

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 3 waste management scenarios. Environmental performance was measured for global warming potential using CO₂ 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 according to the conditions reported by the company Outotec Technology. Syngas obtained is then burned and cleaned following same scheme as scenario 1. Scenario 3 is similar to scenario 2, except for the fact that 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 better 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 CO₂ 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.

Resumo

Embora a deposição de resíduos em aterro seja a opção menos preferida na hierarquia de gestão de resíduos, mais da metade dos resíduos de Portugal são encaminhados para aterros. Isto dificulta as acções para atingir a meta de eliminação de resíduos em aterros de 10% estabelecida pela Diretiva de Aterros da UE 2018/850. Através de uma análise do ciclo de vida, este estudo tem como objetivo comparar o desempenho ambiental de 3 cenários de gestão de resíduos. O desempenho ambiental foi analisado para o potencial de aquecimento global usando CO₂ equivalente para um horizonte temporal de 100 anos. O Cenário 1 baseou-se no esquema de valorização operado na Valorsul, onde os resíduos sólidos urbanos RSU, sem pré-tratamento, são incinerados para produção de eletricidade através de uma turbina a vapor. O Cenário 2 consistiu num tratamento mecânico dos RSU, incluindo a separação da fração orgânica dos resíduos, para obter um combustível de melhor qualidade com menor teor orgânico, combustível derivado de resíduo CDR, que é gaseificado de acordo com as condições relatadas pela empresa Outotec technology. O gás de síntese obtido foi queimado e limpo seguindo o mesmo esquema do cenário 1. O cenário 3 é semelhante ao cenário 2 exceto pelo fato de, neste caso, a fração orgânica dos resíduos não ser separada durante o pré-tratamento, pelo que o CDR obtido tem uma fração orgânica mais elevada. Com base no balanço de massa e energia simulado através do *software* Aspen Plus V11 para todos os cenários, foi possível constatar que ao ter um combustível de melhor qualidade é possível melhorar os impactos ambientais (menos impacto nos cenários 2 e 3 do que no cenário 1) e que a gaseificação tem 70% menos emissões de CO₂ equivalente do que a combustão. Apesar dos resultados promissores da gaseificação relativamente ao seu potencial de aquecimento global, uma análise do estado da tecnologia indica que esta não tem maturidade suficiente para ser uma solução a curto ou médio prazo, necessitando de mais investigação e testes.

Palavras-chave

Gaseificação, Combustível Derivado de Resíduos, Tratamento Mecânico-Biológico, Combustão, Análise do ciclo de vida, Resíduos para energia.

Table of Contents

Acknowledgements	v
Abstract.....	vii
Resumo	viii
Table of Contents	ix
List of Figures	xi
List of Tables	xiii
List of Abbreviations	xv
List of Symbols	¡Error! Marcador no definido.
1 Introduction.....	1
1.1 Municipal Solid Waste - Environmental Impacts.....	2
1.2 Municipal Solid Waste Framework in Portugal	3
1.2.1 Municipal Solid Waste Generation in Portugal	3
1.2.2 Treatment and Destination of Residues in Portugal	3
1.3 Motivation and Objectives	6
1.4 Outline	7
2 Literature Review	8
2.1 Waste to Energy Technologies	9
2.2 Waste Management Life Cycle Assessment	9
2.3 Gasification	11
2.4 Gasification Projects and Commercial Plants	17
2.5 Gasification Challenges and Opportunities.....	24
2.6 Municipal Solid Waste Pre-treatment.....	26
2.6.1 Mechanical Treatment	28
2.6.2 Mechanical-Biological Treatment.....	28
3 Methodology and Performance Assessment	31
3.1 Base Case – Valorsul.....	32
3.2 Life Cycle Assessment.....	34
3.3 LCA Development	36
3.3.1 Goal, Scope, System Boundaries and Functional Unit.....	37
3.3.2 Analysis Tools – Aspen Plus V11	41
3.3.3 Scenarios Characterization.....	42
3.3.4 Assumptions and Limitations	45
4 Results and Discussion	47
4.1 Life Cycle Inventory Analysis	48
4.2 CO ₂ emissions analysis	56

4.3	Analysis Considerations.....	68
5	Conclusions.....	71
	References	74

List of Figures

Figure 1. 1. MSW Direct Destination in Portugal for 2014-2021. Extracted from (Agência portuguesa do ambiente, 2022).....	5
Figure 2. 1. Entrained flow and fixed bed gasifier design sketch. (Lian, et al., 2021).....	15
Figure 2. 2. Fluidized bed gasifier and rotatory kiln reactor design sketch. (Lian, et al., 2021)..	16
Figure 3. 1. Valorsul energetic valorisation plant in <i>Plataforma Ribeirinha da CP, Loures</i> . Extracted from: (Valorsul, 2023)	33
Figure 3. 2. Scenario 1 schematic representation with system boundaries selected for LCA	38
Figure 3. 3. Scenario 2 schematic representation with system boundaries selected for LCA	39
Figure 3. 4. Scenario 3 schematic representation with system boundaries selected for LCA	40
Figure 4. 1. Scenario 1 - Mass incineration section simulation in Aspen Plus.....	48
Figure 4. 2. Scenario 1 - Boiler and steam turbine and gas cleaning sections simulation in Aspen Plus.	48
Figure 4. 3. Scenario 2 - Mechanical pretreatment and treatment sections simulation in Aspen	50
Figure 4. 4. Scenario 2 - Gasification and combustion sections simulation in Aspen.....	50
Figure 4. 5. Scenario 2 - Boiler and steam turbine and gas cleaning sections simulation in Aspen	51
Figure 4. 6. Scenario 3 - Mechanical pretreatment and treatment sections simulation in Aspen	52
Figure 4. 7. Scenario 3 - Gasification and combustion sections simulation in Aspen.....	52
Figure 4. 8. Scenario 3 - Boiler and steam turbine and gas cleaning sections simulation in Aspen	53
Figure 4. 9. Results of impact analysis for scenarios 1, 2 and 3 – Total global warming potential	57
Figure 4. 10. Sensitivity analysis - CO _{2eq} per ton of MSW with energy required for RDF variation for scenarios 2 and 3	59
Figure 4. 11. Sensitivity analysis - CO _{2eq} per ton of MSW with electro producer emission factor variation between 2011 and 2021 for scenarios 2 and 3.....	60
Figure 4. 12. Flue gas and syngas global warming potential indicator and energy estimated in aspen for all scenarios.	61
Figure 4. 13. Sensitivity analysis - Energy estimated at turbine and for drying per ton of MSW with biowaste content in MSW variation for scenario 1.....	62
Figure 4. 14. Sensitivity analysis - Energy estimated at turbine and for drying per ton of MSW with biowaste content in MSW variation for scenario 2.....	63
Figure 4. 15. Sensitivity analysis - Energy estimated at turbine and for drying per ton of MSW with biowaste content in MSW variation for scenario 3.....	64
Figure 4. 16. CO _{2eq} per ton of MSW in flue gas and syngas with biomass in MSW variation for all scenarios.....	66
Figure 4. 17. CO _{2eq} per ton of MSW in flue gas and syngas with plastic in MSW variation for all scenarios.....	67

List of Tables

Table 2. 1. Gasification reaction mechanism. (Shahabuddin & Alam, 2022).....	12
Table 2. 2. Commercial gasification projects MSW/RDF and residues. Status updated by 2023.(Gomes, Brito, Santos, Assis, & Nobre, 2023) (Department for Business, Energy & Industrial Strategy, 2021) (Department for Business, Energy & Industrial Strategy, 2021).....	18
Table 2. 3. Commercial gasification projects biomass and others. Status updated by 2023. (Gomes, Brito, Santos, Assis, & Nobre, 2023) (Department for Business, Energy & Industrial Strategy, 2021)	19
Table 2. 4. RDF gasification and MSW mass incineration performance comparison. Extracted from (Vaish, et al., 2017)	27
Table 3. 1. Environmental impact characterization for LCA	41
Table 3. 2. Proximate and ultimate analysis for MSW simulated in LCA scenarios.....	42
Table 3. 3. Mass percentage distribution of MSW components per particle size diameter range	43
Table 3. 4. Characterization scenarios analysed in LCA. Information extracted from (IEA Bioenergy, 2018) (FICHTNER Consulting Engineers Limited, 2014) (FURTADO, 2014) (Ardolino, Lodato, Astrup, & Arena, 2018) (Sorrels, 2019)	44
Table 3. 5. Material recovery rate for paper, plastics and metals. Extracted from (Themelis & Bourtsalass, 2022).....	45
Table 4. 1. Mass balance results related to the functional unit for scenarios 1, 2 and 3	54
Table 4. 2. Electro producer emission factor variation between 2011-2021 in Portugal. Extracted from (DGEG – Direção Geral de Energia e Geologia, Direção de Serviços de Planeamento Energético e Estatística, 2022)	60
Table 4. 3. HHV and LHV estimation for MSW, RDF and RDF with higher organic content	65
Table 4. 4. Energy comparison between MSW, RDF, RDF with higher organic content and hydrogen produced.....	65
Table A. 1. Extended information commercial gasification projects status around the world. Information updated to 2023.....	81
Table B. 1. Municipal solid waste composition and flows normalized.....	89
Table B. 2. Municipal Solid Waste Complete Ultimate and Proximate Analysis	89
Table B. 3. Aspen Plus specification details on calculation blocks and design spec for all scenarios	90
Table B. 4. Scenario 1 equipment specifications and details simulated in Aspen	93
Table B. 5. Scenarios 2 and 3 equipment specifications details simulated in Aspen	94
Table B. 6. Aspen Plus V11 mass balance for scenario 1 - Part 1	97
Table B. 7. Aspen Plus V11 mass balance for scenario 1 - Part 2	97
Table B. 8. Aspen Plus V11 mass balance for scenario 2 - Part 1	98
Table B. 9. Aspen Plus V11 mass balance for scenario 2 - Part 2	99
Table B. 10. Aspen Plus V11 mass balance for scenario 2 - Part 3	100
Table B. 11. Aspen Plus V11 mass balance for scenario 3 - Part 1	101
Table B. 12. Aspen Plus V11 mass balance for scenario 3 - Part 2	102
Table B. 13. Aspen Plus V11 mass balance for scenario 3 - Part 3	103

List of Abbreviations

APA	Agência Portuguesa do Ambiente
ASR	Automotive Shredder Residue
BEIS	Department of Business, Energy & Industrial Strategy (UK)
BFB	Bubbling Fluidized Bed
CEWEP	Confederation of European Waste to Energy Plants
CFB	Circulating Fluidized Bed
CHP	Combine Heat and Power Cycle
C&I	Commercial and industrial waste
DOE	Department of Energy (U.S)
EPA	Environmental Protection Agency (U.S)
ER	Equivalent Ratio
ETVO	Estação de Tratamento e Valorização Orgânica
EU	European Union
GHG	Greenhouse gas
GWP	Global Warming Potential
HHV	High Heating Value
IEA	International Energy Agency
ITVE	Instalação de Tratamento e Valorização de Escórias
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCA	Life Cycle Analysis
LHV	Low Heating Value
MBT	Mechanical-Biological Treatment Plant
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
MT	Mechanical Treatment Plant
NIR	Near Infrared Spectroscopy
PM	Particulate Matter
PVC	Polyvinyl Chloride
RDF	Refuse Derived Fuel
ROC	Renewable Obligation Certificates
SRF	Solid Recovered Fuel
WtE	Waste to Energy

List of Symbols

Atm	Atmosphere (pressure unit)
CO _{2eq}	Emissions of CO ₂ equivalent
D ₉₅	Percentile 95%
GWh	Giga Watt hour
kg	kilograms
kt	kilotons
kWe	kilowatt electrical power
kWh	kilowatt hour
kWth	Thermal kilowatt
MJ	Megajoule
MWe	Megawatt electrical power
MW _{th}	Thermal Megawatt
Nm ³	Normal cubic meter

Chapter 1

Introduction

This chapter presents a brief overview of the current problems in solid waste management and shows the situation of the waste sector in Portugal, its current capacity, and its trend in waste generation, treatment, and destination. The chapter ends with the motivation of this study. The objectives and a general structure of the document.

1.1 Municipal Solid Waste - Environmental Impacts

Within the current economic and production model, from the extraction of raw materials, through transformation processes to the final consumer, there is an extensive flow of materials and energy. Once the materials have fulfilled their intended purpose, at consumer's discretion, they are disposed as waste. The European Directive 2008/98/EC defines waste as "any substance or object, which the holder discards or intends or is required to discard." (European Union L 312, 2008).

Municipal solid waste (MSW) constitutes a sub-category of total waste generation that is a leading component of human health problems and environmental degradation. Municipal solid waste consists of non-hazardous products that are discarded every day from households, commercial activities including schools and businesses. Municipal solid waste is a highly non-homogeneous mixture composed of product packaging, furniture, food scraps, paper, plastic, cardboard, appliances and other easy to discard items.

One problem related to municipal solid waste is that their actual management system has a challenge to tackle waste in a sustainable manner. MSW management involves activities of collection, transport, storage, treatment and disposal of waste. All of these steps within management demand energy and produce sub-products that cause several impacts on environment and human health. If all required energy comes from fossil fuel sources, greenhouse gas emissions associated with waste management will be higher, along with the impacts on the environment (water sources, soil and air) where sub products, including sub products generated to obtain the energy required, are discharged.

According to the 2022 Portuguese Emissions Inventory, greenhouse gas emissions, without accounting for emissions from the Land Use, Land Use Change, and Forests (LULUCF) sectors, are estimated to be around 57.6 million metric tons of CO₂ equivalent for the year 2020. The waste and wastewater sectors combined are responsible for 7.6% of these, followed by: agriculture 12.2%, industrial processes and products use with 13.2% and finally energy with 67.1% (mostly energy production and transportation). (APA, 2021)

Within emissions inventory, all greenhouse gas generation within the processes involved in solid waste management is included, however, there are two major contributors to emissions in the waste sector: landfills followed by waste incineration. According to the U.S. Environmental Protection Agency (EPA), in 2021, municipal solid waste landfills GHG emissions represented nearly 82% of the total emissions from waste sector in the USA (EPA, 2022). The second most contributing source of GHG in waste sector is waste combustion or incineration, mainly due to pollutants leaving the system in the flue gas and as solid residues.

MSW landfilling impact on environment is not exclusively related with GHG emissions, the natural disintegration of waste, cause the emerge of harmful pollutants that agglomerate and creates detrimental effects to air, water, and soil environment such as:

- Generation of leachate that constitute toxic effects on water environment

- Depleting land resources;
- Aesthetic nuisance - mainly due to foul odor, noise, dust, appearance, and susceptibility to explosion/fire hazards. Bad odors generate olfactory contamination to nearby populations and attracting insects that can be disease vectors;
- Risk associated with landfill stability;
- The uncontrolled production of landfill gas that leads to ozone depletion, contribute to global warming effect and causes uncontrolled fire hazards in the waste piles.

1.2 Municipal Solid Waste Framework in Portugal

1.2.1 Municipal Solid Waste Generation in Portugal

In 2020, waste sector in Portugal was responsible for the emission of 4,352 kt CO_{2eq} of greenhouse gases (European Environment Agency, 2023). This emission is the result of the generation of 5'279,000 tons of municipal waste of which 95% was generated in mainland Portugal in the same year (Agência portuguesa do ambiente, 2021). In 2021, Portugal's production of MSW was 5'311,000 tons corresponding to 513 kg per capita (Agência portuguesa do ambiente, 2022). 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 and far from the 2020 target of 410 kg per person (Agência portuguesa do ambiente, 2021).

Statistics show 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. For 2005, the average value for the European Union EU was 506 kg per capita and Portugal's production was 452 kg per capita. In 2021, as previously discussed, the difference between Portugal's production and European average was approximately 3%.

Although the generation of waste is an undesired and sometimes unavoidable consequence of most processes, there are two factors that increase its production: the economic growth of society and population growth. Waste generation growth in Portugal between 2014 and 2021 has averaged 2%, this growth is mainly due to the economic growth of the country because its population growth rate is relatively low (Agência portuguesa do ambiente, 2022). Portugal had on average for 2021 a population growth rate of 0.3% per year, a value lower than the world average (The World Bank, 2022).

1.2.2 Treatment and Destination of Residues in Portugal

In Portugal, solid waste management starts with the collection of the two 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

corresponds to glass, plastic/metals and paper/cardboard. In 2021, 78% of the waste generated corresponded to undifferentiated waste collection, 21% corresponds to selective collection and 1% to other MSW producers (Agência portuguesa do ambiente, 2022). The trend since 2014 is that the percentage of undifferentiated collection decreases (from 86% to 78%) while selective collection, and with this users' effort to separate waste, has increased from 14% in 2014 to 21% in 2021.

In terms of existing infrastructures, mainland Portugal has 30 sorting stations, 19 mechanical/biological treatment units, 5 biological treatment units dedicated to biowaste selectively collected, 34 landfills and 2 energy recovery plants located in Porto and Lisbon, which are responsible for the waste management units of LIPOR and Valorsul respectively (Agência portuguesa do ambiente, 2022). On the island of *Madeira* there is an incineration unit under the responsibility of company *Águas e Resíduos da Madeira* and under the responsibility of company Teramb there is another incineration unit on the third island of the *Azores*, for a total of 4 incineration units with energy recovery in Portugal (Agência portuguesa do ambiente, 2021).

According to the confederation of European Waste-to-Energy plants (CEWEP), in 2020 Europe had 504 WtE plants operating, without including hazardous waste incineration plants, that treated thermally 101 million tonnes of waste (CEWEP, 2021). The incinerators units in Portugal, 4 in total, thermally treated 1.16 million tonnes of waste, 1.14% of Europe total incineration capacity.

In terms of the destination and treatment of waste, there are two distinctions: its direct destination and its final destination. The direct destination is the first step of the waste after sorting, it is the treatment that is given to the waste that is usable. After their direct destination, where they are treated and valorised, the remaining waste is taken to its final destination, where it ends its chain within the 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 landfill. Figure 1. 1 indicate direct for municipal solid waste in mainland Portugal between 2014 and 2021 according to Portuguese environmental agency APA (*Agência portuguesa do ambiente*).

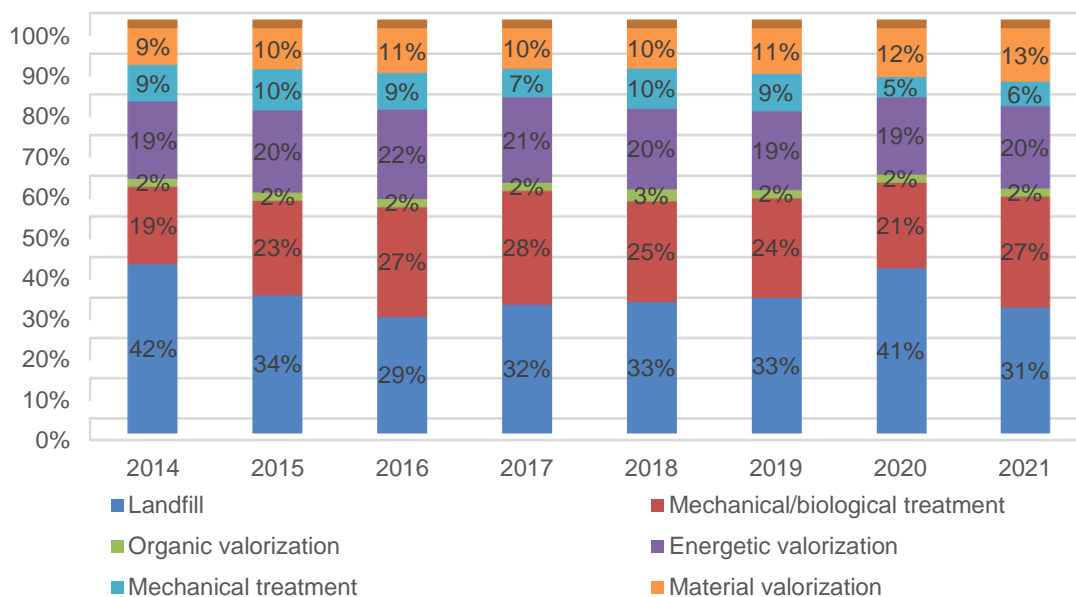


Figure 1. 1. MSW direct destination in Portugal in 2014-2021 (Agência portuguesa do ambiente, 2022)

Between 2014 and 2016 there was a clear tendency of reducing the amount of waste directly disposed in landfills, however, there is a reversal of the trend with an increase of 12% in 2020 respect to the lowest point in 2016. The increase between 2019 and 2020 was accelerated and is justified by the Guidelines and Recommendations for waste management in the pandemic situation of COVID-19 (Agência portuguesa do ambiente, 2021). In 2021 the tendency of decrease was already visible.

The percentage of energetic valorisation has remained stable with an average of 20%. Energetic valorisation in Portugal is done by means of mass incineration in which waste has not previous treatment and is directly conducted to the incineration chamber using equipment such as electrohydraulic grabs. Based on this, in 2021, 51% of municipal solid waste in mainland Portugal had direct destination without any prior treatment, a value close to 2014 that shown the need of improvement in this area. The remaining 49% had as direct destination mechanical treatment (6%), mechanical/biological treatment (27%), organic valorisation (2%) and material valorisation (13%).

The large deceleration in the percentage of processes with pre-treatment between 2019 and 2020 reflects the impact again of the measures against COVID-19. In Portugal, the guideline established that undifferentiated waste, for safety reasons, should not be subject to any type of treatment, especially when this could involve contact with workers, and should be disposed of directly in landfills or incinerated (Agência portuguesa do ambiente, 2021). This doesn't detract from the fact that, landfills have been and continue to be the preferred direct destination of MSW in mainland Portugal.

In 2021, MSW final destination after treatments processes previously discussed was: 55.7% to landfills, 18.8% to energetic valorisation, 7.2% to composting/anaerobic digestion, 14% to recycling and 1.7% to other valorisations (Agência portuguesa do ambiente, 2022). This information allows to estimate the real situation of the country, which, in spite of making efforts to treat its waste, in reality sends more than half of waste to landfills.

Increase in the percentage of waste disposed in landfills from direct and final destination (31% vs 55.7% respectively) is because landfills also receive refuses and rejects from treatment processes: mechanical treatment, mechanical/biological treatment, organic valorisation and material valorisation. When comparing the total MSW sent to treatment in mainland Portugal, 49% from Figure 1. 1, it can be analysed that half of them are not being recovered and that explains the increase in 25% of MSW designated to landfills.

Unfortunately, this value of waste finally disposed in landfills (55.7%) is high and, when compared to the average value for the European union between 1995 and 2021, indicates Portugal's challenging situation. According to the European Statistical Office EUROSTAT, in average, 61% of wastes in 1995 were disposed in landfills in the EU while in 2021 the percentage was 23%, almost half of it (eurostat Statistics Explained, 2023). Material recycling is the treatment that increased the most in the studied years followed by composting and incineration with a lower rate compared to recycling.

In March of 2023, Portuguese Strategic Plan for Urban Waste 2030 (PERSU 2030) was approved, which defines challenging targets for the Portuguese waste sector. According to the plan, waste disposal in landfill target should be 10% in 2035 and recycling target, which was 32% in 2021, has been set at 55% in 2025, 60% in 2030, and 65% in 2035. (Agência Portuguesa do Ambiente, 2021)

In addition to being quite ambitious challenges, it gives a glimpse of the challenge in terms of the design capacity of existing treatment plants and future solutions to handle the total waste generated. The balance by 2035 implies that, even if recycling and landfill targets are met, 25% of the waste will still be collected without sorting and will be sent to landfills or incinerated. Part of this fraction is non-recyclable, and therefore their only destination is incineration or landfill. The only way to reduce the amount of non-recyclable waste in the urban waste is to reduce the production of this type of waste, by means of less consumption of new good, waste prevention, material reuse, repair, and similar strategies.

Assuming that waste production in Portugal remains at the 2021 value of 5,311,000 tons and following previously analysis, by 2035, approximately 1,327,750 tons of unsorted waste will be sent to landfills or incineration. Mainland Portugal's incineration capacity, combining Valorsul and Lipor incinerators, is approximately 1,040,000 tons (AVALER , 2019). This indicates that the country would require an additional incineration capacity of almost 300,000 tons to meet the landfill target. It's important to note that this scenario is very conservative, considering the highly ambitious targets and that it is unlikely that waste production will not increase over the next 12 years. (AVALER , 2019)

1.3 Motivation and Objectives

To date, the race to achieve environmental sustainability in countries has become one of the main focuses of effort, especially because despite the advances made, there is still much to be done to achieve the goal of containing the temperature increase to a maximum of 2°C. In Portugal, the municipal solid waste sector, as a contributor to the gases that promote global warming, faces significant

challenges in meeting the global targets. The management of the residual fraction from sorting facilities and undifferentiated solid residues is at the top of the agenda to be addressed because part of their disposal is being done in landfills, limiting and hindering actions to achieve the target of landfills disposal. EU Landfill directive 2018/850 set a target to reduce the discarding of wastes to 10% of the total by 2035 (Gomes, Brito, Santos, Assis, & Nobre, 2023).

The motivation to work with solid waste also responds to the fact that exploring its use contributes to working with a raw material that, unlike biomass, does not act as a CO₂ sink. Biomass also acts as a CO₂ sink, contributing to the retention of greenhouse gases, helping global sustainability objectives. Solid waste does not have this characteristic and therefore using it as a raw material decreases the share of biomass in processes to obtain clean energy and/or fuels.

Following this context, the objective of this study becomes 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? With this important issues arise and become sub research questions part of the analysis: Do the existing solutions have a favourable technical/economical balance? Are there variables/processes to which the solutions are more sensitive? Solutions are sustainable in the long term?

The 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 analyse, by means the life cycle analysis, the environmental performance of three waste management scenarios using incineration process as base case. Management scenarios proposed covers UE waste treatments best practice guidance and advance thermal technologies.

To achieve the objective of the study, the software Aspen Plus V11 is used to perform energetic and mass balance of the overall scenarios designed as well to quantify CO₂ equivalent within processes streams. Information gathered from previous studies and from available industrial processes are part of the tools managed in this analysis to responds to the objective question.

1.4 Outline

In order to comply with the objective, this thesis is composed of 5 chapters, namely:

- Chapter 1: Introduction - Introduction to the environmental problem of waste framed in Portugal
- Chapter 2: Literature Review - Waste treatments state of the art
- Chapter 3: Methodology and Performance Assessment - Theoretical development of the scenarios and LCA methodology
- Chapter 4: Results and Discussion – LCA outcomes analysis and interpretations
- Chapter 5: Conclusions

Chapter 2

Literature Review

This chapter presents a summary of the current state of the art in solid waste management strategies, focusing on gasification and mechanical/biological treatments. The chapter presents the theory surrounding gasification, the status of some gasification projects in the world, an analysis of the main technologies and a definition of the mechanical-biological treatment of solid wastes prior to thermal valorisation strategies.

2.1 Waste to Energy Technologies

The U.S Environmental Protection Agency EPA created the concept of waste hierarchy as a guideline which identifies basic waste management strategies with preferred order of action to reduce and manage waste with less impact on human health and environment (REA Renewable Energy Association, 2011). In waste hierarchy, waste prevention is the top preferred option, followed by the 3R strategy concept: reduce, reuse and recycle of waste. For those streams which material is not subject to the 3R strategies or is not effectively applicable, the route to follow is recovery, by means energy recovery or nutrient recovery before final disposal in landfills. Even though this priority order for strategies implementation is aligned with Portugal's waste management plans, as mentioned before, actual scenario is that more than half of Portugal's waste is directed to landfills, the last and less preferred option in waste management hierarchy.

Waste to energy technologies (WtE) are part of the recovery segment of strategies in which waste potential energetic value is recovered to produce energy in the form of electricity, heat, and chemical energy. WtE technologies offers several advantages such as GreenhouseGas (GHG) emissions reduction, more efficient alternatives to waste treatment, enhanced social component through the creation of jobs in waste management sector and sustainable production of energy (Gomes, Brito, Santos, Assis, & Nobre, 2023). Waste to energy strategies have an important role in the energy/waste balance. Waste production is increasing as well as energy demand, finding routes to produce energy out of an abundant raw material is a double benefit approach.

