI. MATERIAL RECOVERY RATE FOR PAPER, PLASTICS AND METALS. [19]

	%Average material recovery
Total paper recycled	31.1
Total plastic recycled	20.6
Ferrous metals	89.5
Non-ferrous metals	82.8

A. Assumptions

The following hypothesis and assumptions were considered for Aspen Plus V11 simulations and LCA analysis.

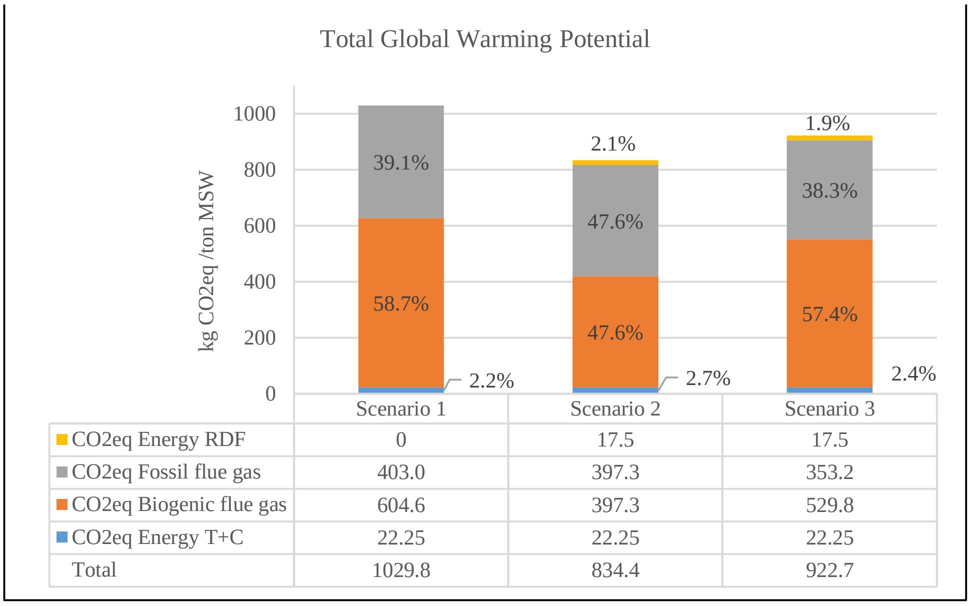
- Tars composition was assumed as benzene C_6H_6 and phenol C_6H_6O.
- As intermediate and end products, syngas and flue gas composition was assumed as only formed by: H_2O, CO, CO_2, CH_4, SO_2, NO, N_2O, N_2, O_2, H_2, H_2S, NH_3, tars and ash.

- Reactors were simulated as isothermal at equilibrium conditions.
- Heat and pressure losses were negligible.
- Ash is inert in reactions.
- Dry air was considered at standards conditions
- Metal's stream is composed by 89.7% ferrous metals and 10.3% non-ferrous metals [20].
- In Aspen Plus V11, glass was simulated as silica, ferrous metals were simulated as iron and non-ferrous metals were simulated as aluminium.
- Bulky items were separated with 100% efficiency.
- MSW composition studied was assumed as constant.
- Energy required was all electrical energy.

IV. RESULTS AND ANALYSIS

LCA was developed for climate change impact category through global warming potential indicator. Global warming potential was measured following EPA 2009 guidelines for 100-year time horizon model using kg of CO_2eq/ton of MSW treated as result indicator. CO_2eq was distinguished in 2 types of sources: biogenic and fossil.

Biogenic CO_2 emissions obtained from biogenic carbon fraction oxidation was fixed as 60% of total CO_2 emissions from untreated MSW and RDF with prior MT scheme and was fixed as 50% of total CO_2 emissions for RDF with prior MBT scheme [21].



	Scenario 1	Scenario 2	Scenario 3
🟨 CO2eq Energy RDF	0	17.5	17.5
■ CO2eq Fossil flue gas	403.0	397.3	353.2
🟧 CO2eq Biogenic flue gas	604.6	397.3	529.8
🟦 CO2eq Energy T+C	22.25	22.25	22.25
Total	1029.8	834.4	922.7

Figure 4. Results of impact assessment for scenarios 1, 2 and 3 - total global warming potential

To account for the environmental impact associated with energy required, CO_2eq emission factor per GWh of electricity estimated by the Portuguese General Direction of Energy and Geology for 2021 was used. Electro producer emission factor was 250 ton CO_2eq/GWH and considered Portugal's electric energy mix for 2021 [22]. In 2021, 66% of Portugal's electricity originated from renewable sources, hydro production corresponded to 31%, wind energy 29%, biomass 6% and solar 1% [23].