The concept of waste to energy encompasses many technologies that can be divided into thermochemical and biochemical routes depending on their working principle. Biochemical technologies include anaerobic digestion and fermentation.(Ren, 2020).Thermochemical routes encompass several technologies such as incineration or combustion, gasification, plasma gasification, pyrolysis, thermal depolymerisation and hydrothermal carbonization. The most studied and implemented technologies for solid waste management in Europe are: incineration, gasification and pyrolysis.

The principle of operation of the thermochemical pathways is to break down waste molecules into smaller reactive molecules using thermal energy. The small molecules recombine with each other releasing more energy than required to perform the initial molecular breakage (Ren, 2020).

2.2 Waste Management Life Cycle Assessment

Currently, incineration is the most mature and implemented waste to energy technology with more than 2000 incineration plants in operation around the world (Kalogirou, 2018). However, recent years' trends indicated that waste management sector is trying to develop new solutions to replace incineration, which may contribute with less pollutants emissions in air, soil and water and higher energetic performances. In this sense, advanced thermal conversion technologies, including gasification and pyrolysis, are increasingly being tested. This is also promoted by the growing demand of clean fuels as well as the requirement for reducing fossil fuels dependency.

The selection of the appropriate waste to energy technology is a complex decision as the selected option should embrace environmental, economic, and social impacts and must consider the specificity of the solid waste and the geographical location of the solution. Waste characteristics change with the income level, location, and societal patterns of the producers. These aspects provide no simple guidance for selecting the best waste to energy solution, specific conditions should be considered.

Life cycle assessment (LCA) is a support tool to evaluate the overall environmental impact considering the entire life cycle of a product that has been used to evaluate and decide between different waste management scenarios. Life cycle assessment is an holistic approach which helps to identify the environmental impacts (e.g., global warming, acidification, ecotoxicity and human toxicity) at different stages of a waste treatment, helping to adopt activities with lower environmental impacts (Dastjerdi, Strezov, Kumar, He, & Behnia, 2021).

A systematic study conducted on waste to energy technologies LCA studies in 35 countries around the world between the year 1981 and 2019, compiled 101 studies to analyse the characteristics of the LCA performed and the results obtained (Dastjerdi, Strezov, Kumar, He, & Behnia, 2021). The study evaluated the best performing scenarios in terms of GHG emissions and energy balance for MSW and residual MSW. For MSW, only comparing incineration with CHP, mechanical-biological treatment and gasification, the best performing scenario for GHG emissions is incineration with CHP followed by mechanical-biological treatment with refuse derived fuel (RDF) production. In this last analysed scenario, the stabilized RDF produced was disposed in landfills instead of being directed to an energy recovery facility, having a negative energetic balance (consumption higher than production). Therefore, considering GHG emissions associated with energy, incineration with CHP scenario analysed was better for MSW. Gasification has also positive impacts on GHG emissions but compared to incineration with CHP is lower.

For residual municipal solid waste, same study compared gasification and incineration with energy production and landfill without energy generation, and concluded that the best-performing scenario considering GHG emissions and energy balance is gasification, since incineration has a higher production of GHG, and landfilling lacks of energy production.

A different LCA jointly conducted by the University of Science and Technology of China and the Albi School of Mines in France, compared 4 scenarios for the treatment of municipal solid waste using data based on the on-site operation of several reference facilities (Dong, Tang, Nzihou, & Chi, 2019). Scenario 1 consists of incineration in a moving grate with flue gas treatment and electricity production with values obtained from 110 French incineration plants. Scenario 2 consists of MSW pre-treatment (size reduction), followed by pyrolysis in rotary kiln and products combustion (with electricity generation), the reference plant is located at Burgau, Germany (Dong, Tang, Nzihou, & Chi, 2019). Scenario 3 consists of MSW pretreatment (size reduction and pelletization) to form a refuse derived fuel RDF followed by gasification in a circulating fluidized bed and syngas cleaning and final combustion (with electricity generation) used in Kymijärvi, Finland. Finally, scenario 4 is gasification without MSW pretreatment, coupled with ash melting in a shaft furnace with electricity generation, the reference plant is located at Japan (Dong, Tang, Nzihou, & Chi, 2019).

For one ton of the same municipal solid waste, the study conducted an LCA and obtained the results for 11 impacts including: global warming (GWP), acidification (AP), eutrophication (EP), ozone layer depletion (ODP), photochemical ozone creation (POCP), terrestrial ecotoxicity (TETP), freshwater aquatic ecotoxicity (FAETP), human toxicity (HTP), marine aquatic ecotoxicity (MAETP), and abiotic depletion (ADP elements and ADP fossil) (Dong, Tang, Nzihou, & Chi, 2019).

Gasification of municipal solid waste, designated as scenario 3 in the study, has the lower environmental impacts values in four categories. Scenario 3 is better than the other scenarios analyses for acidification (AP), photochemical ozone creation (POCP), terrestrial ecotoxicity (TETP) and fossil abiotic depletion (ADP). This does not imply that its performance in the other categories is detrimental, on the contrary, the study conclude that it is the best performing scenario overall and above the pyrolysis scenario (Dong, Tang, Nzihou, & Chi, 2019).

The advantage of scenario 3 (gasification of municipal solid waste) is that it considers a previous treatment of the solid waste, through shredding and pelletization to form refuse derived fuel RDF, increasing the quality of the feedstock to the gasifier. Partial oxidation process is improved in the gasifier when a fuel with less humidity and higher superficial area, like RDF, is used.

2.3 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, containing mainly methane (CH₄), carbon dioxide (CO₂), carbon monoxide (CO), hydrogen (H₂), condensable short-branched hydrocarbon gases (tars) and a solid material (char) that remains after light gases and tar have been driven out. The syngas is a stepping for further processing and production of biochemicals and biofuels as well as heat and power (IEA Bioenergy, 2021).

Although incineration and gasification are both thermochemical oxidation processes, there are two main differences between them: degree of the oxidation in the thermochemical reaction and final product obtained. Incineration is the total oxidation of the fuel to produce a gas product mainly composed by carbon dioxide CO₂ and water H₂O, this gas, called flue gas, has no value as fuel since CO₂ is a non-flammable, non-combustible gas and will not support combustion. Gasification is the partial oxidation of the fuel to produce syngas composed by hydrogen, methane, carbon monoxide, carbon dioxide, water vapours, as well as other hydrocarbons and condensable compounds. CO is the intermediate species in the oxidation route, is a less oxidized compound that still have two free bounds to react, therefore is a more reactive specie that, as well as hydrogen, is flammable.

Thus, syngas or synthesis gas is a fuel gas that can be used in internal combustion engines, can produce electricity in gas turbine or can be used in chemical synthesis (e.g., Fischer–Tropsch, higher alcohol synthesis, hydrogen production) (Gomes, Brito, Santos, Assis, & Nobre, 2023). The energy recovered through this process is higher than that of other thermochemical techniques such as combustion and pyrolysis and the production of pollutants such as NO_x, dioxins and furans is less than combustion

because the oxygen deficient atmosphere (Ramos, 2020).

Gasification chemistry can be considered as two conversion mechanisms, the first one corresponds to the initial drying and pyrolysis and the second mechanism correspond to cracking and reforming of previously formed gases. In the first mechanism, carbon-based raw material particles are rapidly heated at high temperature, releasing high volatile compounds. These gases generated in the pyrolysis and drying, namely water vapour (from the humidity of the material), organic liquids and non-condensable gases, such as CO, H₂, CO₂, are separated from the solid carbon (i.e. char) and ash content of the solid material. The vapour/liquid product comprises mostly of polyaromatic hydrocarbons and tar (i.e. dark, oily, viscous material, consisting mainly of heavy organic and mixed oxygenates). Subsequently, volatiles and char undergo a second reaction mechanism where with increasing temperature and oxidant agent they modify their composition due to the occurrence of several reactions becoming the final syngas. Set of chemical homogeneous and heterogeneous reactions involved in gasification is shown in Table 2. 1.

Table 2. 1. Gasification reaction mechanism. (Shahabuddin & Alam, 2022)

Reaction Name	Reaction	Enthalpy (kJ/mol)	Type
CO oxidation	$CO + \frac{1}{2}O_2 \rightarrow CO_2$	-283.0 (Exothermic)	Partial oxidation – Oxidation zone
Hydrogen combustion	$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$	-242.0 (Exothermic)	Partial oxidation – Oxidation zone
Partial carbon oxidation	$C + \frac{1}{2}O_2 \rightarrow CO$	-111.0 (Exothermic)	Partial oxidation – Oxidation zone
Boudouard reaction	$C + CO_2 \leftrightarrow 2CO$	+172.0 (Endothermic)	Heterogeneous – Reduction zone
Steam gasification	$C + H_2O \leftrightarrow CO + H_2$	+131.0 (Endothermic)	Heterogeneous – Reduction zone
Hydrogasification	$C + 2H_2 \leftrightarrow CH_4$	-75.0 (Exothermic)	Heterogeneous – Reduction zone
Reverse water-gas shift	$CO + H_2O \leftrightarrow CO_2 + H_2$	-41.1 (Exothermic)	Homogeneous – Reduction zone
Steam-methane reforming	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	+206.3 (Endothermic)	Homogeneous – Reduction zone
Dry methane reforming	$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$	-247.0 (Exothermic)	Homogeneous

Most of these reactions are endothermic and require a consistent amount of energy to proceed. Depending on the energy source for the activation of the reactions, there are two types of gasification: autothermal and allothermal gasification. It is called autothermal or direct gasification when the heat required for the reactions is generated directly by the partial oxidation of the carbonaceous feedstock with the oxidizing agent inside the gasifier, i.e., the heat required is supplied by a partial combustion of the fuel. 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. In allothermal systems, also referred as indirect gasification, the combustion or energy source is an independent external system and heat is carried to the gasification reaction zone without the partial combustion of the feedstock.

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 (Umweltbundesamtes, 2017) and will depend on the oxidizing agent (in combustion systems ER value is more than 1 considering an excess of oxidizing agent to guarantee complete combustion). Oxidizing agent could be air, pure oxygen, carbon dioxide or high pressure steam, although there are a variety of options, each has advantages and disadvantages for the overall process.

In gasification process, using air is the cheapest option, however, air is mostly composed of nitrogen, and nitrogen generates a dilution effect that lowers the temperature in the reaction zone, slowing down all endothermic gasification reactions and favouring the production of pollutants such as nitrogen oxides NO_x. Lowering of the temperature also favours the production of other pollutants such as dioxins and furans and increases the energy requirements to increase the temperature, which for a autothermal system implies injecting more oxidizing agent to increase the exothermic combustion (increase the ER ratio) and thus the energy, but it approaches the complete oxidation of the fuel and decreases the quality of the gaseous product obtained (reduce its high heating value HHV) (Gomes, Brito, Santos, Assis, & Nobre, 2023).

Pure oxygen is one of the best alternatives because it eliminates the dilution effect of nitrogen, but industrially it is a process with high costs that destabilizes the economic balance of the gasification solution (Gomes, Brito, Santos, Assis, & Nobre, 2023). High temperature steam has also been studied as an innovative solution especially because injecting steam is favouring the production of hydrogen as predicted by the steam reforming reaction in Table 2. 1. The problem with high temperature steam is that the energy balance is not favourable, because there is a significant energy cost to heat this steam to the temperatures of the gasification reactions (above 600°C) (Gomes, Brito, Santos, Assis, & Nobre, 2023).

When using CO₂ as agent, external energy supply is needed because CO₂ doesn't produce the energy required to support the endothermic reactions (Department for Business, Energy & Industrial Strategy, 2021). Actually, majority of gasification facilities operates with air and/or steam under autothermal schemes and the temperature control is done with the oxidant flow which sustains the exothermic oxidation reactions of the feedstock. Along with the gas agent, there are other important parameters that should be considered:

- Particle Size

The particle size of MSW is a key concern, as untreated MSW can contain large objects. Particle size of solid material entering gasification is important because it impacts gasification reactivity and carbon conversion. Smaller size particles result in higher specific surface area, in this surface area is where reactions are going to take place, therefore, with more effective reaction area, carbon conversion is increased and accelerated.

- Moisture

Moisture content has an inverse effect on gasification efficiency, more moisture in the feedstock decrease thermochemical processes performance and therefore product gas calorific value. High

moisture feedstock implies higher quantity of water that needs to be dried, consuming the energy originally destined to the activation of the endothermic reactions. In the case of allothermal gasifiers, this implies higher external energy consumption and thus higher costs. In the case of autothermal gasifiers, this implies greater injection of oxidizing agent that makes partial combustion with the feed and generates more energy.

- Chemical composition

Feedstock chemical composition analysis is important to identify components precursors of tars, dioxins and inorganic compounds that will generate ashes and inert materials that will generate solid residues. Ashes melting and agglomeration will cause slagging or clinker formation in the gasifier, reducing its efficiency, limiting exchange surface area of the equipment. Ash as well can melt and sinter in the pores of feedstock particles blocking them. Blocked pores prevents the gasification reagents from accessing the active sites of the feedstock particles, reducing reactivity (Shahabuddin & Alam, 2022).

For MSW there is a particularity in terms of composition and is the share of plastic in the mix. Some plastics contain chemical that lead to hazardous emissions when they are subjected to thermochemical process. An example is the PVC or polyvinyl chloride, a plastic that contains chlorine that is a precursor to dioxins and furans formation (GAIA, 2017).

- Feedstock energy content

If the energy content of the feedstock is low the amount of energy to recovered will also be low and thus, technical viability and economical attractiveness is reduced. Another challenge for low energy content feedstock is the requirement for external energy source to meet and sustain endothermic reactions. For autothermal gasifiers, low energy content fuels increasing the risk of having an unsustain combustion inside the reactor, or the risk to have an unstable combustion than creates more pollutants and unburned products in the gas, besides the requirement of more air/O₂. Unfortunately, the energy content of MSW is as low as 9.8-16 MJ/kg (Sajid, et al., 2022), almost have of the energy contained in bituminous coal with 30 MJ/kg of heating value (The Engineering ToolBox, 2023)

- Temperature

Gasification temperature is one of the most important variables to control products yield, including undesirable products as tars. Raising the temperature, following LeChatelier principle, enhances the kinetics of slow and endothermic reactions, produce higher yields of syngas, increase char conversion and reduce tar content, since thermal cracking of tars into permanent gases such as CO and H₂ occurs at temperatures above 1000°C (Arena, 2012). However, working at high temperatures increases the melting risk of various mineral phases in the system, promotes coalescence of solid particles, represent an increasing energy demand as previously mentioned (increase ER relation) and reduce syngas heating value (Gomes, Brito, Santos, Assis, & Nobre, 2023).

- Reactors

Regarding gasifier configuration, they typically fall into five main categories, the fixed-bed (updraft and

downdraft), fluidized bed (bubbling and circulating), entrained fluidized bed, rotary kiln and plasma reactors. All these reactors have advantages and disadvantages, and the selection depends on the scale of operation, the characteristics of the feedstock, and the desired application of the produced gas (Gomes, Brito, Santos, Assis, & Nobre, 2023).

- Fixed Bed Reactors

Fixed-bed gasifiers are the simplest technology for solid gasification with a cylinder-shaped space where fuel and gasifying agent are introduced. These gasifiers can use different gasifying agents and gasification takes place over time, from approximately 900–1800 seconds at high pressures. The reactor operates at high pressures between 1 and 100 bar and with temperatures from approximately 500–1200°C, resulting in a high carbon conversion (Gomes, Brito, Santos, Assis, & Nobre, 2023). Fixed bed technologies include updraft gasifiers and downdraft gasifiers as indicated in Figure 2. 1 .

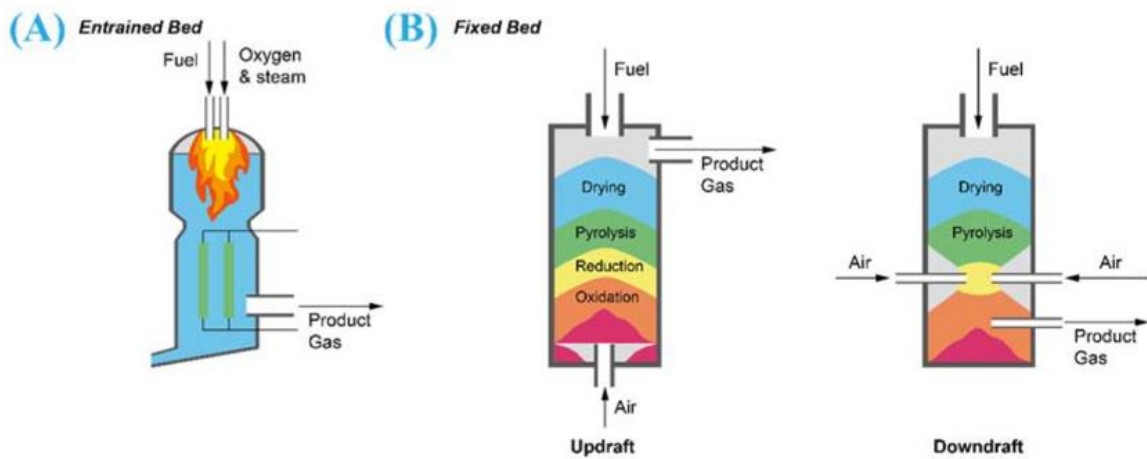


Figure 2. 1. Entrained flow and fixed bed gasifier design sketch. (Lian, et al., 2021)

In an updraft gasifier, the feedstock is inserted into the top of the gasifier, while the gasifying agent is introduced into the side or bottom of the reactor. The production of syngas takes place along the reactor and the output of this gas takes place at the upper level of the reactor, while the ash is deposited at the bottom of the reactor. For these gasifiers, fuel's moisture content must be less than 50%, ash content must be less than 15% in dry basis and typical particle diameter varies between 5-80 mm (Gomes, Brito, Santos, Assis, & Nobre, 2023). In the downdraft reactor, the raw material enters in the top of the reactor and the gasifying agent enters in the side or top of the gasifier; thus, the syngas output takes place at the bottom of the reactor (Gomes, Brito, Santos, Assis, & Nobre, 2023). For these gasifiers, fuel's moisture content must be less than 20%, ash content must be less than 5% in dry basis and typical particle diameter varies between 5-80 mm (Gomes, Brito, Santos, Assis, & Nobre, 2023).

- Fluidized Bed Reactors

In this type of gasifier, the feedstock is introduced into the reactor and it is fluidized by means of a fluidization medium (sand for example) to enhance thermal and mass diffusion phenomena. These reactors can maintain a temperature range between 700 and 1000°C. Solid waste may take longer to react, resulting in increased heat transfer and leading to higher carbon conversion (Gomes, Brito,

Santos, Assis, & Nobre, 2023). Bed materials can be inert or have catalytic activity during gasification, improving syngas quality (Ramos, 2020). Fluidized bed gasifiers have two main configurations, bubbling fluidized bed (BFB) and circulating fluidized bed (CFB) as indicated in Figure 2. 2 .

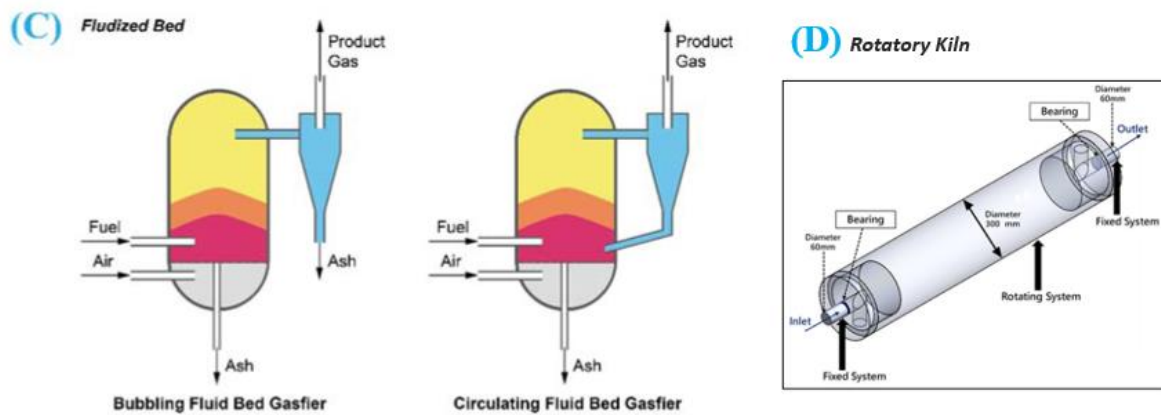


Figure 2. 2. Fluidized bed gasifier and rotatory kiln reactor design sketch. (Lian, et al., 2021)

Bubbling fluidized bed gasifiers are designed to operate under low gas speed conditions between 1 and 3 m/s, and at temperatures between 800 and 1000°C. Particles are moved with the gas and are divided by a cyclone; hence, the raw syngas flows to the next stage, while the particles fall to the bottom of the reactor. For these gasifiers, fuel's moisture content must be less than 55%, ash content must be less than 25% in dry basis and particle diameter should be less than 6 mm (typically) (Gomes, Brito, Santos, Assis, & Nobre, 2023).

In a circulating fluidized bed gasifier, the gasification is conducted in two steps. First, there is a bubbling fluidized bed chamber that reacts with solid waste and generates syngas. In the second step, a higher gas speed is introduced, usually between 3 and 10 m/s, to drag the solid. Finally, the cyclone allows solid particles to separate and circulate in the fluidized bed chamber (Gomes, Brito, Santos, Assis, & Nobre, 2023). For these gasifiers, fuel's conditions are the same as bubbling bed technology.

- Entrained Flow Reactors

It is a deployable and mature technology for handling conventional feedstock, such as coal, lignite, and biomass because of its higher throughput and high product gas quality. Entrained flow reactors operate with feed and oxidant agent in co-current flow with very short residence time. Feedstock is ground to particle size less than 1 mm to promote mass transfer and allow transport in the gas phase (IEA Bioenergy, 2021). In general, these reactors are operated at high temperatures (between 1200 and 1500°C), high pressures (between 20 and 80 bar) (Gomes, Brito, Santos, Assis, & Nobre, 2023) and on slagging range (above the ash-melting point) which increase destruction of tar, producing a tar-free-syngas (IEA Bioenergy, 2021).

- Rotatory Kilns

Rotary kiln reactor contains a steel cylindrical-shaped chamber, which moves slowly complying with two objectives: moving solids into and out of a high-temperature reaction zone and mixing solids (Arena, 2012). Kiln is typically comprised of a steel cylindrical shell as indicated in Figure 2. 2 lined with abrasion-resistant refractory to prevent overheating of the metal (Arena, 2012). Rotary kilns reactor

operating temperatures is approximately 300–600°C. The rotary kiln reactor operates slowly and with a downward inclination relative to the exit end; thus, the feedstock passes through the reactor for gasification. The feedstock is introduced at the top of the reactor, while the oxidizing agent is injected into the bottom of the oven (Gomes, Brito, Santos, Assis, & Nobre, 2023).

- Plasma Reactors

The limitation, for autothermal gasification systems, arises from the relationship between the oxygen demand (oxidizing agent) and the desired temperature level, more oxygen must be injected to have more temperature, but this shifts the reaction towards combustion. Plasma gasification is a type of allothermal gasification that uses an external source of heat allowing to disconnect the chemical oxygen demand from the thermal level required. This technology uses electrically ionized gas at approximately 10000°C through plasma torches with pressures between 1 and 3 bar enabling to break with high efficiency the feedstock into tar-free syngas. In the plasma reactor, the feedstock is introduced at the top of the chamber, while the gasifying agent is inserted into the side of the reactor (Gomes, Brito, Santos, Assis, & Nobre, 2023).

The inorganic materials, that remains in the solid residue in other gasification technologies, in plasma gasification are transformed into inert and glazed slag. Since the energy source is external, plasma gasification can treat a wide range of low calorific value materials including liquids and solids. Plasma technology has no minimum requirement in terms of fuel's moisture, ash content or particle size. High quality of syngas and few and inert residues are great advantages for plasma reactor, however, their main drawback is the high operational cost and the origin of the source of electricity required. If electricity is obtained from a renewable source, then the overall process is sustainable when gasifying municipal solid waste or biomass, this is not the case when electricity is obtained from fossil fuels.

2.4 Gasification Projects and Commercial Plants

Gasification is already a commercialized and mature technology for fossil fuels feedstock, mainly coal. In recent years this technology has received increasing attention to treat biomass and municipal solid waste in order to increase sustainability as part of the circular economy framework, however the share is still low. In 2020, gasification market was led by coal, with a production of 152,490 MWth representing approximately 62% of global gasification market, followed by natural gas with approximately 7% and biomass and waste with less than 5% as a whole (Gomes, Brito, Santos, Assis, & Nobre, 2023).

The Asia-Pacific region (especially China, India and Japan) is the largest contributor to coal's leadership in the gasification market. Europe, being a bit more advanced in strategies and policies for municipal solid waste treatment as previously discussed, is home to the largest number of solid waste gasification projects.

There are a variety of licensed technologies and processes associated with the gasification of biomass feedstock listed in annexe A. Table 2. 2 and Table 2. 3 shows, out of the technologies listed in annex A, some examples of mature technologies that are widely implemented in commercial gasification plants, along with the type of feedstock and final product obtained.

Table 2. 2. Commercial gasification projects MSW/RDF and residues. Status updated by 2023.(Gomes, Brito, Santos, Assis, & Nobre, 2023) (Department for Business, Energy & Industrial Strategy, 2021) (Department for Business, Energy & Industrial Strategy, 2021).