Energy required was distinguished in 2 main sources: energy from pre-treatment and energy from thermal process and gas cleaning scheme. Energy from pre-treatment or energy to produce RDF, was fixed as 70 kWh/ton MSW for scenarios 2 and 3 [24]. From information reported by Valorsul for its energetic valorisation plant, self-consumption electricity value of 89 kWh/ton MSW [25] was fixed as the electricity consumption for combustion/gasification and gas cleaning for all 3 scenarios.

Figure 4 summarized global warming potential for 3 scenarios analysed in terms of CO_2eq emissions per ton of MSW. Total global warming potential was categorized as: CO_2eq associated to the energy required for RDF production (exclusively for scenarios 2 and 3 pre-treatment), fossil CO_2eq from flue gas, biogenic CO_2eq from flue gas and CO_2eq from electricity required in thermal and gas cleaning processes (energy T+C in figure 4).

Scenario 1 has the highest impact in terms of global warming with 1029.8 kg CO_2eq/ton MSW, from which 97.8% corresponds to emissions released directly from combustion in flue gas. Energy required for the process represents a minimal share with a value of 2.2% for scenario 1. Scenario 2 is the scenario with the lowest impact with 834.4 kg CO_2eq/ton MSW, 20% less than scenario 1 CO_2eq emissions. Fossil CO_2 for scenario 2 contribution is equal to biogenic CO_2 contribution and biogenic share is higher than for scenario 1, 47.6% in scenario 2 vs 39.1% in scenario 1.

Scenario 3 represented 10% less environmental impact than scenario 1 and 95.7% corresponded to emissions in flue gas. For this scenario1, total CO_2eq is 922.7 kg/ton MSW and more than half of its emissions (57.4%) corresponded to biogenic CO_2.

Following the assumptions made in this study, having pre-treatment and performing gasification as an intermediate step before combustion showed an improvement in environmental impact.

Even though energy consumption increase in scenarios 2 and 3 compared with scenario 1, CO_2eq share associated to total energy (pre-treatment, thermal process and gas cleaning scheme) is low, 4.8% for scenario 2 and 4.3% for scenario 3. Since electricity mix in Portugal has a high share of renewable energies, 66% in 2021 and 88% in 2023 [23], the environmental impact associated to energy is low. The main contributor to waste management environmental impact for all scenarios analysed is the direct emissions of CO_2 in the flue gas.

Figure 5 shows a sensitivity analysis that was performed by varying electricity consumption associated exclusively with pre-treatment. Electricity consumption to produce RDF was varied from 70 kWh/ton MSW to 870 kWh/ton MSW and the new global warming impact was estimated for scenarios 2 and 3 and was compared to the total CO_2eq value for scenario 1 (highest global warming impact scenario)

For scenario 3 to have the same total global warming impact as scenario 1, electrical energy consumed to produce RDF must be greater than 470 kWh/ton MSW, 7 times greater than current estimated value of 70 kWh/ton MSW. The same analysis for scenario 2 with respect scenario 1 indicates that electricity for pre-treatment must be greater than 870 kWh/ton MSW, approximately 12 times higher than actual energy estimation. Since main share of global warming potential indicator is direct emissions of GHG, total impact on climate change for scenarios 2 and 3 is less sensitive to energy requirements variation.

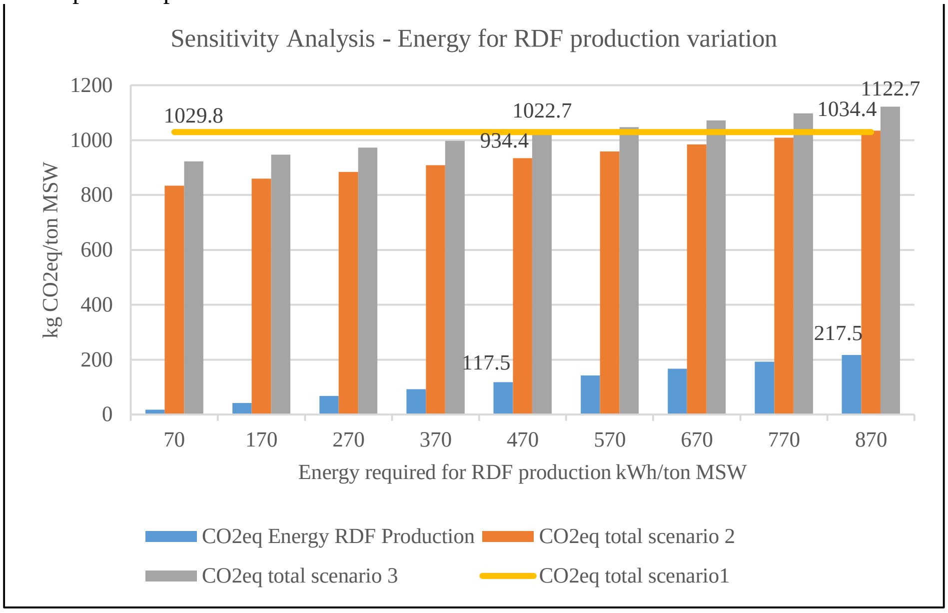


Figure 5. Sensitivity analysis - Global warming potential with energy required for RDF production variation for scenarios 1 and 3

Figure 6 and figure 7 shows 2 sensitivity analysis to cope with waste composition uncertainty. Although variation can be in any of its constituents, plastic was selected for the sensitivity analysis due to its current relevance as recycling material and biowaste was selected due to its moisture content impact.

Figure 6 indicated the behaviour of global warming potential indicator of syngas and flue gas in kg CO_2eq/ton MSW, with biowaste content variation from 100 to 1000 kg/ton MSW. Impact associated with syngas (yellow line for scenario 2 and dark blue for scenario 3) is significantly lower than the impact associated with flue gas for all biowaste values varied.

When analysing each trend line equation slope in figure 6, it is possible to verify that CO_2eq change in the flue gas is higher than CO_2eq change in the syngas (For all scenarios, upper lines in figure 6 corresponding to flue gas behaviour has higher values of slope than syngas behaviour in the 2 bottom lines). For each 100 kg of biowaste in MSW mix increase, impact due to flue gas increase 3 times higher than syngas impact with the same biowaste variation.

Figure 6 also indicate how the scenarios with higher biowaste content in MSW/RDF, scenarios 1 and 3, always have greater CO_2eq emissions than scenario 2. The trend is always increasing.

Plastic content sensitivity analysis behaviour, exposed in figure 7, is similar to biowaste sensitivity analysis; global warming potential indicator is always increasing with the increase in plastic content. Even though the impact on flue gas is always higher than the impact in the syngas, as was the case of previous sensitivity analysis, the magnitude of the slopes in trend lines indicated that flue gas CO_2eq emissions/ton MSW are much more sensitive than syngas emissions.

Comparing biowaste and plastic variation sensitivity study it is possible to analyse that change rate in CO_2eq emissions in flue gas is much higher when plastic is varied than when biowaste is varied. I.e., global warming potential indicator is more sensitive to plastic content variation.

Scenario 1 is the most sensitive to variation in MSW composition, being more sensitive to plastic content since the slope of their trend line in figure 7 the highest value. Proximately analysis of plastic gives an indication of this behaviour, 96% of plastic is volatile material and, regarding ultimate analysis, plastic has higher oxygen content with is related to the formation of contaminants.

Since CO is not a GHG, contrary to CO_2, syngas impact is always less than flue gas and as well, syngas environmental impact behaviour is always less sensitive to composition variation than flue gas. In practice, this implies that gasification process is more flexible because its impact will not vary over a wide range. On the Contrary, flue gas can have negative peaks of environmental impact with MSW variation.

Although the very promising results of gasification regarding its global warming potential, an analysis on the technology status indicates that it does not have enough maturity to be a short- or medium-term solution. Many projects for gasification of MSW or RDF have failed in the recent past, and further investigation and testing is needed to overcome the current technology lack of maturity.