Location	Feedstock	Status / Start Up Date	Output	Technology
Yoshii, Japan	MSW	1999	Steam	Alter NRG / Westinghouse Plasma Corporation (Fluidized bed and Plasma) – Technology from Canada
Pune, India	Hazardous waste	Due to technical issues it has never produced any power	1.6 MWe	
Shanghai, China	Hazardous Waste	Demonstration facility	Electricity	
Tees Valley, UK	RDF	Project abandoned	50 MWe	
Hoddesdon, UK	RDF	Shutdown	9 MWe	
Belfast, UK	RDF	Operational / 2019	15 MWe	Biomass Power limited (Moving grate) – UK company
Oldbury, UK	ASR and industrial waste	Shutdown	11 MWe	Chinook Sciences (RODECS™ batch process)
Vasai, India	MSW	N/A	250 kWth, 30 kWe	Concord Blue (Staged reformer)
Skigar, Japan	MSW	N/A	1 MWe	
Izumo, USA	Woodchip	2006	0.25 MWe	
Averoy, Norway	MSW	2000	Steam and electricity	Energos (Moving grate) – Technology from Norway
Milton Keynes, UK	RDF	Operational / 2018	Electricity	
Derby, UK	RDF	Mothballed in 2019	Electricity	
Ishinomaki, Myagi, Japan	Mixed MSW	2003	Hot water, 2.6 MWe	
Paju, Seoul, Korea	Mixed MSW	2011	Steam supply	Kobelco Eco Solutions (Bubbling fluidized bed) - Technology from Japan
Kofu, Yamanashi, Japan	Mixed MSW	Under construction	Not available	
Barry, UK	Waste wood	Commissioning	10 MWe	Outotec Energy Products (Bubbling fluidized bed) – Technology from USA
Hull, UK	RDF	Operational since 2020 but it is not at full capacity	28 MWe	
Levensat, UK	RDF	Operational / 2017	10 MWe	
Oregon, USA	Biomass	Operational	35 MWe	
Tennessee, USA	Wood waste	Operational	5 MWe	
United Kingdom	RDF	Demonstration	2 MWe	
Ottawa, Canada	Post recycled MSW	Closed due to technical issues	5 MWe	
Karlsruhe, Germany	MSW	Shutdown	Syngas for power generation and district heating	Thermoselect (High temperature fixed bed systems) – Technology from Japan
Chiba, Japan	Industrial waste	N/A / 1999	Syngas to export	
Mutsu, Japan	MSW	N/A / 2003	Syngas to engine	

Location	Feedstock	Status / Start Up Date	Output	Technology
Vassa, Finland	Biomass	2006	230 MWe, 170 MWth	Valmet (Circulating fluidized bed)
Lahti, Finland	SRF/RDF	2012	50 MWe, 90 MWth	
Enerkem Alberta Biofuels LP/Edmonton Waste-to-Biofuels Project, Canada	MSW	Operational / 2016	Biofuels (Methanol and ethanol)	Enerkem (Bubbling fluidized bed) – Technology from Canada
Advanced biofuel solutions limited Swindon, UK	RDF	N/A / 2022	Biomethane	Advanced biofuel solutions limited Radgas (Bubbling fluidized bed) – Technology from UK
Midlands, UK	RDF, Biomass, Clinical and hazardous wastes	Under construction	H ₂ and liquid fuels	Kew Technology (Bubbling fluidized bed) – Technology from UK

Table 2. 3. Commercial gasification projects biomass and others. Status updated by 2023. (Gomes, Brito, Santos, Assis, & Nobre, 2023) (Department for Business, Energy & Industrial Strategy, 2021)

Location	Feedstock	Status / Start Up Date	Output	Technology
Kessennuma, Japan	Clean woodchip	Closed due technical issues	800 kWe	A.H.T Syngas Technology (Fixed bed)
Kalimantan, Indonesia	Black coal	2011	6,930 kWe	downdraft/updraft) – Technology from Germany
Harboøre Varmeværk, Denmark	Wood chips	2001	1 MWe, 1.9 MWth	Babcock & Wilcox Volund (Fixed bed updraft) – Technology from USA
Yamagata, Japan	Wood chips	2007	2 MWe	
Wildshausen, UK	Clean wood	N/A / 2006	270 kWe	Biomass Engineering limited (Fixed bed downdraft) – Technology from Ireland
Oxford, UK	Clean wood		250 kWe	
Merseyside, UK	Clean wood		2,000 kWe	
Merthyr Tydfil, UK	Waste wood	N/A / 2007	1,000 kWe	
Luoyang, Henan province, China	Local hard coal	2013	Fuel gas	British Gas/Lurgi (Fixed bed updraft) – Technology from Germany
Freiberg, Germany	Lignite	2014	2,300 Nm ³ /h syngas	
Dartmoor BioPower, UK	Waste wood	Shutdown	3.5 MWe	
Welland BioPower, UK	Waste wood	Operational	9 MWe	Nexterra (Fixed bed updraft) – Technology from USA
Veterans Affairs Hospital, USA	Construction & demolition and waste wood	Not operational	2 MWe and building heating	
University of British Columbia, Canada	Construction & demolition and waste wood	Operational	District heating	
Gothenburg, Sweden	Woodchip, forest residues and bark	Mothballed in 2018	Biomethane	GoBiGas (Dual fluidized bed gasifier, circulating combustion and bubbling gasifier)

Location	Feedstock	Status / Start Up Date	Output	Technology
Varkaus, Finland	Bark, wood chip, forestry residues and sawdust	Project abandoned	Syngas suitable for refining into renewable diesel	Sumitomo Foster Wheeler (Circulating fluidized bed)

Technologies compiled in Table 2. 2 and Table 2. 3 shows a trend between the type of reactor used and the carbonaceous material to be treated. Technologies such as A.H.T Syngas Technology, Babcock & Wilcox Volund, Biomass Engineering Limited, British Gas/Lurgi and Nexterra, which use fixed bed reactors, are more focused on the handling of more homogeneous material such as woodchip, briquetted lignite, coal, waste wood, etc. When treating waste, technologies such as Kobelco Eco Solutions, Outotec Energy Products and Valmet uses fluidizing bed designs.

The following is information on some of the commercial technologies for waste gasification with energy generation. Annexe A shows in more detail the commercial technologies highlighted.

- Energos (DP Clean Tech, 2023)
 - Raw material: MSW, RDF and commercial & industrial waste
 - Pretreatment: Shredding and metals (ferrous and non-ferrous) separation
 - Description: Coupled combustion process in which drying, gasification and combustion of waste occur on a horizontal moving grate. Drying and gasification occurs in a separated section and then syngas from the grate undergoes complete combustion using a mixture of air and recycled flue gas. Combustion heat is used to generate steam and electricity. Bottom ash is discharged from the gasification unit at the end of the grate
 - Product: Syngas is burned to produce steam and then electricity
 - Syngas cleaning required: NO – flue gas cleaning is required
- Outotec Energy Products (Metso, 2012)
 - Raw material: Biomass feedstock, MSW as RDF, commercial & industrial waste
 - Pretreatment: No available information
 - Description: Staged gasification system operated with a refractory lined air-blown bubbling fluidized bed gasifier using air as oxidant agent. Syngas generated in the fuel bed is immediately burnt in a close coupled combustor.
 - Product: Syngas is burned to produce steam and then electricity
 - Syngas cleaning required: NO – flue gas cleaning is required.

Although the technologies claim to handle municipal solid waste, increasing their commercial attractiveness, the reality is that all the technologies explored pretreat the waste to achieve the required conditions in their reactors, generating the real feedstock, the refuse derived fuel RDF. Some technologies and projects include the pretreatment process to produce this refuse derived fuel, whereas others rely on waste suppliers to produce the required RDF. In the latter case, strict quality control will be required to ensure that the fuel supplier always maintains the quality (Department for Business, Energy & Industrial Strategy, 2021).

Biomass Power Limited, Plasco Conversion Technologies Inc and Energos technologies have a distinguishing factor: their gasification technology work with a moving grate reactor, a technology more commonly used for combustion. Moving grate for gasification has demonstrated that produce a syngas which has a very low concentration of hydrogen and carbon monoxide, has high particulate matter and pollutants concentration (Department for Business, Energy & Industrial Strategy, 2021), i.e., has the combustion problems. For these technologies, upgrading syngas (if desired) requires high investment and gas cleaning process is more exhaustive.

Electricity production remains the most common product of gasification, and the number of commercial plants producing electricity compared to the number of existing operational commercial plants for biofuel production is significantly higher for both biomass and solid waste.

Most of the gasification technologies for the production of biofuels or syngas suitable for further refining are not mature technologies with technology readiness levels between 6-8; they are not yet in commercial operation but key component systems have been demonstrated in a similar operating environment (Department for Business, Energy & Industrial Strategy, 2021). UK Department for Business, Energy & Industrial Strategy (BEIS) listed 7 advanced gasification technologies for fuel production, namely: Advanced Biofuel Solutions Limited, Enerkem, GoBiGas, Kew Technology, PowerHouse Energy, Sumitomo Foster Wheeler and thermoChem Recovery International (Department for Business, Energy & Industrial Strategy, 2021). The following is general information respecting innovative technologies for biofuel production based on solid waste gasification. Annexe A shows more details regarding biofuel production technologies.

- Advanced Biofuel Solutions Limited – Radgas technology (Department for Business, Energy & Industrial Strategy, 2021)
 - Raw material: RDF from MSW shredded and without ferrous and non-ferrous metals. Limits on Sulphur and chlorine content of waste is also required.
 - Pretreatment requirements description: Mechanical pretreatment (shredders, screens, metal separation, drying and density separation). Glass, stones, metals and large dense objects are removed.
 - Product: Biomethane
 - Description: Dried RDF is heated in a conventional bubbling fluidized bed (BFB) gasifier using a mixture of steam and oxygen as the bed fluidizing and gasifying agents. Gasification in this process is autothermal. Residual ash and char generated during gasification are continuously discharged from the fuel bed and sent for disposal offsite. The syngas produced is treated in a series of clean-up systems starting from a high temperature plasma converter to reduce tar's content.
 - Syngas cleaning required: YES
- Enerkem (Department for Business, Energy & Industrial Strategy, 2021)
 - Raw material: Pre-treated wood, pre-treated municipal or commercial waste
 - Pretreatment requirements description: Wood, municipal or commercial waste streams require pre-treatment. Standard mechanical pre-treatment (Shredders, screens, metal

separation, drying and density separation. Rejected material is composed of glass, stones, metals and large dense objects.

- Product: Renewable Methanol and ethanol.
- Description: The fuel is converted to syngas in a pressurised bubbling fluidised bed (BFB) gasifier using O₂ and steam as the fluidising medium. Syngas passes from the fluidised bed into a thermal refiner where O₂ is added to heat the syngas and to crack any long chain hydrocarbons and tars. Methanol is obtained through catalytic syngas conversion
- Syngas cleaning required: YES

Comparing the technologies for electricity production and biofuel production, several differences can be found. The first difference is the oxidizing agent used, for electricity generating technologies it is mostly air or O₂ while for biofuel production it is a mixture of air and steam. Using the air-steam mixture allows to control the proportion of H₂:CO in the syngas, allowing to control the quality and applicability of the syngas obtained. Hydrogen and carbon monoxide ratio defines the application of the gaseous product since they are reactants in further conversion reactions. For the synthesis of fuels through the Fischer tropesch process for example, this parameter should be between 1-2, for methanol production should be 2 and for methane production should be 3 (National Energy Technology Laboratory (NETL) , 2022).

The second difference is in the process sequence. For energy production it is common to find that the syngas is burned directly and then the flue gas from the combustion undergoes a cleaning process before being released into the atmosphere. For biofuel production, the syngas is cleaned and upgraded after the gasification process.

From listed gasification technologies is evident that the majority of commercial plants work with biomass as agricultural residues, wood and more homogeneous materials than MSW. This feedstock preference is not random, although solid waste is abundant and is a problem that needs to be solved, handling it at the industrial level in gasification plants has been a difficult path for the industry. Biomass, although it has its challenges due to its moisture and ash content, represents in general a material with constant characteristics, while solid residues have a high heterogeneity that contrasts with the stable requirements of thermochemical processes.

From the information presented in Table 2. 2 and Table 2. 3 regarding commercial plants status updated to 2023, it can be seen that various plants working with MSW or RDF closed due to technical issues, mothballed or projects were abandoned after few operational hours in demonstration phase. Some cases of failed projects are discussed below based on the information reported on (GAIA, 2017)

- Air product, Teeside, Tees Valley, UK
 - Technology: Alter NRG / Westinghouse Plasma Corporation
 - Status: Project abandoned
 - Justification: Design and operational challenges. The CEO of Air Products stated: “The technology is proving to be a lot more difficult than people thought at the beginning”
- Plasco, Ottawa, Canada

- Technology: Plasco Conversion Technologies Inc
- Status: Closed due to technical issues
- Justification: Some of the emissions issues disclosed included high sulphur dioxide emissions and other emission exceedances. Over these three years, operating problems were so extensive that the facility only processed waste on 25% of days, and on those day sit processed an average of 23 tons per day. This is approximately 7% of what Plasco projected it could process (85 tons per day).
- Thermostelect, Karlsruhe, Germany
 - Technology: Thermostelect
 - Status: Shutdown
 - Justification: Operational problems included low or no electricity generation in some years, corrosion, water pollution, water consumption, and exceeding air permits for dioxins, NO_x, particulates, and HCl. During five years of operations the facility just processed 20% of contracted waste. This resulted in additional costs of fulfilling municipal waste management contracts with local governments. Energy generation proved a challenge: in 2002 the facility used 17 million cubic meters of natural gas to heat the waste, and did not deliver any electricity or heat back to the grid.
- Developer Resource Recovery Solutions (RRS), Derby, UK
 - Technology: Energos
 - Status: Mothballed in 2019
 - Justification: Crucially, the issues with the plant meant the income from generating electricity from processing waste was “significantly lower than base case”, the plant only processed 51% of its design flow. As a result, there was a significant risk that its Renewable Obligation Certificates (ROCs) would “not be available”. One of the main issues also appears to be at the plant’s front end. Its materials recovery facility (MRF) and mechanical biological treatment (MBT) units were unable to produce enough refuse-derived fuel to “maintain performance of the plant’s lines (Walsh, 2021). Problems with the MRF included (Walsh, 2021):
 - Recycling rate was 4.8% compared with the 7.4% target rate
 - Air knife used for sorting plastics materials for recycling was failing as there were high levels of plastic film in the rigid plastic bales.
 - Multiple breakdowns and blockages including shredder breakdowns.

Several gasification projects have failed due to technical and commercial reasons, either for not meeting energy generation, revenue or emissions targets (GAIA, 2017). Research on facilities in Europe finds that many facilities have failed due to economic problems, citing inadequate revenues and costs from preparing feedstock (GAIA, 2017). 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 other types of materials such as solid waste. Another common practice is to test the technology at pilot plant level with solid waste and then scaled up to industrial level. However, 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 gasification performance.

Recalling the experience of the gasification plant in Derby, under Energos technology, one main failure reason was the inability to produce enough refuse derived fuel (with specific conditions imposed by the technology) to feed the system and to achieve steady stable operations. Failed projects allow lessons to be learned from them for implementation in future projects, but they also involve a process of overcoming the perceived risks of implementing waste gasification technologies.

2.5 Gasification Challenges and Opportunities

Although the specific circumstances of individual projects differ, several common topics have been identified that led to the difficulties experienced. The department of energy from USA (DOE) and the Department for Business, Energy & Industrial Strategy from UK identified lessons learned and opportunities to improve gasification projects based on the barriers identified and the experience gained in UK and USA. The list of opportunities, barriers and lessons learned include:

- Barriers:
 - Commercial pressures on projects leading to a lack of robustness in plant design and auxiliary systems (Department for Business, Energy & Industrial Strategy, 2021). Solid waste management is an issue of high public interest that causes community pressure on these types of projects. There is evidence of projects that have had high levels of community resistance due to the "not in my back yard" phenomenon, in which there is opposition to the implementation of projects in their local areas.
 - Underestimating the impact of feedstock variability on reliable plants operation (Department for Business, Energy & Industrial Strategy, 2021). Parameters influence and interaction briefly discussed sometimes is not well addressed.
 - Underestimating the complexities of significant scale-up of existing technologies (Department for Business, Energy & Industrial Strategy, 2021).
 - Development of projects based on support mechanisms that incentivized projects that may otherwise have not had a favorable business case (Department for Business, Energy & Industrial Strategy, 2021). To be dependent on state aid and incentives for projects with high projected sustainability. When the technology fails to achieve the minimum results to apply for these incentives, the project becomes economically unfavorable.
 - "Large scale" gasification processes, especially for waste feedstock, doesn't match (yet) the scale of competing traditional fuel based operation for energy production (Gomes, Brito, Santos, Assis, & Nobre, 2023).

- Lessons learned and opportunities:
 - If historical operational data is not available for process equipment there is considerable risk associated with assuming that high levels of performance will be achieved. This risk will always be present for new technologies but needs to be understood and managed to deliver successful projects with an appropriate balance between risk and return (Department for Business, Energy & Industrial Strategy, 2021).
 - The existence of reference facilities does not always indicate that a technology is 'proven', or that it would be reasonable to assume high operational availability in any future project. Consideration needs to be given to the actual performance achieved, scale, configuration and feedstock used at any reference facility. Changing from operation on biomass to operation on waste is a significant step (Department for Business, Energy & Industrial Strategy, 2021).
 - Solid wastes have a relatively low energy density compared to other fuels. This makes them more expensive to transport. Therefore, the availability of feedstock needs to be considered on a regional basis (Department for Business, Energy & Industrial Strategy, 2021).
 - Develop waste preprocessing and handling strategies to reduce feedstock variability of MSW streams entering thermochemical processes. This includes the optimization of sorting processes to truly separate recyclable products from residual fraction (Office of Energy Efficiency & Renewable Energy, 2019).
 - Apply gasification technologies to sorted and pretreated MSW to produce high quality syngas (Office of Energy Efficiency & Renewable Energy, 2019). In this item the main objective is the creation of a fuel derived from waste that is more homogeneous and allows to have more stable feeding conditions to the process.

Japan is a good example that the successful implementation of a technology might depend more on the policies in-place and legal framework, than on its financial viability. It is estimated that between 25% and 30% of its waste is gasified and the percentage of waste that is sent to landfill is 10% (WEKA Industrie Medien, 2023). Their success is based on a combination of strict policies and technological advances. Japan's average landfill disposal rate is the highest in the world, the island has such a high space limitation that landfill disposal is practically impossible. This constraint has forced waste policies to involve the active participation of society in the selective collection of waste for recycling, enabling the stream of unsorted MSW to have a good quality for energy valorisation processes, and to seek strategies such as gasification to reduce the emissions of solid waste.

Municipalities in Japan must treat and recycle their waste in the area, transporting solid waste with high moisture and low energy density from one place to another is prohibited, forcing each community to have small pre-treatment and treatment facilities to produce good quality RDF. These small treatment units, which include gasification plants, are part of the success of the implementation of the technology. Small scale gasification plants have fewer scale-up problems and are easier to maintain and operate (WEKA Industrie Medien, 2023). Also, in Japan all WtE plants are required to vitrify their ash after combustion in order to use them in construction, by means of electric furnace, or thermal plasma melting,

or other means. These regulations allow for the introduction of thermal treatment processes that would be considered uneconomic in other developed nations. (THEMELIS & MUSSCHE, 2013)

In Europe, gasification technologies have reportedly been on the verge of a breakthrough in the waste industry for decades, according primarily to the providers of these technologies. Amazing and ostensibly new concepts have been extolled time and again, but none of these concepts has yet been viable and at the same time affordable. That's why the technology maturity is still not proved in Europe.

2.6 Municipal Solid Waste Pre-treatment

An alternative strategy for technologies such as gasification, is to process the municipal and commercial waste first to generate refuse derived fuel (RDF). Refuse derived fuel is a term applied to segregated components of waste with high energy density (Sajid, et al., 2022). 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 process requirements. Typically, the process chain consists of coarse shredding, sifting, magnetic belt, eddy current separation and fine comminution. Ferrous and non-ferrous metals as well as coarse and fine fractions are recovered separately (IEA Bioenergy, 2020). Depending on the degree of pretreatment required, some RDF is produced by just shredding MSW and removing some metals as well (Department for Business, Energy & Industrial Strategy, 2021).

Another common designation for the fuel generated based on MSW treatment is the solid recovered fuel (SRF), that is RDF produced under European quality assurance system. According to the European Parliament, RDF is a fuel produce from the treatment of solid waste and SRF is a fuel produced from non-hazardous waste in accordance with EU standards EN 15359 (European Parliament, 2021), i.e., SRF is a more strictly defined sorted waste. The standardization process that aims to produce a better defined quality of RDF useful for specific purpose was recently started with ISO/TC 300 "Solid recovered Fuels" (IEA Bioenergy, 2019).

Actually, RDF production is primarily targeted towards the purpose of combustion and it is explored for other WtE techniques. Processes for RDF production are known as solid waste pretreatment processes and are defined as all intermediate process steps, through which physical or chemical characteristics of a biomass resource are modified, before it is used for final conversion into a useful energy carrier (IEA Bioenergy, 2019).

Evaluations than have been made as part of IEA Bioenergy task 33 studies highlight that mechanical and mechanical-biological pretreatment of MSW can allow waste to meet the physical and chemical specifications required of gasification facilities. Capital costs for the pretreatment systems are moderate and generally worth the benefit of making a low-cost, readily available feedstock stream available (IEA Bioenergy, 2020).

From the total solid waste, depending on the process, only a part will be converted to RDF which can vary between 40% to 70% by weight of raw MSW (Vaish, et al., 2017) (Plavac, Sutlović, & Filipan, 2016). Excluding mainly the organic fraction of waste the RDF total mass is reduced, but the percentage of high energy density compounds increases. With higher percentage of combustible and less content of inert materials the calorific value of the RDF increases when compared to MSW. Typical values of MSW low heating value (LHV) are in the range of 7-15 MJ/kg for MSW in Europe while RDF LHV is in the range of 10-20 MJ/kg (IEA Bioenergy, 2019).

Table 2. 4 shown a comparison, in terms of energetic performance, of two RDF gasification processes (Termiska gasification and Battelle gasification) and two MSW combustion processes (Essex country mass burn incineration plant and SEMASS suspension-fired incineration plant).

Table 2. 4. RDF gasification and MSW mass incineration performance comparison. Extracted from (Vaish, et al., 2017)

Metrics of comparison	Termiska gasification process	Battelle gasification process	Essec mass incineration plant	County burn plant	SEMASS suspension-fired incineration plant
MSW capacity (tons/year)	642,400	341,275	831,105		910,000
RDF capacity (tons/year)	506,255	239,075	N/A		N/A
HHV of product gas (GJ per ton MSW)	6.8	7.1	N/A		N/A
Volume of product gas (m ³ /ton MSW)	906	396.5	6700+		6700
Net power for sale (kWh/ton MSW)	636	612	476		550

Termiska gasification process consist of a combined bubbling and circulating fluidized bed operated approximately at 850°C and atmospheric pressure. After cleaning, syngas is used in a combined cycle turbine. Battelle process uses a circulating fluidized bed of sand at atmospheric pressure (Themelis & Klein, 2003). RDF production for incineration processes is zero because they treat municipal solid waste “as received”. Table 2. 4 allows to identify key differences and advantages of using RDF in thermochemical processes, namely:

- The volume of product gas per ton of municipal solid waste treated is less than 20% for RDF gasification than for MSW incineration. This is explained by the fact that, when working in reduction environment (under stoichiometric conditions), the volume of air or oxidant agent introduce is less, this implies less gas mass leaving the system. This situation is especially noticeable when working with air because the nitrogen in it is an inert gas than dilutes the gas mass. This trend also applies for MSW and RDF gasification comparison, because when working with MSW the gasification process requires more oxidant agent to dry the feedstock and to provide energy.
- Net power for sale - kWh/ton MSW - is higher for RDF gasification than MSW incineration. This is one of the main attractions of gasification since the syngas obtained is a fuel gas that can be

burned at higher temperatures than those reached in the combustion process, increasing the thermal energy available for power generation. The syngas can be burned directly in more efficient systems such as gas turbines or it can be burned for steam production which is then fed to steam boilers.

RDF production is aligned with the solid waste management hierarchy. Countries with high RDF production, such as Germany, base their RDF production on undifferentiated solid waste, without affecting the selective collection and recycling strategies for plastics, paper, cardboard, organic material, glass, etc. Therefore, the production of RDF, as well as its subsequent handling in thermochemical processes, does not compete with recycling, they are complementary activities.

2.6.1 Mechanical Treatment

Mechanical treatment is the basis and the minimum requirement for the production of refuse-derived fuel. The aim in this configuration is to recover materials to recycle and to have at least a shredding for size reduction and a drying according to EN 15359 standard. Plants with only mechanical treatment are also referred as material recovery facilities (MRFs).

Case study 3 “Pretreatment of municipal solid waste (MSW) for gasification” from IEA Bioenergy studies reported the MSW mechanical treatment scheme for Rüdersdorf cement plant, in Germany, in their 2019 report. Mechanical processing is composed by 5 treatments: Precrushing, sifter, ferrous metals separator, non-ferrous metals separator and finally a secondary crushing, to obtain the secondary fuel RDF. In the first step, the MSW is precrushed using a slowly running shredder to generate a size distribution more homogeneous.

In the second step, heavy contents like glass and stones are removed using a wind sifter. In the third and fourth steps the ferrous and non-ferrous metal components are removed by an overbelt magnetic separator and an eddy current separator, respectively. Secondary crushing in fast running shredder decreases particles sizes to less than 50 mm and increase bulk density (IEA Bioenergy, 2019). RDF obtained from this scheme of treatment is burned in the cement plant in a fluidizing bed system.

2.6.2 Mechanical-Biological Treatment

Mechanical biological treatment coupled with advance thermochemical process is one of the five options proposed by the German environmental agency (*Umweltbundesamt* in German) to treat household waste (waste collected as mixed residual waste) with high preference (German Environment Agency, 2018). Mechanical biological treatment comprises a combination of mechanical and biological processes to treat mixed residual waste. Possible configuration consists always of several mechanical processes including grinding, shredding, dimensional sorting etc. and a core biological treatment like bio stabilization, bio drying, aerobic digestion (composting) and anaerobic digestion. In 2017, 507 MBT plants were operating in Europe, with the largest European markets in Germany, Austria, Italy, Switzerland, Netherlands and UK (IEA Bioenergy, 2019) (Lombardi, Zingaretti, Verginelli, & Costa, 2022).

The main distinction between the different concepts of mechanical biological treatment is made on the basis of the order of the technical processes and the aim of the biological treatment. Depending on the location of the biological treatment within the process chain there can be 2 treatment schemes: dry stabilization (MBS) and splitting or mechanical biological (MBT).

In dry (or bio) stabilization there is not a “splitting” process prior biological treatment, the entire waste is subjected to a drying process facilitated by heat generated during partially aerobic degradation (partial composting) (German Environment Agency, 2018). Before biological treatment there is a mechanical pre-treatment mainly oriented to coarse shredding and after biological treatment there is a mechanical treatment to separate and refine the fractions of recycled materials (mainly metals and inert) and a fraction suitable for energetic recovery (RDF with low moisture)

In splitting (MBT) the objective is to maximize energy conversion from the organic rich content stream as well as the combustible stream. First a mechanical scheme is performed to reduce waste, separate recyclables (mainly metals) and inert, and a separation by sorting is performed to obtain a heavy and low energy fraction. Low energy fraction (organic rich fraction) is submitted to an anaerobic digestion process to produce biogas and a solid residue that is then subjected to a final degradation process or biological stabilization before landfill disposal. High energy fraction is subjected to further comminution and densification (or not) to produce RDF. If biological treatment is composting, there is no biogas production and the process is used to convert waste into stabilized material for landfilling.

The main difference of MBT and MBS is that in energy recovery only a part of the waste (organic rich fraction) is subjected to biological treatment, contrary to the other schemes where the whole waste is biologically treated.

It is important to highlight that recycled products in mechanical biological treatment facilities are typically of a lower quality than those derived from separate recycle collection systems and also the recycling rate is not as high as expected, mainly for glass, plastics, textiles and paper. As an average of UK MBT plants in 2017, recycling rate for metals (ferrous and non-ferrous) varies between 1-3%, for heavy material (glass and stone) varies between 0-8%, for plastics varies between 0-6% and for organic fines varies between 0-9% (Tolvik Consulting, 2017).

A study made on the MBT facilities in the UK identifies that for plastics, even though optical sorting technologies offered good efficiencies, the technology was expensive and the cost/benefit of adopting them would influence the selection of the solution (Tolvik Consulting, 2017). For glass, textiles and paper the situation is that even when recovered, their quality is low and were unlikely to receive a profitable income.

A study made on the IVAR plant in Norway in 2022 exposed lessons learned in terms of plastic recycling as part of task 36 of IEA Bioenergy. The IVAR plant is one example of high efficiency material recovery facility that combines post-sorting of residual waste with recycling of some of the plastic waste fractions. At the plant five different fraction of plastics, four fractions of paper, bio-waste, glass, and metal packaging are separated (IEA Bioenergy, 2022). In order to achieve high specificity in sorting the plant uses near infrared spectroscopy (NIR) technology along with band magnets, eddy current sorters,

vibration sifters among others high efficiency and also expensive techniques.

The conclusion of the study identified the challenge of plastic recycling, because with current technologies, quality of plastic recycled is not as high as the market require even though the quantity of material recycled is high (quality is the bottle neck for plastic recycling). High quality recycled materials can be sold in the market while medium and low quality products are treated with thermochemical routes. This means that no matter how much plastic the sorting plants recover, only part of it will be suitable for recycling (IEA Bioenergy, 2022).

Chapter 3

Methodology and Performance Assessment

This chapter presents and develops the life cycle analysis methodology dictated by the ISO standard guidelines. A brief description of the case study is made, the objective and scope of the analysis is presented, as well as the functional unit and the environmental impact selected. This chapter ends by presenting the characteristics of the scenarios to be analysed and the main assumptions of the study.

3.1 Base Case – Valorsul

Valorsul - *Valorização e Tratamento de Resíduos Sólidos das Regiões de Lisboa e do Oeste, S.A.*, is the company responsible for the treatment and valorization of approximately 950,000 tonnes of urban solid residues, almost 20% of the country annual waste production, which are produced annually in 19 municipalities of Lisbon and western region (*Grande Lisboa e Região Oeste*): *Alcobaça, Alenquer, Amadora, Arruda dos Vinhos, Azambuja, Bombarral, Cadaval, Caldas da Rainha, Lisboa, Loures, Lourinhã, Nazaré, Óbidos, Odivelas, Peniche, Rio Maior, Sobral de Monte Agraço, Torres Vedras and Vila Franca de Xira* (Valorsul, 2023).

Its area of coverage corresponds to 4% of Portugal, serving 1.6 million inhabitants (Valorsul, 2023) and is one of the four companies in Portugal (including the continental area and the area corresponding to the autonomous regions of Madeira and Azores) where waste is valorised to produce energy.

Valorsul has an integrated municipal waste management system composed by:

- Sorting center

Materials (glass, paper/cardboard and plastic/metal) placed in the recycling points or collected door-to-door in the 19 municipalities in the Valorsul area are sent to the two Sorting Centers located in *Lumiar* and *Vilar Cadaval*. In these facilities, selective waste is separated (through mechanical and manual processes) by type of material in order to be forwarded to the recycling industry (Valorsul, 2023).

- Organics treatment and valorisation plant

Organic Valorisation is composed by the Organic Treatment and Valorisation Plant (ETVO) and the green waste Composting Plant, both facilities located in *Serra da Mira*. Food waste from some of the canteens, restaurants and markets in the Lisbon metropolitan area (north) is sent to Valorsul's Treatment and Organic Valorisation Plant where they are submitted to an anaerobic digestion process to produce biogas (to produce electricity) and an organic agricultural corrective material. The green waste, collected and delivered selectively, is treated and transformed into compost, in the Green waste Composting Station (Valorsul, 2023).

- Solid urban waste treatment plant / Energetic valorisation plant

This unit is responsible for thermal treatment of approximately 2,000 tons per day of undifferentiated waste, residues from sorting facilities and residues from organic valorisation through a mass incineration process. The valorisation plant, shown in Figure 3. 1, is located at *Loures* in *Plataforma Ribeirinha da CP* (Valorsul, 2023).



Figure 3. 1. Valorsul energetic valorisation plant in *Plataforma Ribeirinha da CP, Loures*. Extracted from: (Valorsul, 2023)

Energetic valorisation plant is design to process 662,000 tons of waste per year and it produces electric energy, volatile ash, flue gas and ferrous scrap. 587 kWh of electricity per ton of MSW is obtained (Valorsul, 2023), this electricity produced is enough to supply 150,000 inhabitants (Valorsul, 2023).

Process initiates when trucks unload waste into a large pit with negative pressure (air is constantly extracted to avoid odour's problems and is used in the incineration) and with a capacity to store 12,500 tons of residues (FURTADO, 2014). Operators control two grapples to mix the waste and take it to the hoppers where waste is carried to the furnaces, each grapple has a weight system to quantify the amount of waste fed to the furnaces (FURTADO, 2014). Valorsul energetic valorisation plant is composed by 3 furnaces using Detroit Stoker Reverse-Acting Stoker as grate furnace technology (Valorsul, 2023) incinerating approximately 28 tons per hour of waste at 850-900°C each one. MSW treated have a calorific value between 5,860-10,460 kJ/kg (Valorsul, 2023), to cop this variability, natural gas is used as an alternative fuel to stabilize and improve combustion.

Heat in the flue gas is used to heat water to produce steam (approximately 198,000 kg/h in total for the 3 incineration lines (Valorsul, 2023)) than is passed through a turbine to produce electricity. Low temperature flue gas (after deliver part of its heat) enters the cleaning system where activated carbon, ammonia and lime are injected to treat nitrogenous pollutants, acid gases and other pollutants such as dioxins and furans. Solid pollutants residues including, activated carbon, ashes and slag, are collected in the bag filter and disposed in a special area in the landfill.

Electricity produced from Valorsul is injected in the Portuguese national grid and comes mainly from

energetic valorisation plant (373,904 MWh in 2021) but also from the combustion in gas engines of biogas from organic valorisation treatment (7,110 MWh in 2021) and biogas recuperated at sanitary landfills that is burned to produce electricity (15,989 MWh in 2021) (Agência portuguesa do ambiente, 2022).

- Slag treatment and valorisation facility

The slag treatment and valorisation facility (*ITVE Instalação de Tratamento e Valorização de Escórias*) located in *Vila Franca de Xira*, receives the slag that is the remaining solid after waste is burned at the energetic valorisation plant of Valorsul, and separates ferrous metal, non-ferrous metal, and aggregates. The metal is sent for recycling and the aggregates can be used for road construction (Valorsul, 2023).

- Landfills

As final disposal, Valorsul manage two sanitary landfills: Sanitary landfill “*Mato da cruz*” located in Vila Franca de Xira and sanitary landfill “*do oeste*” located in *Vilar Cadaval* (Valorsul, 2023).

In 2021 Valorsul received approximately 790,000 tons of solid waste of which 39% corresponds to biowaste, 13% paper and cardboard, 9.5% plastic, 7% glass, 1.46% textiles, 7.23% sanitary textiles, 1.72% metals, 2% wood, 9.5% fine waste and the remaining is bulky waste, green waste, hazardous waste and other waste in smaller proportions (Agência portuguesa do ambiente, 2022). The largest proportion of waste (80%) comes as undifferentiated waste and approximately 18% corresponds to waste collected selectively (paper and cardboard, glass and plastic) (Agência portuguesa do ambiente, 2022).

In 2021, Valorsul followed the Portuguese national trend previously discussed in chapter 1, regarding waste management and final disposal. Initially 74% of the waste was treated in the energy recovery plant, 6% was treated in the mechanical and biological treatment plant managed by Valorlis company, 4% went to organic recovery, 13% went to material recovery and 2% were taken directly to landfill (Agência portuguesa do ambiente, 2022). In terms of final destination, 7.8% was taken to landfill and 68.2% of waste was taken to energetic valorisation (Agência portuguesa do ambiente, 2022).

3.2 Life Cycle Assessment

Life cycle assessment (LCA) is a holistic accounting tool for environmental assessment of a product or service; is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (International Standard ISO , 2007). Inputs and outputs refer to natural resources, products or energy demanded and to emissions and effluent (liquid, gas or solids) respectively. The importance of LCA is that it creates a clear framework for environmental evaluation, it set a based where products (or services) can be compared and analysed, independent of specific factors such as localization.

According to the standard ISO 14040:2006 “Environmental management — Life cycle assessment — Principles and framework”, life cycle is defined as: consecutive and interlinked stages of a product (any goods or service) system, from raw material acquisition or generation from natural resources to final disposal (International Standard ISO , 2007). Life cycle assessment purpose is to address and quantify the environmental aspects and potential environmental impacts (e.g. use of resources and emissions) throughout products and services entire life cycle to help in the decision whereas a product is sustainable or not and in product’s comparison in terms of sustainability. Following ISO 14040:2006 principles, life cycle assessment can assist in (International Standard ISO , 2007):

- Identifying opportunities to improve the environmental performance of products at various points in their life cycle
- Informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign)
- The selection of relevant indicators of environmental performance, including measurement techniques, and marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).

Therefore, LCA is an important tool within circular economy strategy since it provides access to sustainability knowledge that helps to change consumption paradigms and helps to identify opportunities for improvement within the economic chain of products. To conduct an LCA, standard ISO 14044:2006 “Environmental management – life cycle assessment – requirements and guidelines” details the requests and details of the study that include four phases:

1. Goal and scope definition

Goal and scope definition is the first phase to conduct an LCA and is the phase in which the basis for the study must be clear and aligned with the intent of the study. According to the scope of the analysis and the limits established in the system to be studied, there are the following variations in the life cycle assessment (Ecochain, 2023):

- Gate to gate: LCA is focused only in a particular value-added process of the entire production chain. It is a partial LCA
- Cradle to gate: LCA focused from the resource extraction to the exit of the factory before it is transported to the consumer. It is a partial LCA
- Cradle to Grave: LCA covers the entire life cycle from resource extraction to disposal. Complete LCA
- Cradle to cradle: LCA covering from resource extraction to a recycling process as an end of life disposal. It is a particular case from cradle to grave model in which the final disposal is a recycling process.

Allocation, following ISO 14040:2006 definition, stands for partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems (International Standard ISO , 2007). Allocation processes arise from the need to incorporate the fact that industrial processes generate more than one product and reuse and recycle intermediate

products or may discard products as raw materials for other processes.

2. Inventory Analysis

The inventory analysis phase involves the compilation and quantification of inputs and outputs for a product (or service) through the cycle determined in the scope (gate to gate, cradle to gate, cradle to grave or cradle to cradle).

3. Impact assessment

As stands in the ISO 14044:2006, impact assessment is the phase aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (International Standard, 2006). The main objective in this phase is to translate the data collected in the inventory phase into impact.

For the specific case of this study, as detailed below, this impact assessment was carried out in a partial manner since only CO₂ equivalent emissions were analysed as part of the potential global warming impact. Therefore, this study refers to the analysis of CO₂ equivalent emissions rather than a total impact assessment.

4. Interpretation Phase

As stands in the ISO 14044:2006, life cycle interpretation is the phase in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations (International Standard, 2006).

3.3 LCA Development

As previously discussed in chapter 2, LCA studies conducted on MSW treatment allowed to compare and decide whereas a specific treatment (incineration, gasification, plasma gasification, anaerobic digestion, composting and pyrolysis) was better than other in specific environmental impacts analysed. From this evaluation a final selection of treatment technology was performed and gasification was selected as treatment with better overall performance.

However, the high specificity and heterogeneity of solid wastes limit the extrapolation of the conclusions of other studies and force the need to perform analyses considering the specific characteristics of the raw material of the area where solutions are to be applied. The main objective of this study is to fulfil this gap of studies conducted using Portuguese MSW and conditions and to propose solutions oriented to waste management companies like Valorsul.

For this purpose, a life cycle analysis study was conducted to evaluate the performance and environmental impact of 3 waste management scenarios for the undifferentiated residual fraction. One scenario corresponds to the base case of Valorsul energetic valorisation plant through mass incineration and the other two scenarios are based on different MSW pretreatments with gasification as

thermochemical conversion technology.

3.3.1 Goal, Scope, System Boundaries and Functional Unit

The goal of the study is to compare the potential environmental impact, focusing on global warming potential (GWP) measured as CO₂ equivalent emissions, of three waste management scenarios with electricity generation which are widespread and nowadays considered as the most promising technologies for waste thermal treatment. Scenario 1 corresponds to the base case of mass incineration, scenario 2 corresponds to gasification using bubbling fluidized bed reactor with a mechanical-biological pretreatment process and scenario 3 corresponds to the same gasification technology as scenario 2 coupled with a mechanical pretreatment process prior to the thermochemical process.

The analysis aims to quantify the contribution from pretreatment stage, thermochemical transformation and gas cleaning stage of the three process life cycles based on an average MSW composition managed at Valorsul. The scope of the study is a gate-to-gate variation where a particular value-added process in the entire waste management chain will be analysed. For the three scenarios the scope is focused on the processes inside the energetic valorisation plant: pretreatment, thermochemical conversion and gas cleaning process.

Analysis motivation is to contribute to the debate on the need for an intermediate step in the management of solid wastes and especially of the undifferentiated fraction that is taken to thermochemical treatments such as gasification or incineration. Is it better to burn the waste in mass incineration systems without pre-treatment or does pre-treatment and gasification with production of a fuel with lower organic content and less inert increase the efficiency of the process and increase the quality and value of the products obtained? Answering this question will contribute to decision making by the entities in charge of waste management, the target audience of the study.

Functional unit coincides with the service provided by actual's Valorsul system, i.e. the thermochemical treatment with electricity generation of 1 ton of undifferentiated municipal solid waste with a composition estimated as average for Valorsul inputs and represented in Table B. 1. The three scenarios were located in Portugal. The system boundaries are schematically shown in Figure 3. 2, Figure 3. 3 and Figure 3. 4 with red dotted lines, they include the waste pretreatment process, the incineration or gasification reaction process, the electricity production unit (boiler and steam turbine) and the gas cleaning system. Waste collection, transportation, solid residues treatment, reprocessing of solids and materials for recycling and recovering and final safe disposal are not included in the boundaries of the study.

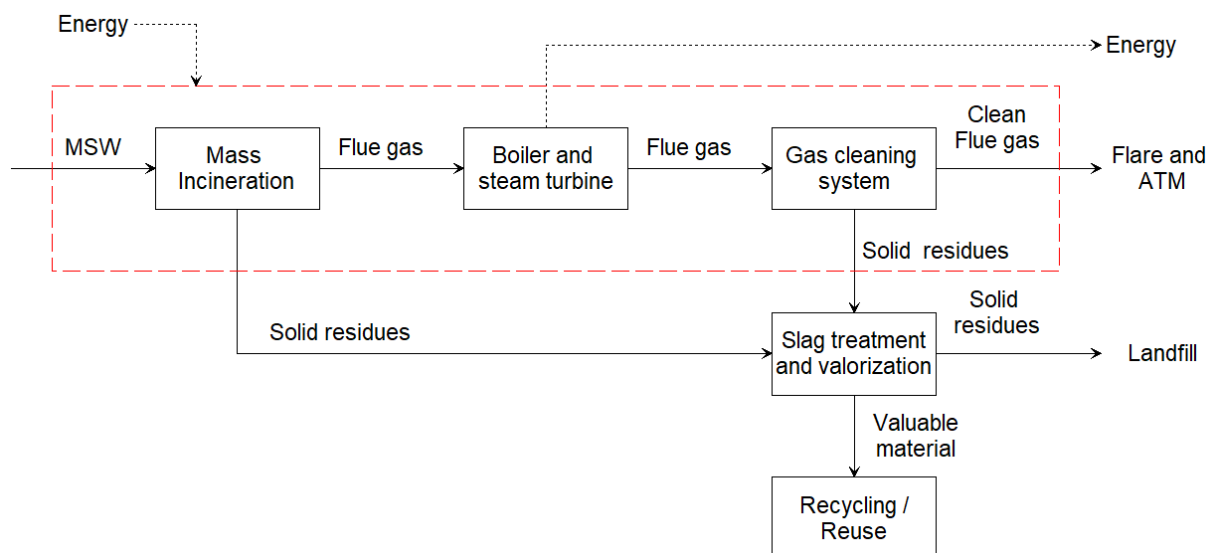


Figure 3. 2. Scenario 1 schematic representation with system boundaries selected for LCA

Scenario 1 (indicated in Figure 3. 2) represents waste management situation in Valorsul's energetic valorisation plant. Waste from undifferentiated collection, along with residues and rejected waste from organic valorisation, sorting facilities and waste from other sources that has characteristics similar to urban solid waste, are mixed and are combusted in the mass incineration process. The resulting high temperature flue gas passes through a steam boiler system where it exchanges its heat with boiler feed water producing superheated steam at 528 bar and 420°C (Valorsul, 2023). Steam passes through a 14-stage condensing steam turbine coupled with an electricity generator that convert its thermal energy into mechanical energy and then to electricity (Valorsul, 2023). After heat exchange, flue gas with less temperature passes through the cleaning system to eliminate pollutants created in the combustion reaction such as NO_x, SO_x, furans and dioxins.

Cleaning system of scenario 1 starts with the injection of aqueous solution of ammonia in the combustion chamber to remove NO_x (nitrogen oxides) following a selective non-catalytic reduction scheme. The following step is to remove acid gases, such sulphur compounds (SO_x) and hydrogen chloride (HCl) through the injection of limewater (also known as lime milk) with an atomizer. To remove dioxins, furans and heavy metals there is an injection of excess solid activated carbon in the gaseous flue gas stream. Finally, flue gas passes through a bag filter to remove particles and solid residues as unreacted activated carbon, lime and ashes.

Slags are collected in the lower part of the furnaces in a system where water is injected to guarantee slag sealing and the slags are pushed to the slag treatment and valorisation unit. Solid residues from slag treatment and valorisation unit are primarily used as aggregates in the construction of roads; if it is not possible to use them for this purpose, they are disposed of in landfills. The estimated energy consumption of the energetic valorisation plant corresponds to 89 kWh per ton of MSW treated (Valorsul, 2023).

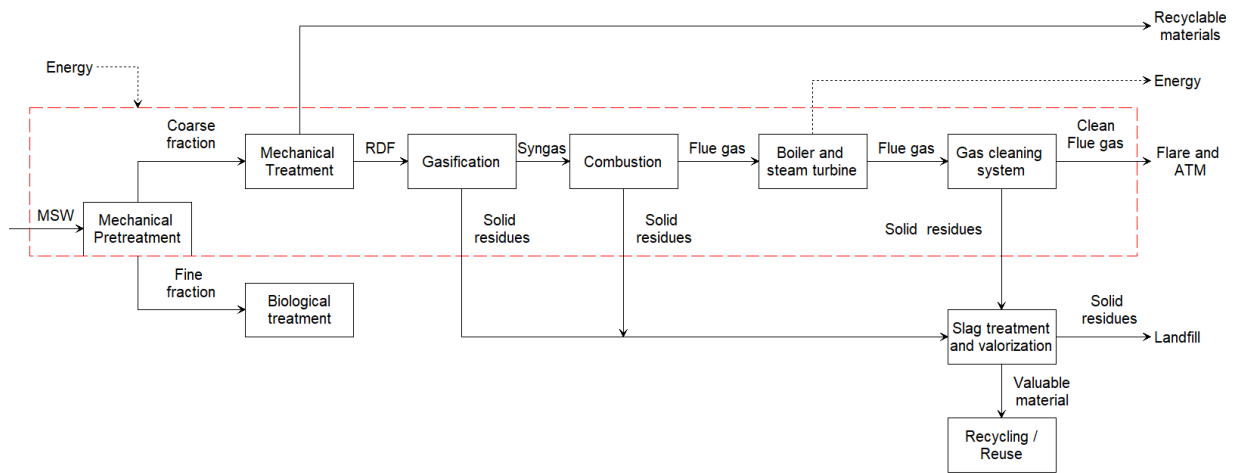


Figure 3. 3. Scenario 2 schematic representation with system boundaries selected for LCA

Scenario 2 (Figure 3. 3) gathers information from two successful case studies of mechanical-biological treatment plants: "Bioenergy power plant MBA" in Lübeck, Germany (Lübeck Entsorgungsbetriebe, 2020) and the commercial-scale study of a waste treatment plant in Finland (Nasrullah, 2015). The mechanical pretreatment consists of an initial manual separation to remove bulky waste and then an initial size reduction to have a particle diameter D_{95} of 150 mm (i.e. 95% of the particles have a diameter less than 150 mm) to homogenize the waste. The shredded waste is separated in a rotary drum screen into two fractions, fine ($D_{95} < 30$ mm) and coarse ($D_{95} > 30$ mm). The fine fraction corresponds to the organic waste that will be taken to biological treatment and the coarse waste will be treated in the subsequent steps of the scheme.

The coarse fraction enters the mechanical treatment starting with a magnetic separation system to separate ferrous metals and an eddy separator for non-ferrous metals. After the separation of metals for recycling, the flow enters an air separator to separate the heavy fraction composed of stones, glass and heavy inert material from the light fraction which is composed of plastic, paper, textiles and others. This light fraction is taken to a near infrared separation process to separate PVC and other materials contaminated with chlorine (rejected material). Finally, the stream is taken to a secondary shredding to achieve a particle size of D_{95} 100 mm (IEA Bioenergy, 2018), this residue is as loose material but can be taken to further processing to form bales of this high quality RDF material.

Gasification process consist of a bubbling fluidized bed gasifier in which air is injected as an oxidizing agent and to make a combustion of a part of the fuel to provide the necessary energy (Autothermal gasifier). The scenario contemplates the gasification operating conditions reported for the Outotec technology, which is one of the best consolidate technologies in the biomass and solid waste gasification market (IEA Bioenergy, 2018). Bed material is crushed refractory clay and air is injected as oxidant and fluidizing agent (FICHTNER Consulting Engineers Limited, 2014)

The gasification temperature is 900°C, the pressure is atmospheric and the air equivalent ratio is 0.4 (the ratio of the amount of air input to the stoichiometric amount required for complete oxidation) (Seo, Alam, & Yang, 2018). After the gasification process, the syngas produced passes through a cyclone for solids removal and is then taken to a combustion chamber where complete oxidation of the syngas

takes place at temperatures between 850-1100°C (FICHTNER Consulting Engineers Limited, 2014). This scheme of syngas combustion is also known as dual-stage incineration and can achieve electricity generation efficiencies of approximately 30% with high reliability. Schemes in which syngas is used for gas turbines reach efficiencies of up to 60%, however, gas turbines allow very low levels of contaminants in the input fuel, which makes the syngas cleaning and purification process more stringent, costlier and more energy demanding. Due to this energy consumption in gas cleaning, the net efficiency of gas turbines is approximately 40% (Seo, Alam, & Yang, 2018).

The cleaning process is the same in all three scenarios and consists of a conventional dry gas cleaning system for the flue gas, also implemented by the Outotec technology (IEA Bioenergy, 2018). The advantage offered by the dry-cleaning system is to operate above the condensation temperature of the acids and water, avoiding their condensation (IEA Bioenergy, 2018). Clean flue gas is burned in a flare and release to the atmosphere.

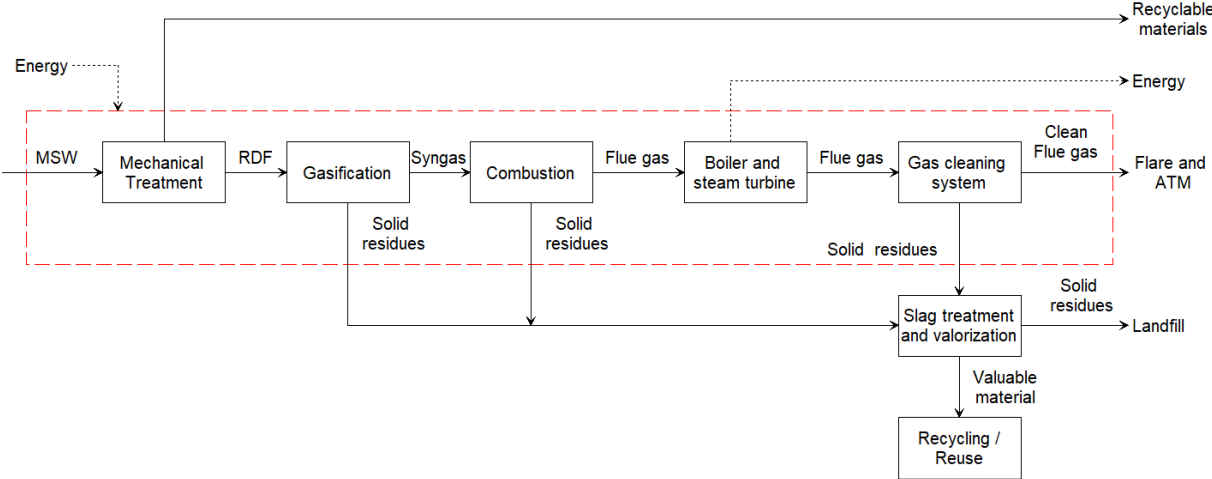


Figure 3. 4. Scenario 3 schematic representation with system boundaries selected for LCA

Scenario 3 shown in Figure 3. 4 is derived from scenario 2, the only difference is the absence of separation of the organic fraction in the pretreatment process, which means that in scenario 2 the organic fraction is separated and sent to an independent organic valorisation process, and in scenario 3 the organic waste is processed through gasification. The scheme starts with a separation of the bulky material, then an initial and light shredding to later enter the same mechanical treatment scheme of scenario 2. The gasification and gas cleaning scheme are also the same of scenario 2. The intention of scenario 3 is to evaluate how strict the pretreatment must be to obtain a good performance in the gasification process.

Although several products can be obtained from gasification, as previously mentioned, electricity was the only product considered in this study since this choice simplifies the comparison with the existing large-scale incineration waste to energy plant in Valorsul. Additionally, studying other technologies for obtaining energy such as the combined cycle of energy and heat would not add value to the study because infrastructure would be required to supply heat, as is the case of district heating, which is not

common in Portugal.

The analysed scenarios allow material and energy recovery (ferrous and non-ferrous metals, plastics, aggregation material for construction sector among others), based on this and 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 collecting the input and output data related to these sub-processes (International Standard, 2006). I.e., each process will be evaluated in their constitutional step, mechanical treatments are evaluated for each individual treatment as well as gas cleaning systems.

The quality of data of the life cycle inventory (LCI) is high since a part of the data derive from several commercial and pilot units, especially for scenario 1 where specific information for Valorsul energetic valorisation unit was applied. For the three scenarios, Portugal's waste management information and Portugal's energy mix characterization was used. The LCA was carried out by using Aspen Plus and manually through excel tool.

Following ISO 14044:2006 mandatory requirements for life cycle impact evaluation, Table 3. 1 summarize impact category, category indicator and characterization model selected for the LCIA to comply with the previously discussed goal.

Table 3. 1. Environmental impact characterization for LCA

Impact category	Climate change
Category indicator	Global warming potential
LCI results	Amount of greenhouse gas per functional unit (ton of MSW treated)
Characterization model	Baseline model for 100-year time horizon of EPA 2009 guidelines
Characterization factor	Global warming potential (GWP ₁₀₀) specific for greenhouse gas (kg CO _{2eq} / kg GHG)
Category indicator result	kg CO _{2eq} /ton of MSW treated (kg CO _{2eq} / functional unit)
Environmental relevance	Accelerated global warming is one of the principal causes of climate change, which represents a serious threat to life on earth due to extreme weather conditions, and devastating natural phenomena (floods, earthquakes, droughts, among others).

3.3.2 Analysis Tools – Aspen Plus V11

Aspen Plus is a process simulation software in the chemical industry with a strong physical and chemical properties database that allows to integrate different industrial unitary operations within a same simulation environment 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 to improve and study processes efficiency and sustainability performance (Aspen Technology Inc, 2023). Aspen plus software proportionate a wide range of tools to simulate and optimize chemical processes working with solids, biomass, gases and liquids, making it a powerful and useful tool for life cycle analysis studies.

One of the many advantages of the software is the ability to alter the thermodynamic packages depending on the compounds in the simulation, as well as the flexibility to simulate process details such as reaction kinetics, equilibrium reactions, separation diameters for the mechanical processes of solids among many other tools.

In this life cycle analysis, numerical simulation (mass and energy balance) for scenarios 1, 2 and 3 was performed in Aspen Plus V11 using Peng Robinson as thermodynamic package and by means of the equilibrium model for gasification and combustion to predict the maximum achievable yield of products in a reacting system (Ahmad, Zawawi, Kasim, Inayat, & Khasri, 2016). Research conducted on gasification systems for biomass indicated that Aspen plus is the most common simulation model for fluidized bed gasifier with more reliability and consistency with experimental data (Ahmad, Zawawi, Kasim, Inayat, & Khasri, 2016).

3.3.3 Scenarios Characterization

The comparison of the scenarios for thermochemical treatments was related to the physical and chemical waste composition listed in Table B. 1 and Table B. 2 on annexe B. Table B. 1 corresponds to the composition from undifferentiated mixed waste received at Valorsul in 2021 according to the annual municipal waste report by the Portuguese ambient agency APA (Agência portuguesa do ambiente, 2022) and Table B. 2 shows proximate and ultimate analysis of the main MSW components (Seo, Alam, & Yang, 2018) (Arafat & Jujakli, 2013).

To comply with Aspen plus V11 software format for data entry, the following adjusting to the information reported on Table B. 1 and Table B. 2 were made:

- Fixed carbon (FC), volatile matter (VM) and ash percentage in the proximate analysis must be in dry basis.
- Composition data was normalized to 100%
- Information regarding ash content in proximate and ultimate analysis must be the same in order to create the non-conventional component in Aspen Plus V11. Ultimate analysis was modified to retaining its initial distribution on an ash-free basis and modifying the ash content to match with the proximate analysis.

The adjusted information, corresponding as well with the information used in the simulation to create the non-conventional components of MSW is shown in Table 3. 2

Table 3. 2. Proximate and ultimate analysis for MSW simulated in LCA scenarios. Adapted from (Agência portuguesa do ambiente, 2022) (Seo, Alam, & Yang, 2018) (Arafat & Jujakli, 2013)

	%w MSW	Proximate analysis (% db)				Ultimate Analysis (% db)					
		Moisture	FC	VM	Ash	C	H	O	N	S	Ash
Plastic	11.4	0.2	2.0	96.0	2.0	64.8	7.8	24.6	0.0	0.8	2.0

	%w MSW	Proximate analysis (% db)				Ultimate Analysis (% db)					
		Moisture	FC	VM	Ash	C	H	O	N	S	Ash
Paper	15.6	10.2	9.4	84.5	6.1	43.2	5.8	44.2	0.3	0.3	6.1
Glass ^a	8.5	-	-	-	-	-	-	-	-	-	-
Biowaste	46.4	70.0	12.0	71.3	16.7	61.0	9.6	12.4	0.3	0.1	16.7
Metals ^b	2.1	-	-	-	-	-	-	-	-	-	-
Textiles	10.4	10.0	7.2	73.3	19.4	45.6	5.5	25.9	3.6	0.0	19.4
Wood	2.5	12.0	14.1	85.2	0.7	49.4	6.1	43.7	0.1	0.0	0.7
Yard waste	1.0	62.0	16.8	70.3	12.9	40.3	5.6	38.9	2.0	0.3	12.9
Bulky waste ^c	2.3	-	-	-	-	-	-	-	-	-	-

^a Glass was simulated as Silica (conventional component) in Aspen Plus V11. Proximate and ultimate analysis is not required.