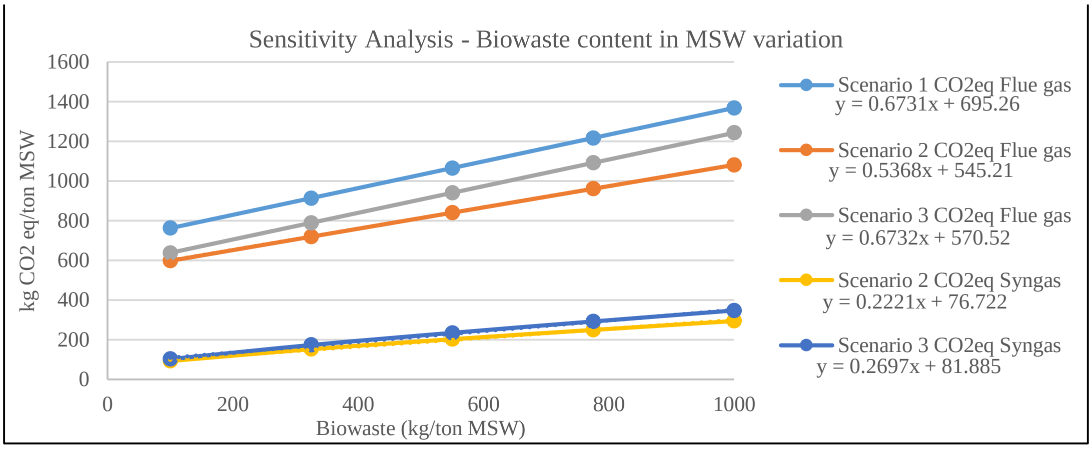


Figure 6. Global warming potential flue gas and syngas with biomass in MSW content variation for all scenarios

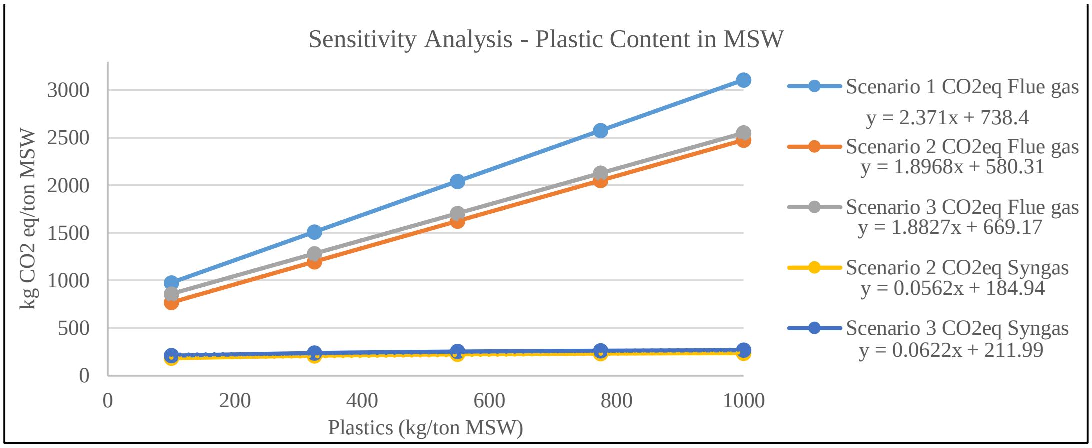


Figure 7. Global warming potential flue gas and syngas with plastics in MSW content variation for all scenarios

V. CONCLUSIONS

The main conclusion, which responds to the objective of this study, is that compared to the other scenarios, the best strategy to treat unsorted MSW with the lowest impact on global warming potential is to pre-treat the waste to produce low organic content RDF and perform gasification combined with combustion. I.e., follow the scheme propose for scenario 2.

The scenario than only represented incineration (scenario 1) is the strategy with highest environmental impact on global warming potential releasing 1030 kg CO_{2eq}/ton of MSW, almost 200 kg CO_{2eq}/ton of MSW more compared with the scenario with lowest environmental impact (scenario 2 with 834 kg CO_{2eq}/ton of MSW emissions) and 107 kg CO_{2eq}/ton of MSW more compared with the scenario with an intermediate performance (scenario 3 with 923 kg CO_{2eq}/ton of MSW emissions).

The production of a better quality fuel, such as the RDF produced in scenario 2, does have a positive impact on the

CO_{2eq} emission; the lower the content of organic material in the fuel and the higher the homogeneity in solid's particle size, the lower the emissions and its environmental impact.

For all scenarios, more than 90% of the CO_{2eq} is due to direct emissions of CO_2 in the flue gas and energy contribution is low because electricity mix in Portugal has a high share of renewable energies. Comparing biowaste and plastic content variation in MSW, thermal processes are more sensitive to plastic content variation, and combustion emissions are more sensible, for both biowaste and plastic variation, than gasification emissions.

Gasification in scenarios 2 and 3 has on average 70% less CO_2 emissions compared to combustion, that is, in terms of impact on global warming, gasification is better than combustion. However, market study allows to conclude that gasification cannot be considered yet a mature and feasible short-or-medium-term solution to be implement in the race to meet the proposed targets for 2030/2035.

For future work it is important to fill the existing gaps regarding the characterization of solid waste and expand the limits of the study. Likewise, a more complete analysis, considering all the impacts dictated by ISO standards will allow for a more complete response to the search for the best solution for waste treatment.

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