^b Metal's stream is composed by ferrous and non-ferrous metals with an assumed composition of 89.7% and 10.3% respectively according to a typical urban waste composition (Fernández-González, Grindlay, Serrano-Bernardo, Rodríguez-Rojas, & Zamorano, 2017). Ferrous metals were simulated as their main component, iron, and non-ferrous metals were simulated as their main component, aluminium (Fernández-González, Grindlay, Serrano-Bernardo, Rodríguez-Rojas, & Zamorano, 2017). For these conventional components, proximate and ultimate analysis is not required.

^c Bulky waste are manually removed with an assumed efficiency of 100%, therefore it is not included in the simulation and its management is outside the established system boundaries.

Particle size distribution for the constituent currents of MSW was obtained from a study made in the faculty of process sciences of the Technical University of Berlin titled "Development of a prototype for the dynamic flow sheet simulation of mixed municipal waste treatment processes" (*Entwicklung eines Prototyps zur dynamischen Fließschemasimulation von Prozessen der Aufbereitung gemischter Siedlungsabfälle* in German) for household waste in Germany (Platzk, 2018). Particle size distribution, in mass percentage, used for scenarios simulation is shown in Table 3. 3 based on the information reported by (Platzk, 2018). The upper limit of the last interval (largest particle size) was taken as 400 mm because it is the typical width of the containers for solid waste collection (Almoverde ecologia , 2008).

Table 3. 3. Mass percentage distribution of MSW components per particle size diameter range.

Adapted from (Platzk, 2018)

	10 mm – 45 mm	45 mm – 100 mm	100 mm – 180 mm	180 mm – 400 mm
Plastics	5%	25%	30%	40%
Paper	5%	20%	30%	45%
Glass	35%	30%	30%	5%
Biowaste / Yard Waste	38%	32%	20%	10%
Metals ^a	8%	32%	32%	28%
Textiles	2%	11%	27%	60%
Wood	4%	16%	25%	55%

^a Particle size distribution was assumed equal for ferrous and non-ferrous metals.

Specific operating information regarding scenario 1 was compiled from official Valorsul reports and websites while operating information for scenarios 2 and 3, detailed in Table 3. 4, was constructed from information gathered for the Outotec process, information reported for various biomass gasification life

cycle analysis studies including data obtained from pilot scale fluidized bed gasifiers and the process conditions reported by the international energy agency IEA Bioenergy as part of its task 33 (IEA Bioenergy, 2018).

The information employed to create the scenarios corresponds to documents and studies preferably focused on solid waste less than 5 years old. Most of the studies are from 2018 onwards to ensure that the operational values are recent and reflect advances in technologies and operation at commercial level. Although this was the main objective, for some parameters the reference documents are older due to the lack of updated studies for municipal solid waste. To satisfy the objective of this study, all the information collected covered the geographical area of Europe and preferably Portugal. When it was not possible to find documents for Portugal, the search area was extended to Europe, giving preference to countries such as Germany and England as important references for solid waste management.

Table 3. 4. Characterization scenarios analysed in LCA. Information extracted from (IEA Bioenergy, 2018) (FICHTNER Consulting Engineers Limited, 2014) (FURTADO, 2014) (Ardolino, Lodato, Astrup, & Arena, 2018) (Sorrels, 2019) (Siemens Energy Global GmbH & Co. KG, 2021)

Variable	Scenario 1	Scenario 2	Scenario 3
Fuel pretreatment	N/A	MBT	MT
Thermal technology	Mass incineration	Bubbling fluidized gasification (Autothermal)	Bubbling fluidized gasification (Autothermal)
Fuel	MSW	RDF (From MBT)	RDF (From MT)
Pressure	1 atm		1 atm
Gasification equivalence ratio	-		0.4
Oxidant medium	Air		Air
Drying temperature	150°C		150°C
Pyrolysis temperature	450°C		450°C
Gasification temperature	-		900°C
Combustion equivalence ratio	1.2		1.2
Combustion temperature	850°C		1000°C
Flue gas outlet temperature	150°C		140°C
Superheated vapour conditions	420°C and 52.8 bar		400°C and 45 bar
Steam outlet conditions	55°C and 0.15 bar (a) (saturated conditions)		55°C and 0.15 bar (a) (saturated conditions)
Gas cleaning scheme	Semi dry gas cleaning		Semi dry gas cleaning
Aqueous ammonia consumption (24% by weight)	785 g of ammonia per ton of MSW incinerated		0.5 mol Ammonia/mol NO in flue gas
Activated carbon consumption	460 g per ton of MSW incinerated		0.5 kg/ton feedstock
Hydrated lime consumption	8 kg of lime per ton of MSW incinerated		6.5 kg/ton feedstock
Baghouse filter removal efficiency	99.9 %		99.5%

All the scenarios include a similar heat recovery unit for electricity generation and gas cleaning scheme

in order to evidence the impact of the pretreatment scheme and the thermochemical conversion performance on the environmental impact. The percentages of recovery of recyclable materials in MSW in the pretreatment were selected from a study of six facilities in Europe with similar schemes as the one proposed for scenarios 2 and 3 and are detailed in Table 3. 5.

Table 3. 5. Material recovery rate for paper, plastics and metals. Extracted from (Themelis & Bourtsalas, 2022)

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

3.3.4 Assumptions and Limitations

Hypothesis and assumptions considered in the implementation of the LCA are listed below along with the limitations that these imply for the analysis of the study.

- Physical composition studied is the composition of the solid waste received by Valorsul in 2021. However, the chemical composition information regarding ultimate and elemental analysis corresponds to a typical composition of urban solid waste that is not specific to Valorsul. Even though it is expected that chemical composition is within the range of the typical values, this may generate discrepancies in the results with respect to the expected behavior of the waste received as undifferentiated waste in Valorsul in 2023.
- In 2021 there were still some measures associated with the COVID-19 pandemic, therefore, waste characteristics for 2020 and 2021 differ from the historical trend of previous years. However, latest official information provided by the Portuguese environmental agency APA corresponds to 2021. 2022 report has not yet been published.
- Municipal solid waste composition studied was assumed as constant. In reality, composition throughout the year will change depending on the season (winter/summer) and weather conditions such as rainfall. This limits the applicability of the study and in the future sensitivity analyses should be performed by varying the composition of the waste and considering extreme cases in its composition.
- Solid particle size distribution was taken from a municipal solid waste sample from Germany. Although it may be a sample that attempts to reproduce the behavior of municipal solid waste in general, it is not representative for waste entering Valorsul energetic valorisation plant. To be able to reproduce the study with consistency, an analysis of the particle size distribution over several samples covering seasonal variations should be performed.
- Aspen Plus V11 is a tool for simulating chemical processes and streamlining the mathematics behind extensive mass and energy balances for systems as complex as chemical plants. Aspen

does not simulate specific technologies, such as optimal sorting technologies, but basic chemical unit processes such as phase and stream separation. Aspen plus makes energy consumption estimates based on temperature and enthalpy balances but does not estimate power/energy consumption of specific equipment. To be able to simulate in aspen plus, technologies must be broken down into their unit operations.

- Bulky items in the “as received” MSW were separated with 100% efficiency, therefore they are not simulated in Aspen Plus V11.
- Glass contained in municipal solid waste was simulated as silica.
- Ferrous metals contained in municipal solid waste were simulated as iron
- Non-ferrous metals contained in municipal solid waste were simulated as aluminum
- Metal’s stream is composed by ferrous and non-ferrous metals with an assumed composition of 89.7% and 10.3% respectively according to a typical urban waste composition (Fernández-González, Grindlay, Serrano-Bernardo, Rodríguez-Rojas, & Zamorano, 2017).
- For Aspen simulations, dry air was considered at standard conditions @25°C and 1 atm.
- Pressure and temperature are uniform inside equipment. No temperature or pressure profile inside reactors was considered.
- Ash is inert in reactions.
- Heat and pressure losses are negligible.
- Combustion reactors for all 3 scenarios and gasifiers for scenarios 2 and 3 are isothermal and at equilibrium conditions. Assuming that the reactors are in equilibrium allows to study the maximum concentrations reached, both for the synthesis gas and flue gas and for the contaminants. However, in reality, time is limited to few seconds (the equilibrium assumes infinite time to reach this condition) and the concentrations may vary.
- Simulations were performed considering steady state
- As intermediate and end products, syngas and flue gas composition was assumed as only formed by: H₂O, CO, CO₂, CH₄, SO₂, NO, N₂O, N₂, O₂, H₂, H₂S, NH₃, tars and solid residues (inert and ash)
- Tars composition was assumed as C₆H₆ (Benzene) and C₆H₆O (Phenol)

Chapter 4

Results and Discussion

This chapter presents the inventory obtained for the simulation of the case studies as well as their interpretation in terms of environmental impact. This chapter analyses the results obtained for the functional unit and performs sensitivity analyses to evaluate the flexibility of the scenarios. The chapter ends with a brief study of the implications of the assumptions made.

4.1 Life Cycle Inventory Analysis

Scenarios were divided into sections to simulate the processes within them ensuring the continuity of the municipal solid waste flow. Scenario 1, illustrated in figures Figure 4. 1 and Figure 4. 2 was divided in 3 sections: mass incineration or combustion (Figure 4. 1), boiler and steam turbine and gas cleaning (both presented in Figure 4. 2).

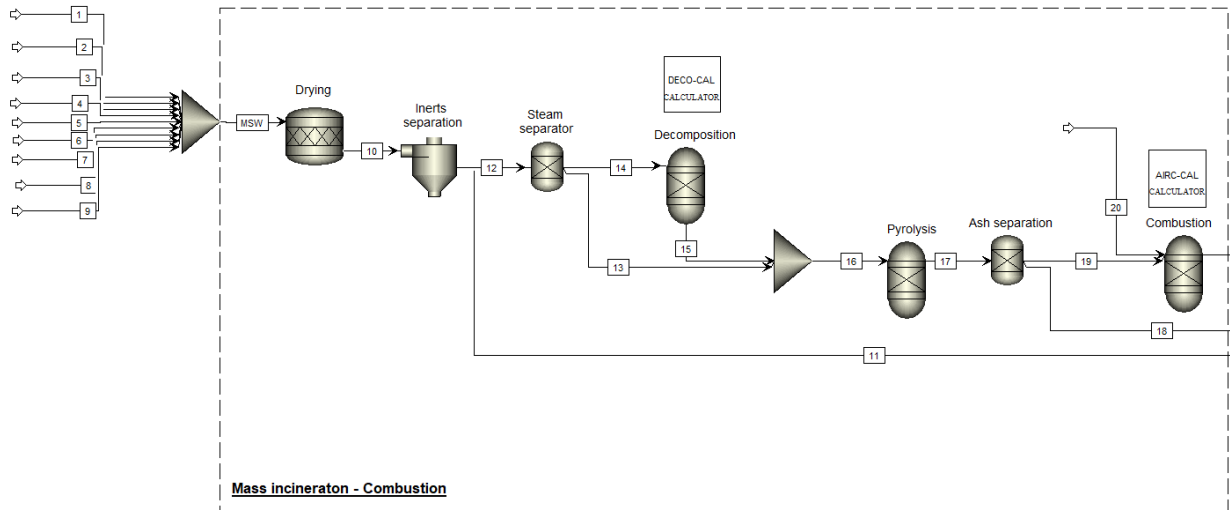


Figure 4. 1. Scenario 1 - Mass incineration section simulation in Aspen Plus.

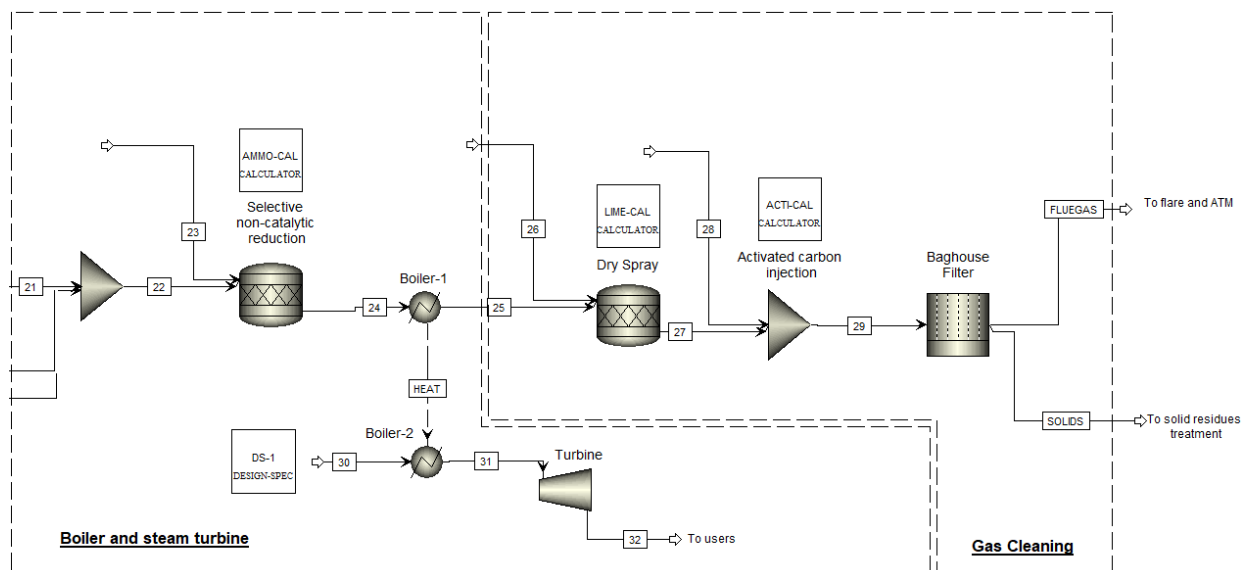


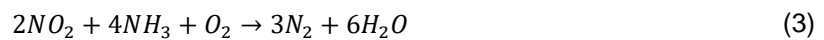
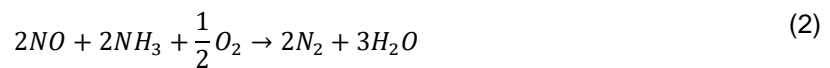
Figure 4. 2. Scenario 1 - Boiler and steam turbine and gas cleaning sections simulation in Aspen Plus.

The process begins with the creation of the solid waste mixture from its constituents (plastics, biowaste, paper, metals, glass, textiles, yardwaste and wood) and their respective characteristics reported in Table 3. 2. Combustion was simulated as their constituent steps by separate as well. First, MSW is dried at 150°C, after drying, in order to simulate only the combustible components of the waste mixture, the inert solids (glass and metal) were separated. After the separation of inert solids, the evaporated water is separated so that the combustible solid enters a decomposition process (devolatilization) to form: C, H₂,

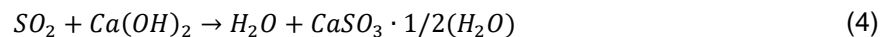
O₂, N₂, ash and sulfur. Decomposition was calculated with ultimate analysis of all waste components using DECO-CAL calculation block showed in Figure 4. 1 and detailed in Table B. 3 on annexe B. Volatile compounds and char enters to a initial pyrolysis stage at 450°C and 1 atm. Ash formed in decomposition and pyrolysis stage is separated to simulate exclusively gaseous phase combustion. Excess air is calculated, using calculation block AIRC-CAL based on the pyrolysis stream outlet composition and following Equation 1

$$Moles_{air} = \%Excess\ air \times \frac{Moles_{carbon} + \left(\frac{1}{2}\right)Moles_{H_2} - Moles_{O_2}}{0.21} \quad (1)$$

Equation 1 comes from the balance of the air required for the stoichiometric reaction of all the combustible material (carbon and hydrogen) and the proportion of oxidizing material (oxygen) present in the fuel. Hot flue gases coming out of combustion are mixed with solid residues (inert and ashes) to consider the effect in temperature of unreactive material. Before entering the steam generation system, aqueous ammonia solution is injected to simulate the real operation in Valorsul, where the aqueous solution is injected directly into the incineration boiler to reduce NO_x contaminants. This selective reduction was simulated as a stoichiometric reactor where reactions 2 and 3 take place (Kam, Morey, & Tiffany, 2015)



The amount of ammonia injected was calculated using specific consumption reported in Table 3. 4 and calculation block AMMO-CAL. After the selective non-catalytic reduction (aqueous ammonia injection), hot flue gas exchange its heat with water to produce steam at 420°C and 52.8 bar. Steam produced, calculated with design spec DS-1 in order to absorb the entire heat delivered by the flue gas when cooled to 150°C, enters a turbine to produce energy. Cold flue gas enters gas cleaning chain, starting with a dry spray system of hydrated lime to reduce sulphur compounds. Lime consumption was calculated with specific consumption and calculator block LIME-CAL. Reaction 4 represent the action of hydrated lime to consume acid compounds (SO₂) to produce a hydrated salt (calcium sulfite hemidrydated) that is dried to finally produce a solid residue (Kam, Morey, & Tiffany, 2015)



Flue gas is then mixed with activated carbon aimed to reduce chlorine components such as dioxins and furans. Since chlorine content was not simulated (it was not reported for MSW ultimate analysis), activated carbon calculated with calculator block ACTI-VAL was injected to count in the total solid residue produce but no reactions take place. Lastly, all solid residues are separated in a baghouse filter, and gaseous flue gas is taken to a flare and vented to the atmosphere.

Scenarios 2 and 3, represented in Figure 4. 3, Figure 4. 4, Figure 4. 5, Figure 4. 6, Figure 4. 7 and

Figure 4. 8, were divided in 6 sections: mechanical pretreatment, mechanical treatment, gasification, combustion, boiler and steam turbine and gas cleaning. As scenario 1, the first step for both scenarios (2 and 3) is to create the solid waste mixture from its constituents. Mechanical pretreatment section for scenario 2 consists of a primary shredding to reduce average diameter to 150 mm followed by a screening process to separate fine fraction (mostly composed of the organic fraction of waste) from the coarse fraction entering the mechanical treatment. Mechanical pretreatment for scenario 3 consists only of primary shredding without screening.

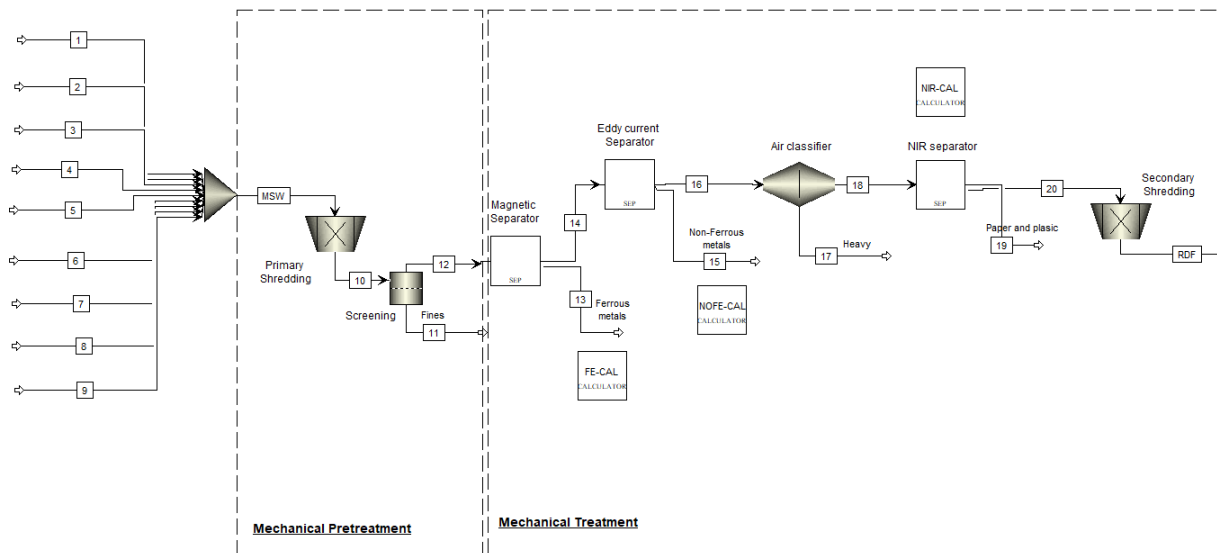


Figure 4. 3. Scenario 2 - Mechanical pretreatment and treatment sections simulation in Aspen

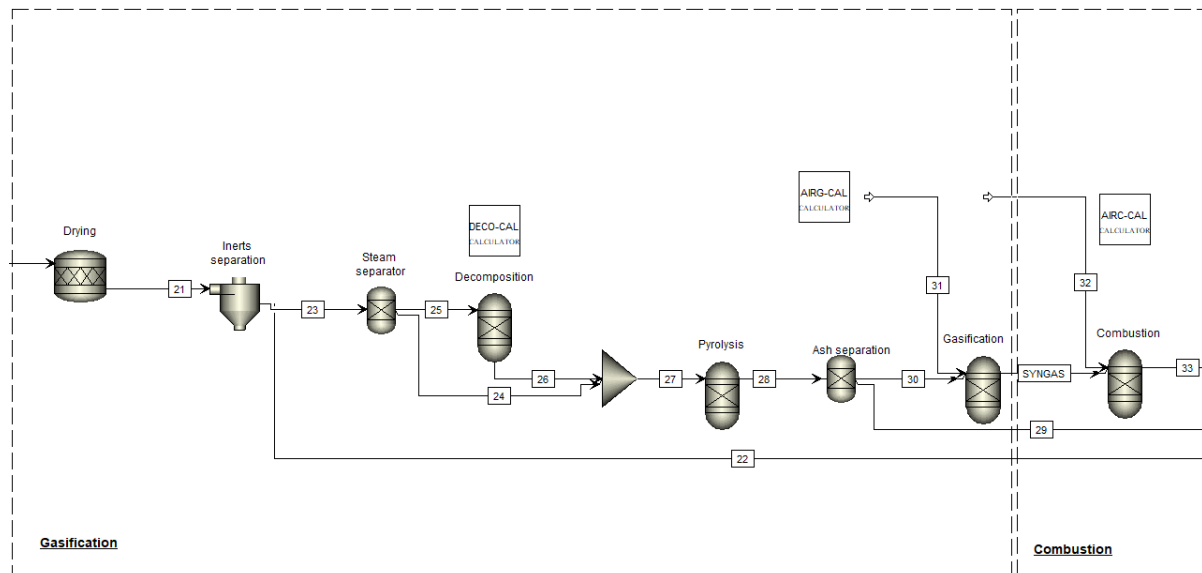


Figure 4. 4. Scenario 2 - Gasification and combustion sections simulation in Aspen

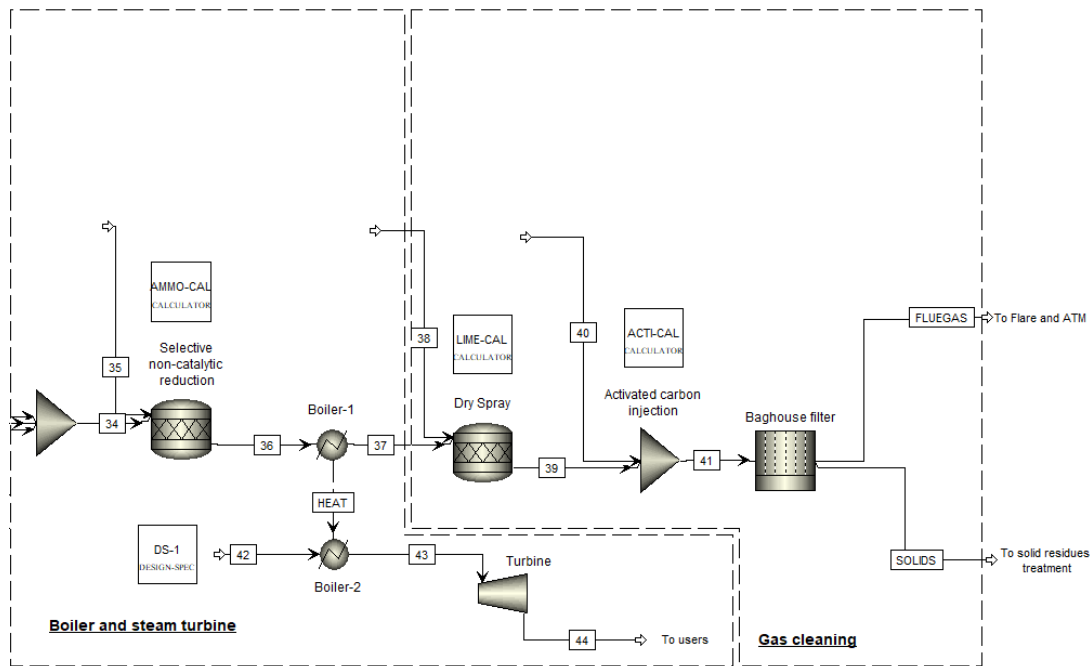


Figure 4. 5. Scenario 2 - Boiler and steam turbine and gas cleaning sections simulation in Aspen

Mechanical treatment starts with magnetic separator to remove ferrous metals followed by eddy current separator to remove non-ferrous metals, both processes were simulated as stream separators since these technologies are not part of Aspen plus simulation package. Split fraction of ferrous and non-ferrous metals was calculated, using block calculators FE-CAL and NOFE-CAL respectively, so that the total recovery fraction of these materials matched the information reported in Table 3. 5. The calculation considered that for scenario 2, in the initial screening process, a portion of the ferrous and non-ferrous metals exited the system because they were smaller in size (following particle size distribution reported in Table 3. 3).

Stream without metals and fine fraction enters an air classifier to separate heavy compounds from the light fraction. This air classifier was mainly oriented to separate glass, therefore the cut density simulated was the density of silica, 2600 kg/m^3 , according to aspen properties. Near infrared technology (NIR) for paper and plastic separation was simulated similar to metals separation, as streams split with a calculation block (NIR-CAL) to achieve the desired material recovery rate. The final step in the mechanical treatment is the secondary shredding to finally produce the refuse derive fuel RDF.

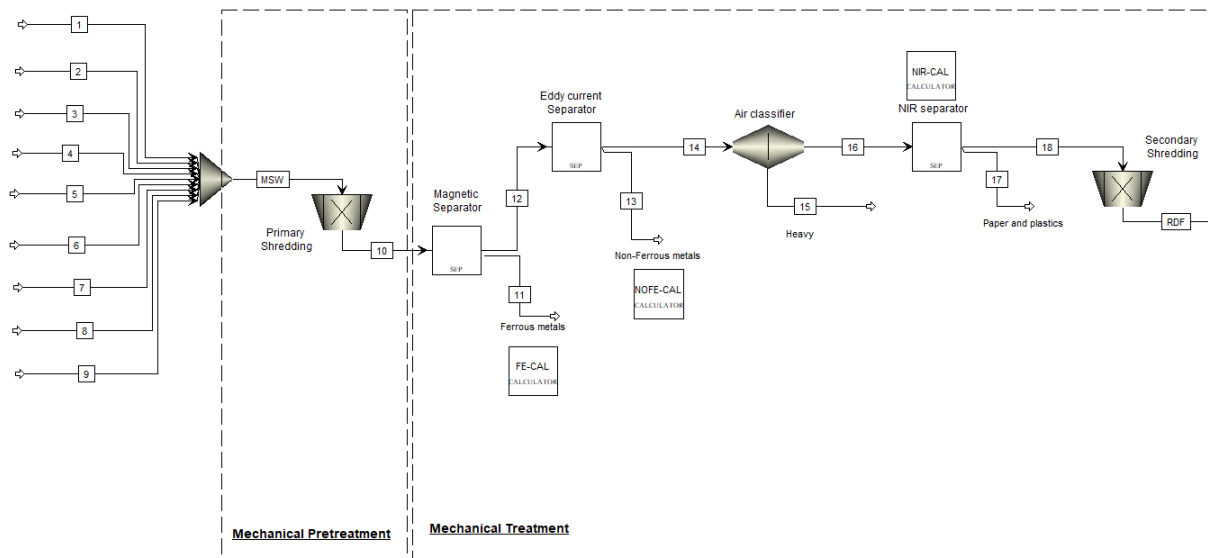


Figure 4. 6. Scenario 3 - Mechanical pretreatment and treatment sections simulation in Aspen

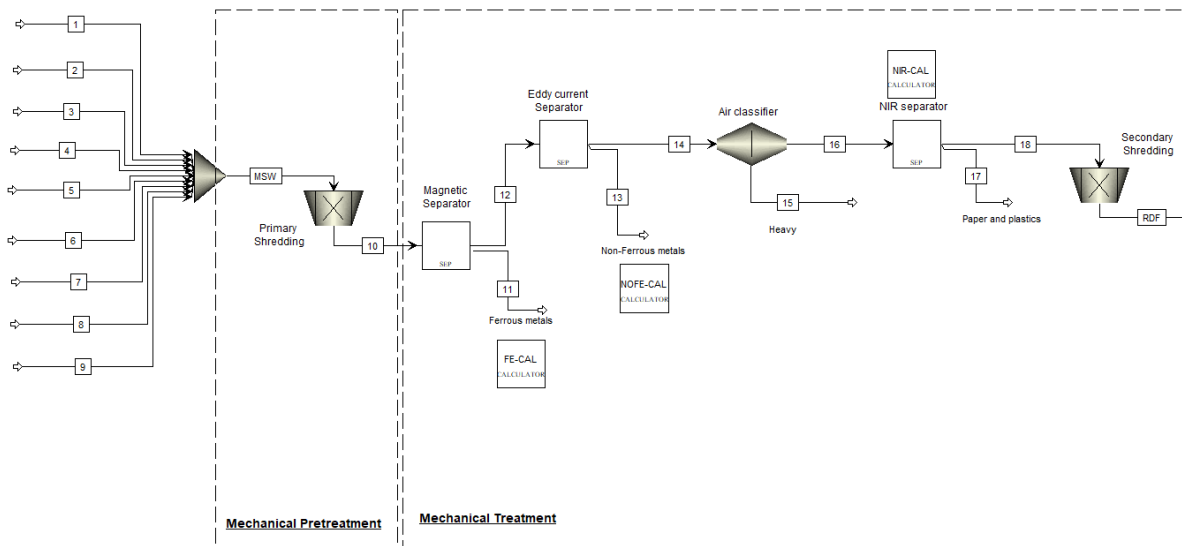


Figure 4. 7. Scenario 3 - Gasification and combustion sections simulation in Aspen

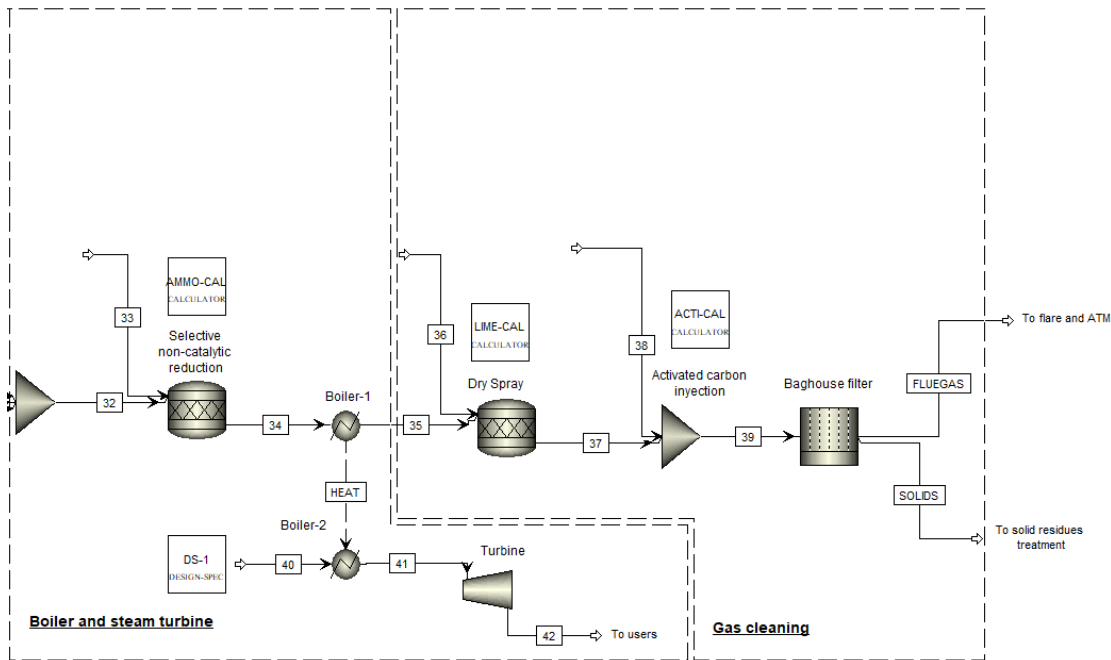


Figure 4. 8. Scenario 3 - Boiler and steam turbine and gas cleaning sections simulation in Aspen

RDF enters the gasification section where the thermal process was simulated as its unitary processes (drying, decomposition, pyrolysis and gasification). Similar to the scenario 1, RDF is dried at 150 °C and inert solids (remaining glass and metals) are separated to simulate the combustible part. After steam separation, solid material is decomposed at 450°C into C, H₂, O₂, N₂, ash and sulfur. Decomposition yield is calculated with the calculator block DECO-CAL that considers the ultimate analysis from MSW constituent (plastics, biowaste, paper, metals, glass, textiles, yardwaste and wood).

Pyrolysis is simulated as a gibbs reactor that reach phase and chemical equilibrium at 450°C and 1 atm. Similar to scenario 1, ashes present after pyrolysis are removed and gaseous stream enters the gasification and combustion reactors. Air required for gasification was calculated using the composition of the stream downstream the pyrolysis reactor and the equation 1 with the equivalence ratio number instead of excess of air. Excess air required for combustion was calculated using block calculator AIRC-CAL considering syngas composition. Details of both calculators blocks (AIRG-CAL for gasification and AIRC-CAL for combustion) are presented in Table B. 3 on annex B)

Boiler and steam turbine and gas cleaning sections are common for the 3 scenarios, the main differences are the temperature reached by the flue gas (150°C for scenario 1 and 140°C for scenarios 2 and 3) and the specific consumption of chemicals. Difference in the temperature corresponds to the risk of reaching acid dew point, since gasification implies, in theory, less acid compounds, the risk of reaching this temperature where corrosion occurs is less, and therefore flue gas can reach lower temperature, exchanging more heat.

All chemicals required in flue gas cleaning system were calculated following specific consumption reported in Table 3. 4. More details on processes specifications simulated for scenarios 1, 2 and 3 is presented in annex B, along with calculator and design specs.

Mass balance within the established system limits, with reference to the assumed functional unit and for

the process conditions reported in chapter 3 is reported in Table 4. 1 for all scenarios. Most important streams for analysis and environmental impact in terms of CO_{2eq} emissions are shown in the table above, for complete stream summary report refer to annexe B.

Table 4. 1. Mass balance results related to the functional unit for scenarios 1, 2 and 3

Stream (kg/ton MSW) [#Stream-Scenario]	Scenario 1	Scenario 2	Scenario 3
MSW	977.4	977.4	977.4
Fines [11-S2]	-	170.3	0
Ferrous metals [13-S2] [11-S3]	-	13.2	16.6
Non-ferrous metals [15-S2] [13-S3]	-	1.4	1.7
Heavy materials [17-S2] [15-S3]	-	45.1	53.9
Paper and plastics [19-S2] [17-S3]	-	25.2	71.8
- Total reusable material (Organic + recyclable)	-	255.2	144.0
RDF	-	722.3	833.4
Gasification air [31-S2] [29-S3]	-	518.0	550.1
Syngas	-	1171.1	1300.2
- CO in syngas	-	388.8	427.6
- CO ₂ in syngas	-	183.5	210.9
- CH ₄ in syngas	-	0.1	0.1
- H ₂ in syngas	-	45.2	51.9
- H ₂ O in syngas	-	152.8	183.4
- N ₂ in syngas	-	399.3	425.0
- H ₂ S in syngas	-	1.2	1.2
Combustion air [20-S1] [32-S2] [30-S3]	4562.3	4139.1	4641.1
Aqueous Ammonia [23-S1] [35-S2] [33-S3]	87.7	76.3	76.3
Hydrated Lime [26-S1] [38-S2] [36-S3]	7.0	4.5	5.2
Activated carbon [28-S1] [40-S2] [38-S3]	0.4	0.3	0.4
Boiler feed water [30-S1] [42-S2] [40-S3]	1537.4	1819.8	2039.9
Flue gas	5470.2	5386.6	6018.4
- CO ₂ in flue gas	1007.6	794.6	882.9
- CH ₄ in flue gas	0.0	0.0	0.0
- H ₂ O in flue gas	768.8	634.7	725.3
- O ₂ in flue gas	175.5	380.2	421.7
- N ₂ in flue gas	3502.7	3574.4	3985.1
- NO ₂ in flue gas	0.0	0.0	0.0
- SO ₂ in flue gas	0.1	0.1	0.1
Solids	164.5	73.9	88.1
- Glass in solids	85.0	25.8	32.6
- Metals in solids	20.6	0.8	0.8

Stream (kg/ton MSW) [#Stream-Scenario]	Scenario 1	Scenario 2	Scenario 3
- Activated carbon in solids	0.4	0.3	0.4
- Ash in solids	52.9	42.5	49.8
- Dehydrated calcium sulfite	5.7	4.4	4.4

The scenarios that contemplate pre-treatment of solid waste (scenarios 2 and 3) have the advantage of having a greater capture of material with potential for recycling or use in biological processes, as is specifically the situation for organic material. Although organic matter can be treated in thermochemical processes, studies show that the best route to treat biowaste and generate energy are biochemical routes such as anaerobic digestion, because they are cleaner in terms of CO_{2eq} generation (Ardolino, Colaleo, & Arena, The cleaner option for energy production from a municipal solid biowaste, 2020). Scenario 2 in that sense allows for better performance by having a higher recovery of recyclable material (metals, plastics, glass) and organic material for further organic treatment per ton of MSW.

In terms of air requirements, the air required for gasification is always less than the air required for combustion because oxidation is partial, however, the total air required (gasification + combustion) is higher in scenarios 2 and 3 than in scenario 1. In fact, the highest total air requirement is found in scenario 3, in which despite the separation of material, the organic material is not separated, which is a material with high carbon content that demands oxygen from the air for its initial partial and then total oxidation.

Scenario 2 is the scenario that requires the least amount of gasification air and the least amount of air for combustion, however total value of air required is slightly higher than scenario 1 (2% higher). If the comparison was considering only thermal processes, gasification and combustion, the air requirement for gasification is always lower and increases with the content of organic material. However, when evaluating total air of scenarios, the reality is that waste gasification as an intermediate step before combustion, increases the total air consumption per ton of solid waste treated, and with that the energy consumption for the oxidizing agent.

In terms of chemical requirements, the consumptions do not differ much because they are measured with respect to the flue gas composition and this gas will have full oxidized species. However, if there is a notable difference in the amount of total solids coming out of the process, it is almost half in scenarios 2 and 3 compared to scenario 1.

There is less solid waste because a large portion of inert solids such as glass and metals, which do not contribute to gasification and which can cause the problems discussed in chapter 2, are recovered in the mechanical treatment phase. Likewise, by removing part of the organic matter, which in its proximate analysis has a high percentage of ashes, ashes generated in the thermal process are reduced and are collected as solids. Ashes and glass are the main contributor of solid in the final solid stream.

Flue gas, for all 3 scenarios, is mainly constituted by nitrogen, followed by carbon dioxide and water, the expected products of combustion and air injection. Carbon dioxide emissions per ton of waste are lower in scenario 2 and are higher for scenario 1. This behaviour is expected because in scenario 2 the

fuel that is actually burned (RDF) is lower than the fuel burned in scenarios 1 and 3.

The main advantage of gasification is found by analysing the composition of the syngas stream, in which 45 kg/ton of hydrogen is obtained for scenario 2 and 52 kg/ton of residue for scenario 3. This hydrogen has a high calorific value and can be used for fuel synthesis as discussed in chapter 2. Based on Aspen simulation, it is possible to analyse that a higher organic content in the fuel allows to have a higher hydrogen production per ton of treated waste.

4.2 CO₂ emissions analysis

Life cycle impact analysis 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 into two types of sources: biogenic CO₂ and fossil CO₂.

The fraction of biogenic CO₂ emissions obtained from oxidation of biogenic carbon fraction in municipal solid waste was fixed as 60% for MSW and 50% for RDF with prior organic separation in agreement with results found by a determination of biomass content in combusted municipal waste in Estonia (Moora, Roos, Kask, Kask, & Ounapuu, 2017) and results from determination of the fossil carbon content in combustible municipal solid waste in Sweden (Avfall Sverige Utveckling, 2012). Since RDF produced with an initial screening process (scenario 2) has less content of organics and higher content of plastics as fossil carbon source, biogenic carbon present in RDF from scenario 2 it is expected to be lower than biogenic content of scenario 1 and 3.

Total CO_{2eq} indicator encompasses the following gases present in the analysed flue gas and their equivalence following EPA 2009 guidelines:

- Carbon dioxide - 1 kg CO₂ fossil = 1 kg CO_{2eq}
- Methane - 1 kg CH₄ = 21 kg CO_{2eq}
- Nitrous oxide - 1 kg N₂O = 310 kg CO_{2eq}

To account for the environmental impact associated with the energy required in the process, it was assumed that all the energy required was electrical energy and the CO_{2eq} emission factor per GWh of electrical energy estimated by the Portuguese General Direction of Energy and Geology (*Direção Geral de Energia e Geologia*) for 2021 was used. The value of the emission factor of the electro producer system is 250 ton CO_{2eq}/GWh and takes into account the electric energy mix of Portugal for 2021 (DGEG – Direção Geral de Energia e Geologia, Direção de Serviços de Planeamento Energético e Estatística, 2022). By 2021, 66% of Portugal's electricity originated from renewable sources, hydro production corresponded to 31%, wind energy corresponded to 29%, biomass corresponded to 6% and solar to 1%, according to the Portuguese energy network company REN (REN, 2023).

The energy required by the processes was separated into two main sources: energy associated with the pretreatment and mechanical treatment of waste and the energy associated with thermal process

and gas cleaning. The energy required for pretreatment and mechanical treatment (energy to produce RDF) was obtained from the same source used to propose scenarios 2 and 3, a study of a municipal solid waste mechanical treatment plant in Finland (Nasrullah, 2015). For the mechanical treatment scheme (including pretreatment) proposed in scenarios 2 and 3, the same energy requirement value of 70 kWh/ton MSW treated was employed (Nasrullah, 2015).

From the information reported by Valorsul for its energetic valorisation plant, the value of self-consumption of electricity of 89 kWh/ton MSW treated was obtained (Valorsul, 2023). This value, which corresponds to the energy value of the thermal process (gasification/combustion) and gas cleaning, was fixed for all 3 scenarios.

Figure 4. 9 summarized global warming potential results for all 3 scenarios of waste management analysed in terms of CO₂ equivalent emissions per ton of MSW. Total global warming potential was divided by subcategories: CO_{2eq} associated to the energy required for RDF production (mechanical treatment and pretreatment exclusively for scenarios 2 and 3), fossil CO₂ equivalent from flue gas, biogenic CO₂ equivalent emissions from flue gas and CO₂ equivalent from the energy required for thermal and gas cleaning processes (Energy T+C in Figure 4. 9).

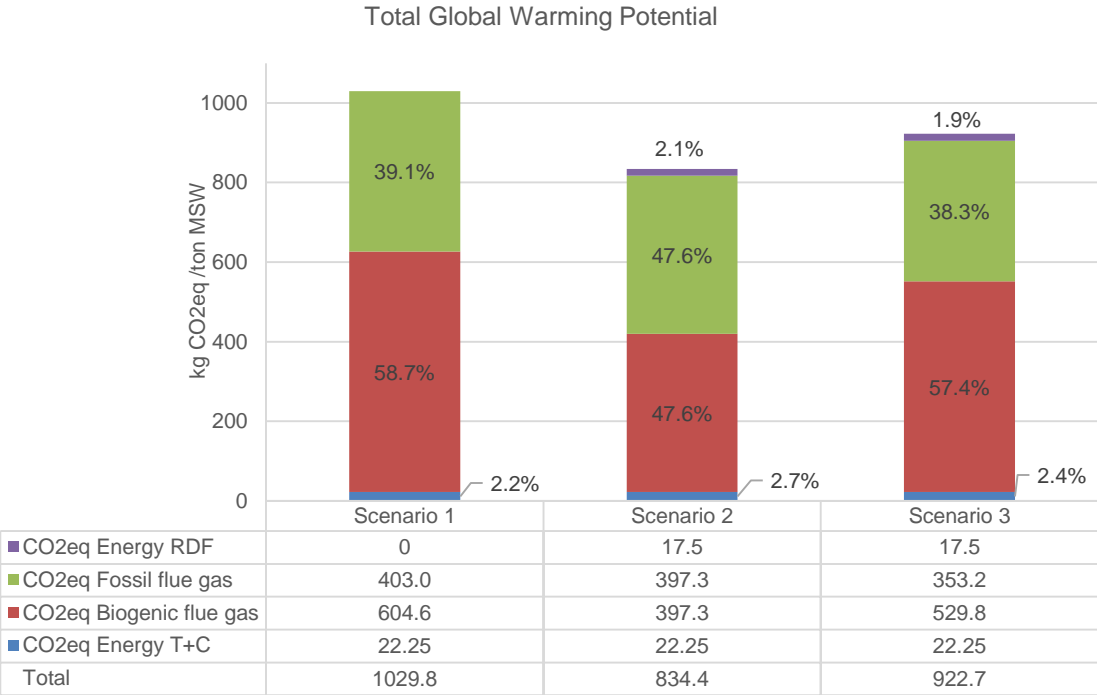


Figure 4. 9. Results of impact analysis for scenarios 1, 2 and 3 – Total global warming potential

Scenario 1 has the highest impact in terms of global warming with a total of 1029.8 kg CO₂ equivalent per ton of waste treated. From the total scenario 1 global warming impact, 97.8% is due to CO₂ emissions released directly from combustion in the flue gas and the energy required for the process represents a minimal share with a value of 2.2%. The scenario with the lowest impact on global warming is scenario 2 with a total value of 834.4 kg CO₂ equivalent per ton of waste treated (20% less than

scenario 1). The contribution of fossil CO₂ for this scenario is equal to the contribution of biogenic CO₂ and its share is higher than for scenario 1 (47.6% in scenario 2 vs 39.1% in scenario 1). Scenario 3 represents 10% less environmental impacts than Scenario 1 and 95.7% of its emissions are in the flue gas. For this scenario, the total CO₂ equivalent is 922.7 kg per ton of MSW and more than half of its emissions (57.4%) correspond to biogenic CO₂.

Figure 4. 9 shows that under the assumptions made in this study and for the characteristics grouped in the three scenarios analysed, scenario 1, where solid waste is burned in an incineration system without prior treatment, has the greatest environmental impact. Scenario 1 impact mostly responds to the direct emission of greenhouse gases, where biogenic CO₂ is the main one.

On the contrary, having a pre-treatment of solid waste and performing waste gasification as an intermediate step before combustion showed to have a positive environmental impact, the impact on global warming decreased in scenarios 2 and 3 compared to scenario 1.

These results are aligned with the conclusions found in the systematic review of 101 life cycle analysis studies compiled by Macquarie University in Australia discussed in chapter 2 (Dastjerdi, Strezov, Kumar, He, & Behnia, 2021). Gasification with energy production has less environmental impact in terms of GHG emissions, than incineration with energy generation, for the same energy generation scheme. This is expected because, as the literature anticipated, with an atmosphere reduced in oxygen, the production of pollutants that are greenhouse gases is reduced.

Likewise, the results agree with the market study carried out for gasification technology, since, when it is possible to have a pretreatment process with RDF production prior to the thermal processes, their performance is improved and environmental impacts are reduced. This is why most of the existing technologies explored had as a prerequisite the formation of an RDF fuel instead of treating MSW directly. The more rigorous the pretreatment is, in terms of minimizing the content of inert and organic material mainly and achieving maximum homogenization of the material, the total CO_{2eq} emissions will be lower, as evidenced in scenario 2 regarding to scenario 3.

For scenarios 2 and 3, the major contribution also comes from the direct emission of greenhouse gases but there is a slightly higher consumption of energy, which in total represents 4.8% of emissions in scenario 2 and 4.3% for scenario 2. For scenarios 2 and 3, there is an additional impact associated with the energy required for pretreatment, which in magnitude is similar to the value of energy currently consumed by Valorsul.

However, as the electricity mix in Portugal has a high share of renewable energies (66% in 2021 and 88% in 2023), the environmental impact is low and therefore the impact associated with the energy is low. The analysis would be the opposite if the major source of electricity in Portugal were fossil sources as it was in the past the burning of coal for electricity production.

To cope the uncertainty associated with the value of the real energy consumption of the processes that make up the scenarios, Figure 4. 10 shows a sensitivity analysis that was performed by varying the electricity consumption associated exclusively with mechanical treatment and pretreatment (exclusive for scenarios 2 and 3). The electricity consumption to produce the RDF was varied from 70 kWh/ton

MSW to 870 kWh/ton MSW, the new global warming impact value was estimated for scenarios 2 and 3 and compared to the total CO₂ equivalent value of scenario 1 (highest global warming impact scenario).

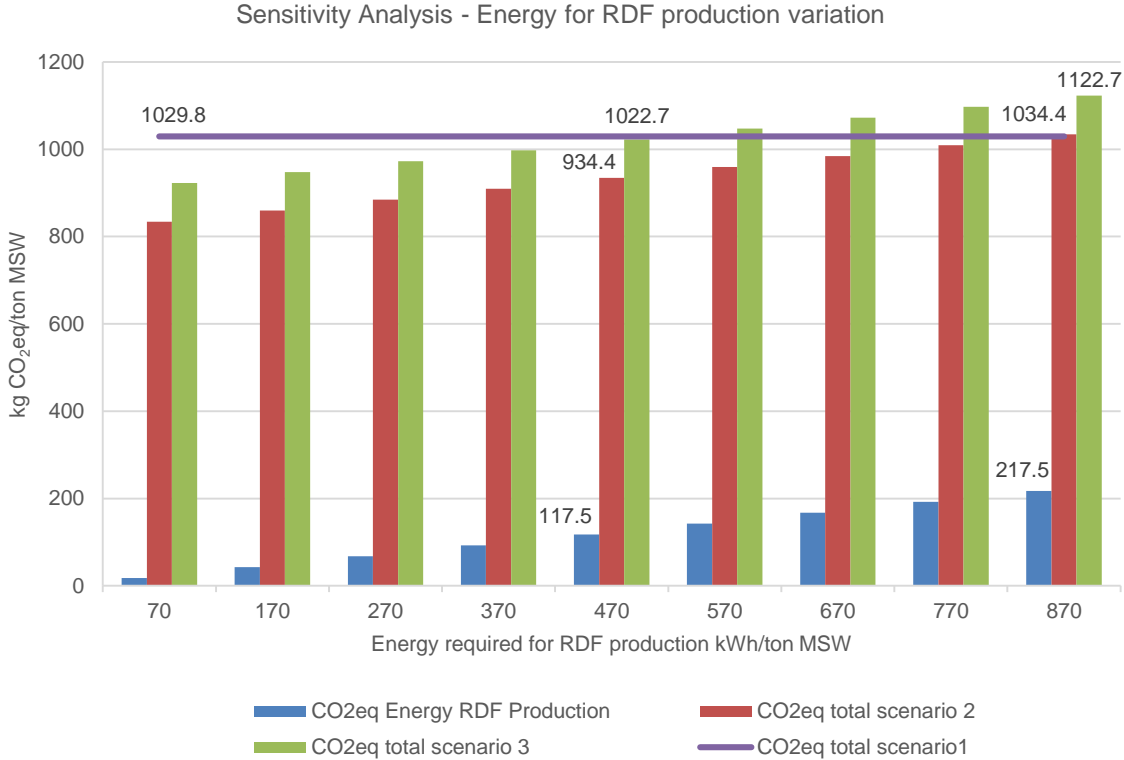


Figure 4. 10. Sensitivity analysis - CO₂eq per ton of MSW with energy required for RDF variation for scenarios 2 and 3

For scenario 3 to have the same total value of impact on global warming as scenario 1, the value of electrical energy consumed to produce RDF must be greater than 470 kWh/ton MSW, that is, it must be a value almost 7 times greater than the currently estimated value. For scenario 2 to have the same total value of CO₂ equivalent than scenario 1, electrical energy for mechanical treatment and pretreatment must be greater than 870 kWh/ton MSW, a value almost 12 times higher than actual energy consumption estimation. Since the main source of global warming potential in the scenarios is the direct emission of greenhouse gases, total impact on climate change is less sensitive to energy variation, as long as the electrical energy mix in Portugal remains with high share of renewable energies.

In 2021, emission factor of the electro producer system was 250 ton CO₂eq/GWh (DGEG – Direção Geral de Energia e Geologia, Direção de Serviços de Planeamento Energético e Estatística, 2022), taking into account that Portugal’s electricity mix for 2021 was mainly originated from renewable sources (REN, 2023). However, the origin of electricity in Portugal has had a significant evolution, because renewable sources did not always have such a high participation. In 2012, renewable energies were responsible for only 28% of the total energy, on the contrary, most of the electrical energy originated from coal and natural gas (REN, 2023).

To evaluate this variation in the origin of electricity, which will be translated into a greater or lesser CO₂eq emission factor, the data reported by the General Direction of Energy and Geology on the emission

factor of the electro-producing system between 2011 (where coal had a greater participation in the production of electricity) and 2021 was varied in the sensibility analysis showed in Figure 4. 11 Information of emission factor per year is summarized in Table 4. 2

Table 4. 2. Electro producer emission factor variation between 2011-2021 in Portugal. Extracted from (DGEG – Direção Geral de Energia e Geologia, Direção de Serviços de Planeamento Energético e Estatística, 2022)

Year	Emission factor (ton CO _{2eq} /GWh)	Year	Emission factor (ton CO _{2eq} /GWh)
2011	368	2017	257
2012	317	2018	254
2013	292	2019	253
2014	284	2020	258
2015	261	2021	250
2016	239		

For the sensibility analysis the consumption of energy was fixed to 70 kWh/ton MSW for mechanical treatment and 89 kWh/ton for thermal process and gas cleaning in order to evaluate the response of global warming potential for scenarios 2 and 3 to electricity emission factor variations. Total CO_{2eq} from scenario 1 is also presented to compare with scenarios 2 and 3 tendency.

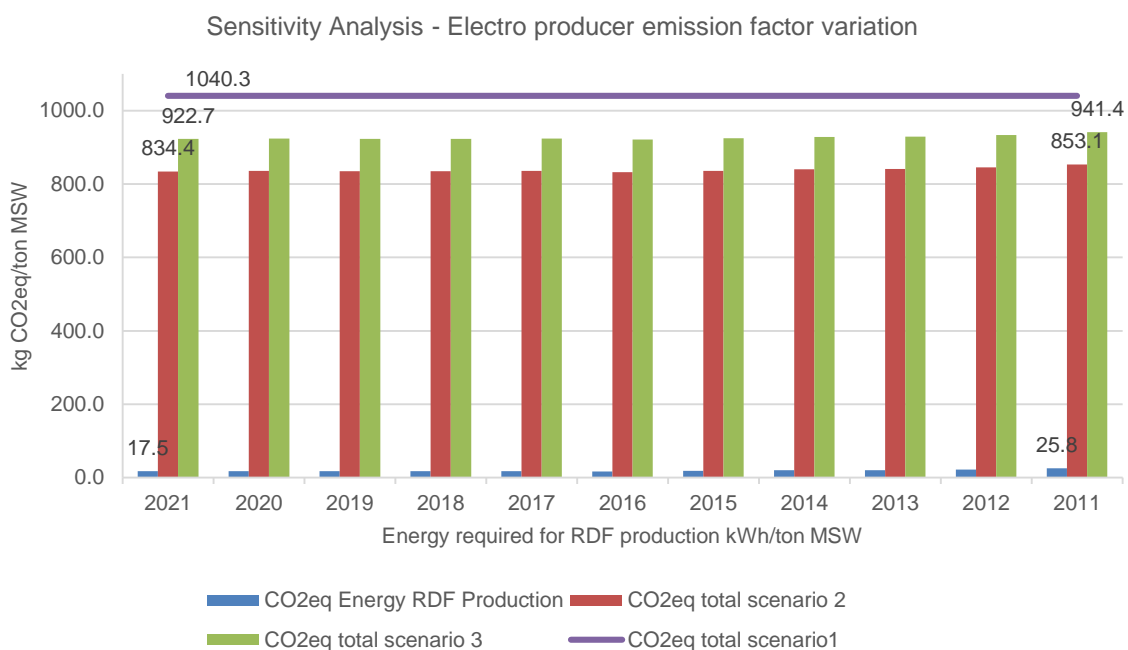


Figure 4. 11. Sensitivity analysis - CO_{2eq} per ton of MSW with electro producer emission factor variation between 2011 and 2021 for scenarios 2 and 3

The emission factor of the energy sector was reduced by 32% in 2021 compared to 2011, evidencing the positive impact that the increase in renewable sources has on greenhouse gas emissions. This reduction in the emission factor represents a decrease in total CO₂ equivalent emissions for scenarios 2 and 3, however the reduction is less than 5% and shows that the system is not very sensitive to this

energy contribution because its greatest source of impact is the composition of the flue gas. Even with the variation of emission factors in the years studied, scenarios 2 and 3 do not reach the value of scenario 1, they are still lower.

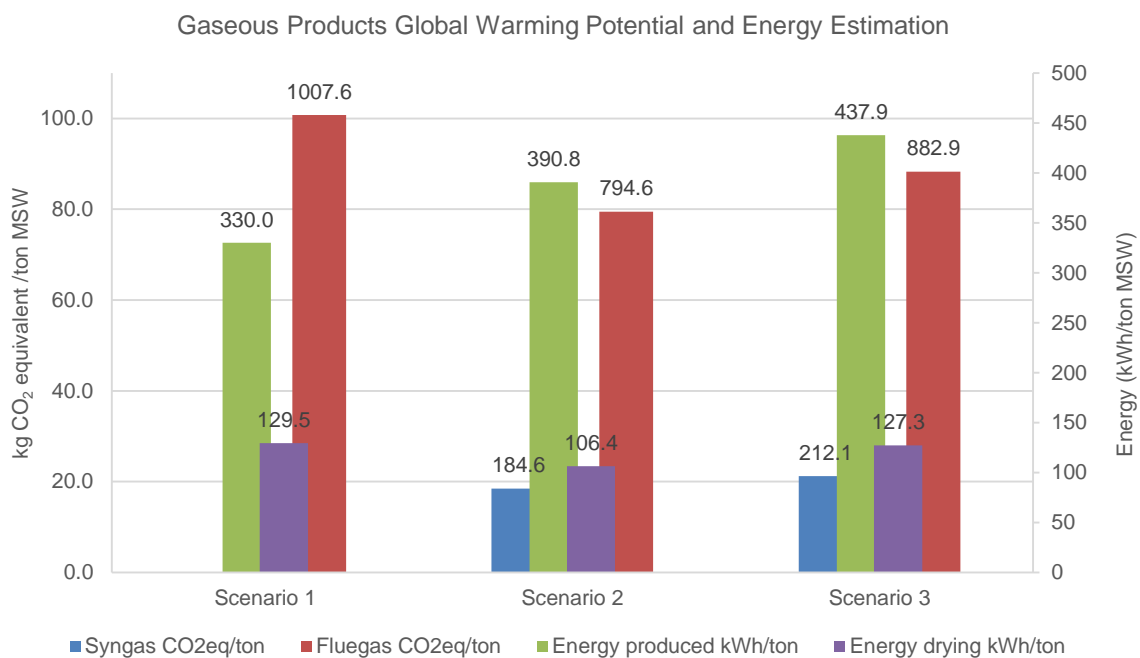


Figure 4. 12. Flue gas and syngas global warming potential indicator and energy estimated in aspen for all scenarios.

Figure 4. 12 compares the performance of gasification and combustion in terms of the global warming indicator. For scenarios 2 and 3, the environmental impact associated with syngas (taking into account CO₂, CH₄ and N₂O present in the gasification outlet stream), is substantially lower than the impact associated with the combustion flue gases, approximately 70% less. The results are consistent with the theoretical framework presented, the gasification of solid waste has a lower impact in terms of global warming than combustion. This result can be understood by evaluating the objective of each thermal process separately. As previously discussed, gasification is a partial oxidation of waste that produces mostly CO, a non-greenhouse gas. On the other hand, the purpose of combustion is to oxidize all the carbon to CO₂, a greenhouse gas. In other words, it is the combustion process that considerably increases the environmental impact on climate change through global warming, not the use of solid waste as feedstock.

Figure 4. 12 also allows to evaluate the energy produced and consumed simulated by Aspen Plus based on the enthalpy balance. Although this does not correspond to actual energy consumption/production, it allows to estimate the energy produced in the turbine and the energy required for the drying process. Scenario 1, in which the waste is incinerated without previous physical alterations, is the scenario that consumes the most energy for the drying process (129.5 kWh/ton MSW) while scenario 2, in which a part of the organic fraction is separated in the pretreatment, is the scenario with the lowest energy consumption for drying, a behaviour expected because the moisture content in the organic matter is the highest of all the constituents of the solid waste (almost 70% according to Table 3. 2).

In terms of energy produced by the turbine, scenarios 2 and 3 have higher energy produced per ton of waste treated, i.e. pretreating and improving the quality of the fuel entering the thermal processes does have a positive impact on the amount of energy available for recovery. Scenario 3 has the highest energy generation, and this can be explained by the fact that since there is more carbon present (carbon that was not previously removed as part of the organic fraction), more carbon will be exothermically oxidized in the combustion and more energy will be available to produce more steam and more energy in the turbine. Scenario 2 produces less energy than Scenario 3 per ton of waste treated but also receives less RDF to the gasification process compared to Scenario 3, due to the separation of organic material for biological treatment.

To analyse the impact of the moisture present in the fuel on energy production and consumption, Figure 4. 13, Figure 4. 14 and Figure 4. 15 show a sensitivity analysis that was performed by varying the composition of biowaste in each of the scenarios and calculating the new value of energy produced by the turbine and consumed to dry the moisture.

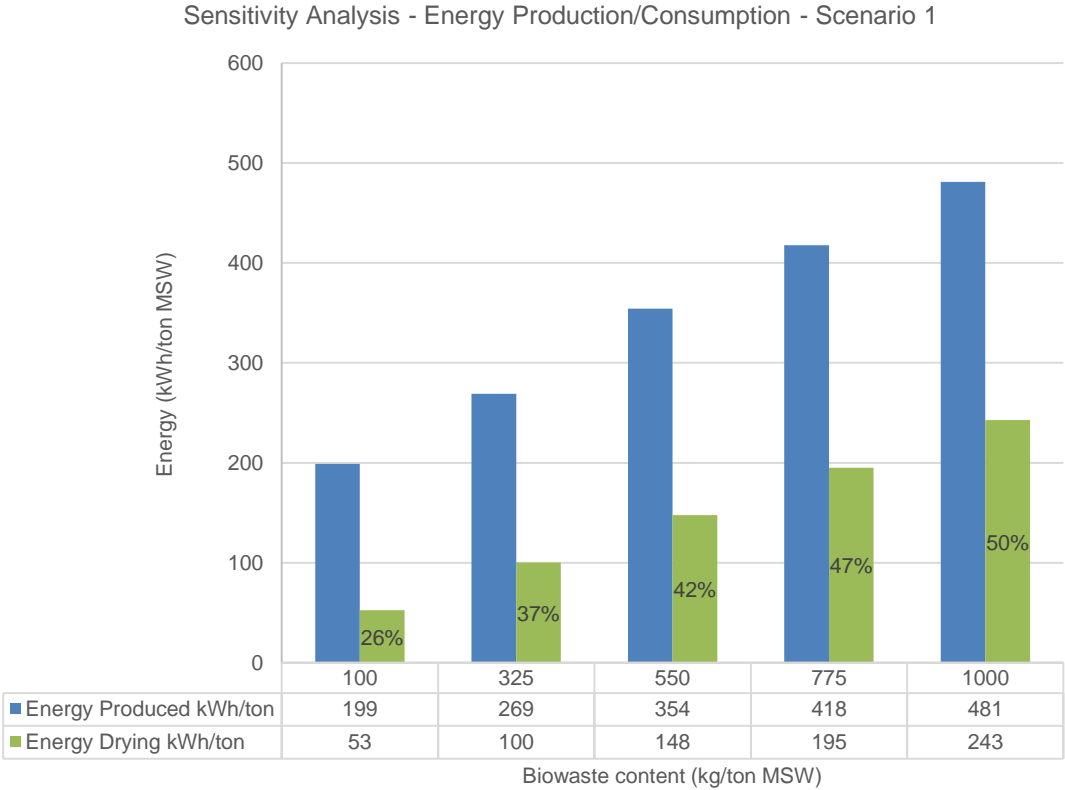


Figure 4. 13. Sensitivity analysis - Energy estimated at turbine and for drying per ton of MSW with biowaste content in MSW variation for scenario 1

As the biowaste content increases, so does the energy produced and the energy consumed, however the growth is not proportional and what is evident from the sensitivity analysis is that the energy requirement grows much faster than the energy production. For scenario 1, initially the energy for drying represents 26% when waste is composed of 100 kg of biowaste, but as the value of biowaste increases to 1 ton, half of the energy produced must be used to dry the moisture. The drying process is therefore an important step and a major contributor to the self-consumption of energy in waste-to-energy plants.

Sensitivity Analysis - Energy Production/Consumption - Scenario 2

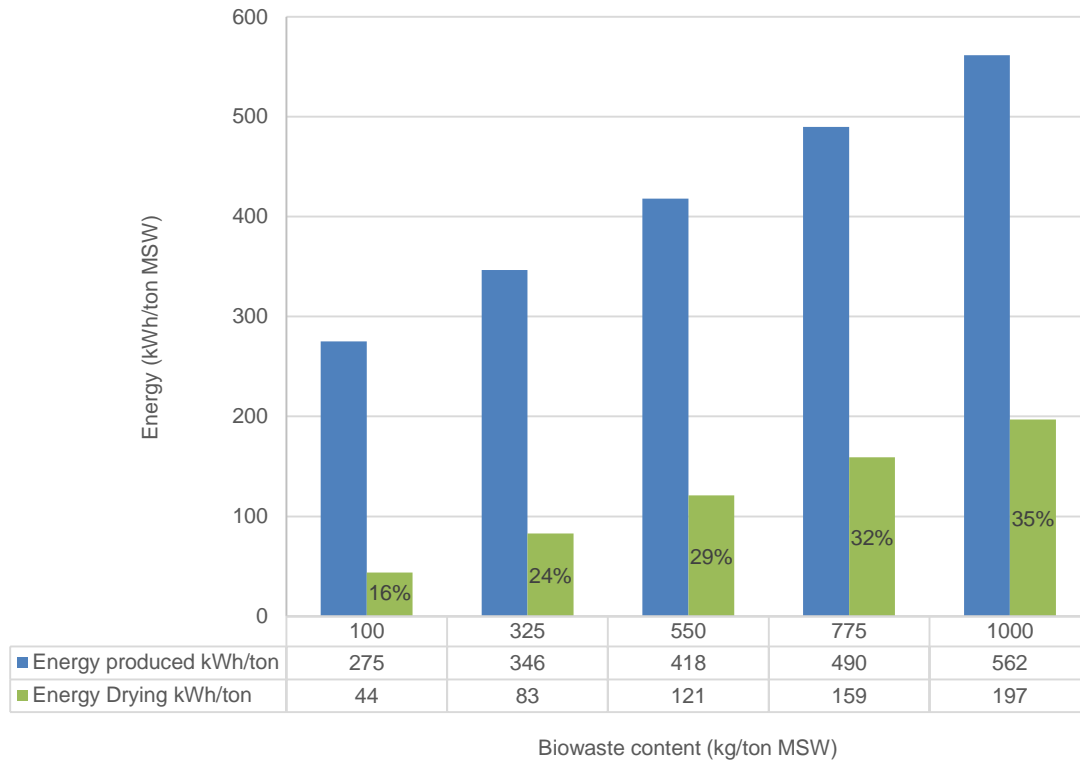


Figure 4. 14. Sensitivity analysis - Energy estimated at turbine and for drying per ton of MSW with biowaste content in MSW variation for scenario 2

For scenario 2 the trend is the same as scenario 1, both the produced and consumed energy increases with the increase in the biowaste content. However, contrary to scenario 1, the value of energy required for drying never equals 50% of the energy produced for the range of variation of biowaste studied. The percentages represented by the energy for drying are lower in all the intervals studied compared to scenario 1. This can be explained through two approaches, the first is that with the previous organic separation, the RDF moisture is less than the MSW moisture and therefore the energy required for drying is less. On the other hand, the RDF produced in scenario 2 has a higher calorific value and is capable of delivering more energy than the MSW from scenario 1. The maximum value of energy required is 35% of the energy produced, a value reasonable if the energy produced is intended to supply internal consumption and to be sold.

Sensitivity Analysis - Energy Production/Consumption - Scenario 3

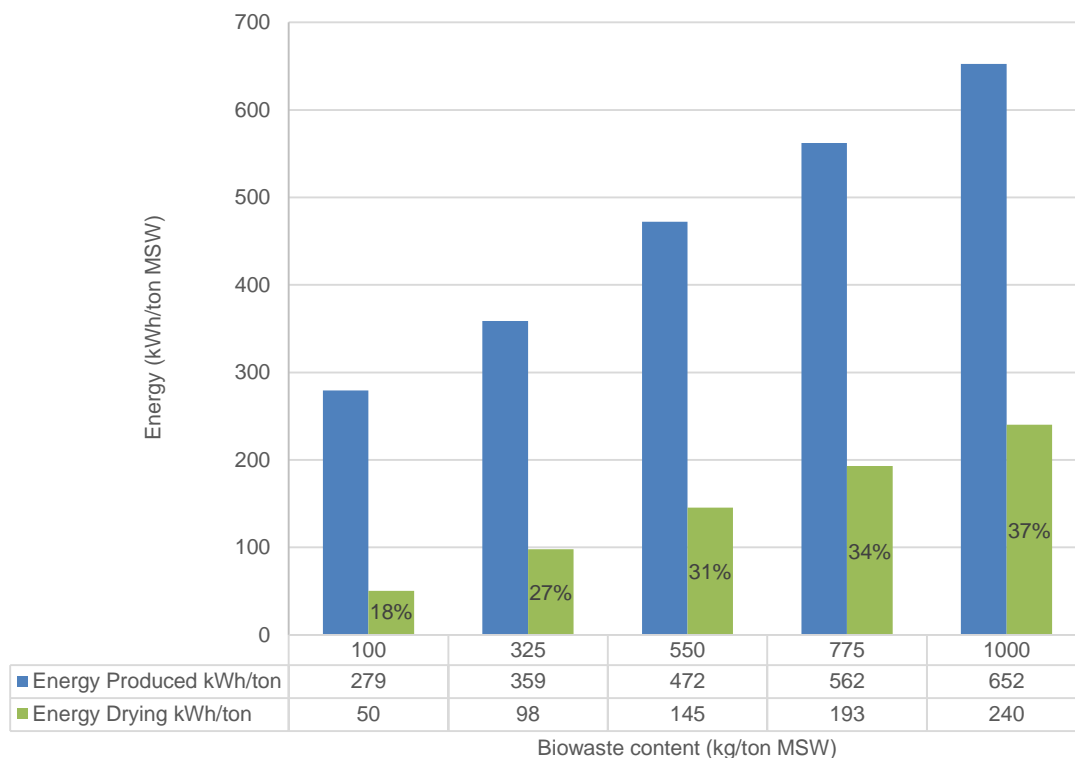


Figure 4. 15. Sensitivity analysis - Energy estimated at turbine and for drying per ton of MSW with biowaste content in MSW variation for scenario 3

Finally, scenario 3 has an intermediate behavior between scenario 1 and 2. The relationship of the variables is directly proportional as already analyzed, however, here there is no prior separation of organic material, therefore the energy expenditure for drying is similar to scenario 1. Although energy consumption is higher than scenario 2 for the same intervals of biowaste content, its percentage with respect to the energy produced is similar or slightly higher than scenario 2. This is explained because the calorific capacity of the waste-derived fuel (RDF) generated in scenario 3 acts as a kind of buffer. That is, the better quality fuel has more energy contained and even when there is a greater requirement for drying, more energy will also be produced in the turbine.

This is consistent with the results found previously, which showed that scenario 3 is the scenario where more energy per ton of waste is produced. The sensitivity analyses carried out for the three scenarios lead to the conclusion that energy is a variable sensitive to the organic matter content in the solid waste.

High and low calorific heating value estimation of the fuels used for all 3 scenarios, as received MSW for scenario 1, RDF for scenario 2 and high organic content RDF for scenario 3, was performed using the correlations described in equations 5 and 6 reported at a modelling study for assessment of waste to energy potential with an accuracy higher than 0.8 ($R^2 > 0.8$) (Amen, et al., 2021). The correlations are applied for the mix of MSW and the mix of RDF obtained after mechanical pretreatment and treatment.

$$HHV \left(\frac{MJ}{kg} \right) = [-1.3675 + 0.3137(C) + 0.7009(H) + 0.0318(O)] \quad (5)$$

$$LHV \left(\frac{MJ}{kg} \right) = HHV - h_g \left(\frac{9(H)}{100} - \frac{Moisture}{100} \right) \quad (6)$$

C, H, O are percentages of carbon, hydrogen and oxygen respectively as determined by ultimate analysis on a dry basis. Percentages of these compounds are within valid range of model's application. The latent heat of vaporization of water (h_g) corresponds to 2.4417 MJ/kg at 25 °C. Results for the fuels entering the thermal process in each scenario (combustion for scenario 1 and gasification for scenarios 2 and 3) is shown in Table 4. 3

Table 4. 3. HHV and LHV estimation for MSW, RDF and RDF with higher organic content

	Scenario 1 As received MSW	Scenario 2 RDF	Scenario 3 RDF with organic material
HHV (MJ/kg)	9.776	12.434	12.012
LHV (MJ/kg)	9.098	11.688	11.298

Information reported in Table 4. 3 confirms the behaviour in terms of energy produced analysed previously, mechanical treatment and pretreatment scheme of scenarios 2 and 3 allows to increase energy embodied in the fuel in approximately 30%, this is as well more energy available to recuperate. Energy content in RDF with organic material is slightly less than RDF because oxygen content is less in biowaste than in plastic, this is bad in terms of energy (less energy in the fuel) but is good since oxygen is also associated with the production of pollutants.

Even though heating value is slightly lower in scenario 3, the mass of fuel entering the process (RDF with organic material) is higher, and therefore, total energy available is also higher than scenario 2. This is advantageous in the sense that it allows to obtain more energy, but in a practical way having more organic matter is a disadvantage because high moisture content entails logistic issues since it increases the tendency of MSW degradation and increase energy consumption to transport water (IEA Bioenergy, 2021).

HHV and LHV for hydrogen is 141.7 MJ/kg and 120 MJ/kg respectively (The Engineering ToolBox, 2023), much higher values compared to the maximum energy per kilogram available for solid waste and waste-derived fuels in scenarios 2 and 3. With these values of energy density, hydrogen looks like a much more attractive compound as a fuel. Table 4. 4 summarizes the maximum energy, using the lower calorific value, without considering energy losses or efficiencies, that could be obtained with the total mass of hydrogen produced in the simulation and the total mass of residue entering to the system.

Table 4. 4. Energy comparison between MSW, RDF, RDF with higher organic content and hydrogen produced.

	Total Mass (kg/ton MSW)	LHV (kJ/kg)	Energy (kJ/ton MSW)	Energy (MJ/ton MSW)
MSW Scenario 1	977.4	9098.3	8892678	8893

	Total Mass (kg/ton MSW)	LHV (kJ/kg)	Energy (kJ/ton MSW)	Energy (MJ/ton MSW)
RDF Scenario 2	722.3	11688.1	8442314	8442
RDF Scenario 3	833.4	11298.5	9416169	9416
H ₂ Scenario 2	45.2	120000	5424000	5424
H ₂ Scenario 3	51.9	120000	6228000	6228

Although the hydrogen produced is not enough to supply the maximum total energy delivered by fossil fuels, with less than 10% of the mass of other fuels, it manages to produce approximately 50% of the energy delivered by solid waste and by the RDF. In this sense, maximizing hydrogen production and studying gasification using steam as an oxidizing agent to favour hydrogen production seems to be a promising route that is also more economically attractive.

Figure 4. 16 and Figure 4. 17 show a sensitivity analysis for the 3 scenarios varying the biowaste and plastic content in municipal solid waste and evaluating its impact on the flue gas and syngas global warming potential indicator. The objective of this sensitivity analysis is to try to evaluate the behavior of the environmental impact with the seasonal variation suffered by the composition of the waste, try to cope their heterogeneity. There are months where there is more content of organic material, as well as there are other months where there is more plastic waste associated with consumption patterns (in December, the Christmas holidays imply a greater disposal of packaging for example).

Although the variation can be in any of its constituents, paper, wood, textiles, etc., plastics were selected for the analysis due to their current relevance as recycling material and biowaste due to their moisture content and the importance they have to find more sustainable alternatives within the framework of circular economy.

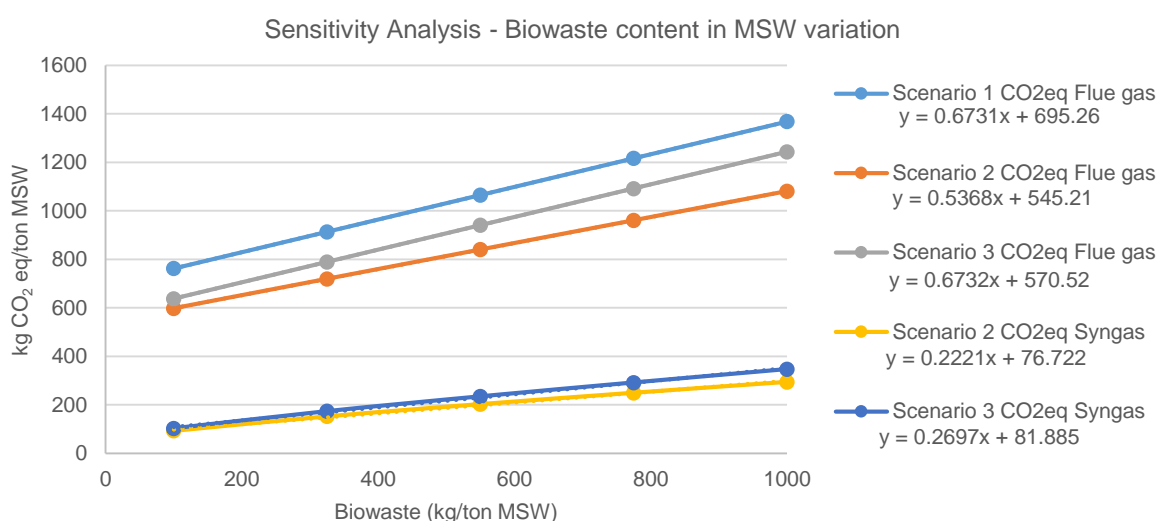


Figure 4. 16. CO_{2eq} per ton of MSW in flue gas and syngas with biomass in MSW variation for all scenarios

Figure 4. 16 shows the difference that exists in the environmental impact of syngas and flue gas. The impact associated with syngas (yellow line for scenario 2 and blue line for scenario 3) is significantly

lower than the impact associated with flue gas for all the values of biowaste varied. Analysing the slope of the trendline equation of each line, it is evidence than the change in the CO_{2eq} in the flue gas is higher than the change in the CO_{2eq} in the syngas (CO_{2eq} flue gas slope is higher than CO_{2eq} syngas slope), for each 100 kg biowaste in the mix of MSW increased, impact due to flue gas increase 3 times than syngas impact. Figure 4. 16 also shows how the scenarios with higher biowaste content in the fuel to be treated, scenario 1 and scenario 3, always have a greater impact in terms of CO_{2eq} emissions than scenario 2. The trend is always increasing and does not seem to show any point for which the impact of scenario 2 is comparable.

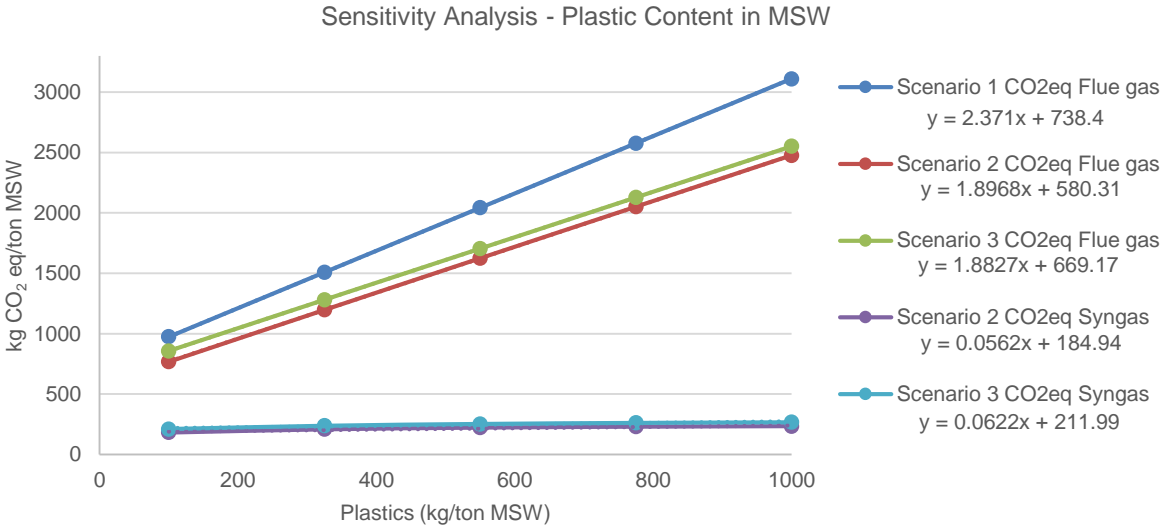


Figure 4. 17. CO_{2eq} per ton of MSW in flue gas and syngas with plastic in MSW variation for all scenarios

Regarding the sensitivity analysis, the curves obtained show the similar behaviour for plastic content and for the biowaste meaning that the impact on the global warming potential is always increasing and directly proportional to the plastic content in the fuel. In turn, the impact on flue gas is always higher than the impact due to syngas. However, the change in impact associated with flue gas is much greater than the rate of change in syngas. If this behaviour is compared with the behaviour obtained from the previous sensitivity analysis, the rate of change in CO_{2eq} impact is much higher when the plastic is varied than when the biowaste is varied. The slope of the trend line for the plastic variation is much greater than the slope of the trend line for the biowaste variation. That is, the indicator of potential climate change is much more sensitive to the content of plastic than to the content of organic material in the waste to be treated.

For scenario 1, the rate of change is higher than for all scenarios with variation in plastic content and for all scenarios with variation in biomass content, i.e. scenario 1 is the most sensitive to variation in plastic content. The proximate analysis of the plastic gives an indication of this behaviour, 96% of the plastic is volatile material and in terms of ultimate analysis, the plastic has a higher oxygen content which is related to the formation of contaminants, in this case of higher CO₂ in final concentration in the flue gas (CO in the syngas). This is why the variation of the impact associated with syngas for scenarios 2 and 3 is very low (sensitivity is low) compared to the sensitivity of the impact associated with flue gas.

Both sensitivity analyses allow us to conclude that the impact on the flue gas is much more sensitive to the variation in the composition of the waste than the impact on the syngas. In practice this implies that gasification, as a process, is a bit more flexible because its impact in terms of $\text{CO}_{2\text{eq}}$ is not as sensitive and will not vary over a wide range. Contrary to this behaviour, the flue gas can have negative peaks of environmental impact with the variation of the residues, that is, the heterogeneity of the residues and its seasonal variation will have a great influence on its potential impact on global warming. The more sensitive the variable is, the more difficult it will be to control, but in this case it also allows the evaluation of the variable on which more importance must be paid to ensure stable operation. In this case, the amount of plastic in the waste plays an important role in controlling the environmental impact of the incineration process.

4.3 Analysis Considerations

The relevance of the results found in this study goes hand in hand with the assumptions made to carry out the simulations and the creation of the comparison scenarios. It is important to note that by assuming equilibrium reactors for the simulation of gasification and combustion, there is an ideal scenario that delivers the maximum concentration of $\text{CO}_{2\text{eq}}$ but not the actual concentration of all gases. Simulating the ideal equilibrium scenario is advantageous for this life-cycle analysis because it delivers maximum results for environmental impact measured as global warming potential, which is the goal the analysis was guided by. However, in reality these processes take minutes or seconds and the $\text{CO}_{2\text{eq}}$ concentration will be lower, on the contrary the concentration of CO , CH_4 and tars will be higher, because the equilibrium state is not reached in such a short time.

For the simulation of nitrogen oxides, the Aspen software shows a limitation to simulate its composition at the exit of the combustion. Aspen Plus V11 has the default combustion reactions, however, the prediction of the concentration of nitrogen oxides is based only on the concentration of nitrogen in the fuel, it does not predict the formation of thermal NO_x (due to high temperatures) or NO_x formed by rapid reactions with CH radicals (prompt NO_x). Its concentration will always be lower than the real one and although this has a high impact on the indicator of potential global warming, treatment with ammonia guarantees that its emissions in the final flue gas are in accordance with the regulations and its impact is low.

For the purpose of this life cycle analysis, which only focused on the indicator of global warming potential, having the maximum $\text{CO}_{2\text{eq}}$ composition was beneficial, as already mentioned. However, if the analysis had considered other indicators or performance parameters, such as tars content or human toxicity, the assumptions and simulation would have to be oriented to find the concentration of pollutants or compounds that cause human health conditions, such as the concentration of chlorinated compounds (dioxins and furans) for example. Another case is the life cycle analysis with the acidification of soils and water as an indicator of environmental impact, for this analysis, obtaining concentrations of acid gases such as nitrogen oxides and sulphur oxides is more important to have an estimate of acidification.

The study carried out allows conclusions to be made solely and exclusively in terms of global warming

potential, on this indicator, considering the assumptions made, the conclusions are valid. To really have a comprehensive study, all the environmental impacts of the process must be considered, not only in gaseous emissions in the air but also considering the acidification of the soil and water, the impact of air emissions that cause destruction of the stratospheric ozone layer, impact on abiotic resources, impact on land use, emission of particulate matter among other impacts dictated by ISO standards. The choice of the indicator of climate change with global warming potential responds to efforts to reduce the emission of greenhouse gases and is in line with the unit of measurement and indicators of the objective climate neutrality for Europe by 2050.

Future work should be based on these results and add the other impacts on the environment to have an analysis with various approaches to the problem. Additionally, the limits of the system must be expanded to have a more holistic vision of waste management. Currently, the scope of the study is a gate-to-gate variation where a particular value-added process was analysed in the entire waste management chain, future work may extend the limits of life cycle analysis to include from the collection of solid waste to the treatment of solids generated, organic treatment for the specific fraction separated in scenario 2, the process to obtain auxiliary services such as chemicals for the cleaning process, water for the boiler and air for gasification and combustion and its subsequent treatment.

Expanding the limits of the system, the direct environmental loads and the avoided loads associated, for example, with a lower consumption of chemicals or a higher consumption of water for the boiler, are analysed and the energy demanded to supply the entire process can be accounted for with greater precision (from the collection, transport, supply of auxiliary chemicals, etc.). Expanding the system increases the complexity of the analysis, increases the need for real and specific information, but refines the results obtained and future interpretation.

A situation that should be analysed in detail in future work is related to the energy required for transport. If the entire life cycle of waste is considered in each of the scenarios, there is an additional distance travelled for scenarios 2 and 3 to take the potentially reusable and recyclable material to specialized units for these treatments. In the case of Valorsul, the specialized treatment units for organic material or the sorting facilities are not close to the energy recovery facilities. If this distance is travelled with some means of transport that uses fossil energy, there will be an increase in the potential climate change indicator and a reduction in the environmental loads avoided by the proper handling of these reusable materials compared to the scenario to incinerate all waste. That is, the difference in the impact of scenarios 2 and 3 with respect to scenario 1 could be reduced.

A parallel objective to the life cycle analysis is to evaluate the implementation of gasification and waste pretreatment within the current Valorsul waste energy recovery scheme. For many gasification systems in the commercial phase, as is the case of the Outotec technology on which scenarios 2 and 3 were based, gasification is understood as the first part of combustion and the system in general is called gas combustion, two stages. In principle, as it is done by technologies such as Outotec and Energos (DP Clean Tech, 2023), gasification and combustion can be carried out in the same furnace, controlling the air supply so that the primary air guarantees sub stoichiometric conditions in the lower part in contact with the solid residue (gasification) and after the generated syngas is burned under conditions of

controlled excess air through secondary air (syngas combustion). After this, the flue gas generated follows the treatment scheme and has less environmental impact, as evidenced in the simulation carried out in this project.

Although there is apparently technical feasibility to have this two-stage combustion, by allowing higher temperatures to be reached, the volume of gases handled increases. With the increase in volumetric flow, the energy requirements increase and the design of the equipment may not be sufficient. A variable that was identified in this analysis that may be relevant to study in the future is the total air required for the thermal processes. Although the air required for gasification is less than the air required for combustion, the total air required for scenarios 2 and 3 is greater than for scenario 1, this implies a greater energy requirement to extract this air and to carry it to the system gasification/combustion and may involve larger equipment to handle more airflow.

Finally, 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. The main problem identified is the incapacity of the pre-treatment processes to achieve a waste with enough quality for the complexity of the gasification process. 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.

Chapter 5

Conclusions

This chapter finalises this study, summarising conclusions, highlighting the most advantageous aspects of the scenarios proposed for possible practical implementation and pointing out aspects to be developed in future work.

For the 3 scenarios analysed, the life cycle analysis led to several important conclusions. The main conclusion, which responds to the objective of this study, is that scenario 2, in which waste is pre-treated to produce a RDF with less organic content that is subjected to gasification and subsequent syngas combustion, is the best scenario in terms of CO_{2eq} emissions. I.e., 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.

On the contrary, 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. Less environmental impact is expected since more organic material implies more carbon available to be fully oxidized to CO₂.

From this main conclusion, others emerge that allow us to respond to the sub research questions initially raised, an example of this is the impact of energy on global warming potential. For all scenarios, more than 90% of the CO_{2eq} is due to direct emissions of CO₂ in the flue gas and energy contribution is low because electricity mix in Portugal has a high share of renewable energies. For scenarios 2 and 3, as long as electricity mix in Portugal has high share of renewable energy as it currently is, total global warming potential impact has low sensibility to energy consumption variation, since most of the CO_{2eq} comes from direct emissions in the combustion flue gas.

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. For all the range of composition analysed, for both biowaste and plastic content variation, there was not a combination. The slope of the curves for flue gas always were higher than syngas curves for all scenarios for biowaste and plastic content change.

In practical terms this implies that gasification is a more flexible solution than combustion, which will be able to provide similar levels of impact for a wide range of changes in fuel composition. This is especially good for solid waste due to its high heterogeneity and its geographical and temporal variation (with the seasons of the year).

Another important conclusion, which also allows us to understand the strategies that must be implemented to treat unsorted solid waste, is that gasification in scenarios 2 and 3 has on average 70% less CO₂ emissions compared to combustion, that is, in terms of impact on global warming, gasification is better than combustion. However, responding to the technical and economic feasibility of the solution, the market study allows us to highlight that gasification, separated from combustion, 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. More investigation and testing is needed to overcome the current technology lack of maturity.

One key point to further analysis is hydrogen as a valuable gasification product. Hydrogen produced in syngas for scenarios 2 and 3 represented less than 10% of the total mass of the fuel feed to thermal processes. However, its calorific value is so high that it allows to produce almost 50% of the maximum energy possible to be produced by other fuels (MSW in scenario 1 and RDF in scenarios 2 and 3) with much less mass. In this sense, maximizing hydrogen production and studying gasification using steam as an oxidizing agent to favour hydrogen production seems to be a promising route in terms of environmental impacts.

It is valid to propose for future life cycle analysis that hydrogen production from MSW gasification is studied to confirm if this option is the waste management scheme with less environmental impact and the most economically attractive aligned with the impulses to make hydrogen a fundamental part of a more sustainable future and more focused within the framework of the circular economy.

For future work it is important to fill the existing gaps regarding the characterization of solid waste and expand the limits of the study to include the impacts of complementary processes such as transportation, treatment of the separated organic fraction, treatment of the solid residue generated, processes for obtaining and treating auxiliary services like water and chemicals, among others.

The characterization must include everything from the composition for the different months of the year, to its elemental and ultimate analyses, as well as the composition of the metals present in waste. Kinetic studies must also be expanded to truly understand and model with greater precision the behaviour of solid waste in gasification and combustion and to predict the composition for a certain time. A review of the literature showed how difficult it is to find this information specifically for municipal solid waste in Portugal, and this is a point on which future work can be based.

Likewise, a more complete analysis, considering all the impacts dictated by ISO standards, as well as including the social and economic aspects that must accompany a fully viable solution, will allow for a more complete response to the search for the best solution for the treatment of waste to be implemented by solid waste management entities.

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Annex A

Extended Details Commercial Gasification Projects

This annex expands the information on commercial gasification projects, their current status, the feedstock used and the type of reactor used to give a general idea of the process. It explains in more detail some of the most widely used technologies for obtaining electricity or biofuels from biomass gasification and municipal solid waste in particular.

A.1 Commercial gasification projects

Table A. 1. Extended information commercial gasification projects status around the world. Information updated to 2023

Location	Feedstock	Status / Date operational	Output	Technology
Chur, Switzerland	Hydrochar	Commercial demonstrator decommissioned	200 kWe	A.H.T Syngas Technology (Fixed bed downdraft/updraft) – Technology from Germany
Utashinai, Japan	MSW and ASR	2003	4.7 MWe	Alter NRG / Westinghouse Plasma Corporation (Fluidized bed and Plasma) – Technology from Canada
Mihama-Mikata, Japan	MSW and sewage sludge	2003	Domestic hot water	
Wuhan, China	Biomass	2013	Diesel fuel	
Ansager, Jutland, Denmark	Wood chips	2006	37 kWe	Babcock & Wilcox Volund (Fixed bed updraft) – Technology from USA
Ishikawa, Japan	Wood chips	2008	2.5 MWe	
Shikokuchuo-shi, Japan	Wood chips	2008	Fuel gas	
Culcheth, UK	Clean wood	No operational information available / 2006	85 kWe	Biomass Engineering limited (Fixed bed downdraft) – Technology from Ireland
Penrith, UK	Clean wood		1,000 kWe	
Dortmund, UK	Clean wood		270 kWe	
Preston, UK	Wood/coppice	No operational information available / 2007	1,000 kWe	
Stoke, UK	Reclaimed wood		3,000 kWe	
Hoddesdon, UK	RDF	Shutdown	9 MWe	
Belfast, UK	RDF	Operational / 2019	15 MWe	
Schwarze Pumpe, Germany	Hard coal, Lignite, RDF	2000	35,000 Nm ³ /h syngas	British Gas/Lurgi (Fixed bed updraft) – Technology from Germany
Hulunbeier, Inner Mongolia, China	Dried and briquetted lignite	2012	500,000 t/y ammonia, 800,000 t/y urea	
Ordos Tuke, Inner Mongolia, China	Bituminous coal	2013	1'000,000 t/y ammonia, 1'750,000 t/y urea	
New Jersey, USA	Various metal based residues, MSW	2010	Unknown	Chinook Sciences (RODECS™ batch process) – Technology from UK and USA group
Pennsylvania, USA		2011	Unknown	
Mahad, India	Sludge digestate	2011	3 MWth	Concord Blue (Staged reformer)
Omuta, Japan	Sewage sludge	2011	Hydrogen	
Ranheim, Norway	C&I	1997	Steam	Energos (Moving grate) – Technology from Norway
Minden, Germany	C&I	2000	Steam	
Hurum, Norway	MSW and commercial waste	2001	Steam	
Forus, Norway	MSW	2002	Steam and electricity	

Location	Feedstock	Status / Date operational	Output	Technology
Sarpsborg I, Norway	MSW and industrial waste	2002	Steam	
Isle of Wight, UK	MSW and commercial waste	2009	Electricity	
Sarpsborg II, Norway	MSW and industrial waste	2010	Steam	
Glasgow, UK	RDF	2019	Electricity	
Chubu-Kamikita, Aomori, Japan	Mixed MSW	2000	Hot water	Kobelco Eco Solutions (Bubbling fluidized bed) - Technology from Japan
Aiki, Hiroshima, Japan	Mixed MSW	2002	Hot water, 1.3 MWe	
Kazuno, Akita, Japan	Mixed MSW	2002	Hot water	
Nakatsugawa, Gifu, Japan	Mixed MSW	2004	Hot water, 0.9 MWe	
Ono-Katsuyama, Fukui, Japan	Mixed MSW	2006	Hot water	
Nemuro-Hokubu, Japan	Mixed MSW	2007	Hot water	
Sashima, Ibaragi, Japan	Mixed MSW	2008	Hot water, 3 MWe	
Iwade, Wakayama, Japan	Mixed MSW	2008	Hot water	
Kawagoe, Saitama, Japan	Mixed MSW	2010	Hot water, 4 MWe	
Sagamihara, Kanagawa, Japan	Mixed MSW	2010	Hot water, 10 kWe	
Paju, Seoul, Korea	Mixed MSW	2011	Steam supply	
Nishi-Akigawa, Tokyo, Japan	Mixed MSW + dug out landfill waste	2014	Hot water	
Haga, Tochigi, Japan	Mixed MSW + sewage sludge	2014	Heating and 2 MWe	
Kofu, Yamanashi, Japan	Mixed MSW	Under construction	Not available	
Yamagata Koki, Yamagata, Japan	Mixed MSW	Under construction	Not available	
Kamilina, Koki, Nagaro, Japan	Mixed MSW	Under construction	Not available	
Birmingham Biopower, UK	Waste wood	Operational	9 MWe	Nexterra (Fixed bed updraft) – Technology from USA
Boston, UK	Waste Wood	Commissioning	10 MWe	Outotec Energy Products (Bubbling fluidized bed) – Technology from USA
Charlton lane, UK	RDF	Operational / 2022	3.65 MWe	
Hull, UK	Waste Wood	Commissioning	22 MWe	
Ince, UK	Waste Wood	Operational	21.5 MWe	
Connecticut, USA	Construction & demolition waste and Green wood	Operational	37.5 MW3	
Maine, USA	Biomass	Operational	Process Heat	
Washington, USA	Paper sludge, deinked sludge	Operational	Process heat	
Iowa, USA	Wood waste	Operational	6 MWe	
New Jersey, USA	Sewage sludge	Operational	0.75 MWe	
California, USA	Agricultural and yard waste	Operational	Municipal heating	
Tokushima, Japan	MSW	Unclear 2005	Syngas to gas engine	Thermoselect (High temperature fixed bed systems) –
Yorii, Japan	Industrial waste	Unclear 2005	Syngas to boiler	

Location	Feedstock	Status / Date operational	Output	Technology
Nagasaki, Japan	MSW	Unclear 2005	Syngas to gas engine	Technology from Japan
Kurashiki, Japan	Industrial waste	Unclear 2005	Syngas to export	
Osaka, Japan	Industrial waste	Unclear 2006	Syngas for boiler	
OKI Paper Mill, Indonesia	Biomass	2009	Unknown	Valmet (Circulating fluidized bed)
Äänekoski, Finland	Biomass	2017	Unknown	
Huanggang, China	Biomass	Unknown	Unknown	
Dargavel, Dumfries	RDF	Shutdown		Enerwaste / Planet
Fulcrum Sierra Biorefinery, USA	MSW	Operational / 2022	Syngas suitable for diesel production and synthetic aviation fuel	ThermoChem Recovery International (Bubbling fluidized bed)

Of the commercial technologies for waste treatment, the following stand out

- Alter NRG / Westinghouse Plasma Corporation (Juniper Consultancy Services , 2008)
 - Raw material: MSW, RDF, Automotive shredder residue (ASR) and waste tyres
 - Pretreatment: Shredding
 - Description: Conventional fluidized bed gasification system in which air is used as the gasifying agent. Plasma torches located near the solids discharge outlet of the gasifier produce a plume of very hot air (5,000 – 7,000°C) which is then used to melt ash entrained in the syngas. The slag produced is removed from the bottom of the reactor in a molten state.
 - Product: Cleaned syngas is combusted to produce steam to drive a steam turbine or is burned in a gas turbine
 - Syngas cleaning required: YES – before combustion
- Concord Blue (CONCORD BLUE, 2023)
 - Raw material: MSW, RDF, wood chip and hazardous effluents
 - Pretreatment: Process begins with the recycling of valuable resources and the separation of metals, glass and inert materials before drying and shredding.
 - Description: Fuel initially undergoes pyrolysis to produce a high calorific value pyrolysis gas. The pyrolysis gas is then discharged to a reformer where a mixture of steam and O₂ are used to reform the pyrolysis gas into a syngas with a high hydrogen content.
 - Product: Syngas to gas turbine to produce electricity
 - Syngas cleaning required: YES – before combustion
- Kobelco Eco Solutions (Kobelco ECO-Solutions CO, 2023)
 - Raw material: MSW, sewage sludge and commercial & industrial waste
 - Pretreatment: Shredding

- Description: Fluidized bed gasifier using air as oxidant agent coupled to a swirl flow melting furnace. In this system, syngas generated in the gasifier undergoes combustion at approximately 1200°C in the swirl flow melting furnace. Any particles entrained in the syngas undergo combustion in the melting furnace to form a molten slag which is continuously discharged through a tapping hole at the base of the furnace. Incombustible solids in the fuel bed are discharged from the base of the gasifier.
- Product: Syngas is burned to produce steam and then electricity
- Syngas cleaning required: NO – flue gas cleaning is required
- Thermoselect
 - Raw material: MSW, RDF, ASR and industrial waste
 - Pretreatment: Compaction
 - Description: The Thermoselect technology consists of an initial pyrolysis stage followed by gasification in a high temperature (approximately 2000°C) oxygen blown, fixed bed system. Part of the electricity generated is used in the air separation system that provides the oxygen.
 - Product: High quality syngas to be burned in gas engines, to be burned in steam boilers
 - Syngas cleaning requirement: YES –before combustion
- Valmet (Valmet, 2023)
 - Raw material: Biomass and MSW as RDF
 - Pretreatment: Crushers, screens, magnetic separation, dust removal and drying
 - Description: Dried biomass is fed to the circulating fluidizing bed gasifier where silica sand or limestone are used as bed materials and air as oxidant agent. Syngas and solids flows to the cyclone where solid is separated and gas products flows to the hot gas filter before entering steam boiler system
 - Product: Syngas is burned to produce steam and then electricity
 - Syngas cleaning requirement: YES – before combustion

The following is general information respecting innovative technologies for biofuel production based on solid waste gasification.

- Kew Technology
 - Raw material: Densified RDF, biomass, clinical and hazardous waste
 - Pretreatment requirements description: Pre-treatment of the feedstock for the Kew process will include standard mechanical pre-treatment plant such as shredders, screens and metal separation for reduction in particle size and removal of oversize particles, non-combustible materials and ferrous and non-ferrous metals. The feedstock must also be dried and densified into cubes.
 - Product: Three types of syngas of varying concentration of H₂ and CO depending on syngas application (from energy generation to H₂ supply)
 - Description: The Kew process converts densified feedstock in a pressurised BFB gasifier at approximately 7 barg and 800°C using a mixture of O₂ and steam or air depending on the application for which the syngas will be used. Syngas from the gasifier

is then filtered before combustion in a syngas engine or delivery to a syngas upgrading system for liquid fuels production.

- Syngas cleaning required: YES
- ThermoChem Recovery International
 - Raw material: Biomass and RDF from MSW and commercial & industrial waste
 - Pretreatment requirements description: Standard mechanical pre-treatment (Shredders (to 50-80 mm), screens, metal separation, drying (to approximately 10wt% moisture) and density separation. Rejected material is composed of glass, stones, metals (ferrous and non-ferrous) and large dense objects.
 - Product: Syngas which is suitable for upgrading to diesel and synthetic paraffinic kerosene
 - Description: Allothermal two stage steam reforming in two bubbling fluidized bed reformers using natural gas pulse combustion heaters. In the first reactor feedstock is gasified with superheated steam. In the second stage, steam and O₂ are used as fluidizing media and gasifying agent to gasified previously formed syngas, char and unconverted carbon.
 - Syngas cleaning required: YES

Annex B

Aspen Plus V11 Simulation Details and Results

This appendix presents the details and input specifications used for the simulation of the scenarios. In addition, the complete mass balances obtained from the simulation in Aspen Plus V11 for all simulated streams in the three the complete mass balances obtained from the simulation in Aspen Plus V11 for all simulated streams in the three scenarios analysed.

B.1 Municipal solid waste characterization

Municipal solid waste complete characterization, including proximate and ultimate analysis, before data processing to adjust information to simulation software data entry format is shown in Table B. 1 and Table B. 2

Table B. 1. Municipal solid waste composition and flows normalized

	MSW Composition		
	Normalizes		Flow kg/h
	% in MSW	% in MSW	
Biowaste	38.72	46.4	463.99
Paper	12.99	15.6	155.66
Plastic	9.48	11.4	113.60
Glass (Silica)	7.09	8.5	84.96
Textiles	8.69	10.4	104.13
Metals	1.72	2.1	20.61
Wood	2.05	2.5	24.57
Yard waste	0.82	1.0	9.83
Bulky waste	1.89	2.3	22.65
Total	83.45	100	1000

Table B. 2. Municipal Solid Waste Complete Ultimate and Proximate Analysis

	Proximate analysis					Ultimate analysis						
	%Moisture	%FC	%VM	%Ash	Total	%C	%H	%O	%N	%S	%Ash	Total
Biowaste	70	3.6	21.4	5	100	73	11.5	14.8	0.4	0.1	0.2	100
Paper	10.2	8.4	75.9	5.5	100	43.3	5.8	44.3	0.3	0.3	6	100
Plastic	0.2	2	95.8	2	100	60	7.2	22.8			10	100
Glass (Silica)	Simulated as Silica											
Textiles	10	6.5	66	17.5	100	55	6.6	31.2	4.6		2.4	99.8
Metals	Simulated as Iron (Ferrous) and aluminium (nonferrous)											
Wood	12	12.4	75	0.6	100	49.4	6.1	43.7	0.1		0.7	100
Yard waste	62	6.3	26.7	4.9	99.9	40.31	5.64	39	2	0.3	12.75	100
Bulky waste	Not included in the simulation, manual screening											

B.2 Aspen Plus V11 simulation details

Details on calculation blocks and design specs specification is shown in Table B. 3. Calculation blocks are written in Fortran code following software format. Table B. 3 are refer to scenario 2 (S2) flow streams numeration, equivalence with scenario 1 (S1) and 3 (S3) flow streams and equipment tag is indicated in the table for each design spec and calculation block. There are exclusive calculation blocks for scenarios 2 and 3 related to the mechanical treatment process. For these calculation blocks, there is no equivalence with scenario 1.

Table B. 3. Aspen Plus specification details on calculation blocks and design spec for all scenarios

Calculation Design Spec	Block	Specification in Aspen																											
<p><u>DECO-CAL</u></p> <p>Stream equivalence</p> <table border="1"> <thead> <tr> <th>S1</th> <th>S2</th> <th>S3</th> </tr> </thead> <tbody> <tr> <td>1</td> <td>1</td> <td>1</td> </tr> <tr> <td>2</td> <td>2</td> <td>2</td> </tr> <tr> <td>4</td> <td>4</td> <td>4</td> </tr> <tr> <td>7</td> <td>7</td> <td>7</td> </tr> <tr> <td>8</td> <td>8</td> <td>8</td> </tr> <tr> <td>9</td> <td>9</td> <td>9</td> </tr> <tr> <td>14</td> <td>25</td> <td>23</td> </tr> <tr> <td>R-102</td> <td>R-202</td> <td>R-302</td> </tr> </tbody> </table>	S1	S2	S3	1	1	1	2	2	2	4	4	4	7	7	7	8	8	8	9	9	9	14	25	23	R-102	R-202	R-302		<p>SAMPLED VARIABLES:</p> <p>PLASC: COMP-ATTR-VA IN STREAM 1 ID: ULTANAL PAPC: COMP-ATTR-VA IN STREAM 2 ID: ULTANAL BIOC: COMP-ATTR-VA IN STREAM 4 ID: ULTANAL WOODC: COMP-ATTR-VA IN STREAM 8 ID: ULTANAL TEXTC: COMP-ATTR-VA IN STREAM 7 ID: ULTANAL YARDC: COMP-ATTR-VA IN STREAM 9 ID: ULTANAL DECOMC: SENTENCE=MASS-YIELD VARIABLE=YIELD ID1=CIPSD ID2=C IN UOS BLOCK R-202 PLAST: PLASTICSMASSFLOW IN STREAM 25 PAPER: PAPER MASSFLOW IN STREAM 25 BIOWASTE: BIOWASTEMASSFLOW IN STREAM 25 WOOD: WOOD MASSFLOW IN STREAM 25 TEXTIL: TEXTILESMASSFLOW IN STREAM 25 YARD: YARDWASTMASSFLOW IN STREAM 25 PLASH: COMP-ATTR-VA IN STREAM 1 ID: ULTANAL PAPH: COMP-ATTR-VA IN STREAM 2 ID: ULTANAL BIOH: COMP-ATTR-VA IN STREAM 4 ID: ULTANAL WOODH: COMP-ATTR-VA IN STREAM 8 ID: ULTANAL TEXTH: COMP-ATTR-VA IN STREAM 7 ID: ULTANAL YARDH: COMP-ATTR-VA IN STREAM 9 ID: ULTANAL DECOMH2: SENTENCE=MASS-YIELD VARIABLE=YIELD ID1=MIXED ID2=H2 IN UOS BLOCK R-202 PLASN: COMP-ATTR-VA IN STREAM 1 ID: ULTANAL PAPN: COMP-ATTR-VA IN STREAM 2 ID: ULTANAL BION: COMP-ATTR-VA IN STREAM 4 ID: ULTANAL WOODN: COMP-ATTR-VA IN STREAM 8 ID: ULTANAL TEXTN: COMP-ATTR-VA IN STREAM 7 ID: ULTANAL YARDN: COMP-ATTR-VA IN STREAM 9 ID: ULTANAL DECOMN2: SENTENCE=MASS-YIELD VARIABLE=YIELD ID1=MIXED ID2=N2 IN UOS BLOCK R-202 PLASS: COMP-ATTR-VA IN STREAM 1 ID: ULTANAL PAPS: COMP-ATTR-VA IN STREAM 2 ID: ULTANAL BIOS: COMP-ATTR-VA IN STREAM 4 ID: ULTANAL WOODS: COMP-ATTR-VA IN STREAM 8 ID: ULTANAL TEXTS: COMP-ATTR-VA IN STREAM 7 ID: ULTANAL YARDS: COMP-ATTR-VA IN STREAM 9 ID: ULTANAL DECOMS: SENTENCE=MASS-YIELD VARIABLE=YIELD ID1=CIPSD ID2=S IN UOS BLOCK R-202 PLASO: COMP-ATTR-VA IN STREAM 1 ID: ULTANAL PAPO: COMP-ATTR-VA IN STREAM 2 ID: ULTANAL BIOO: COMP-ATTR-VA IN STREAM 4 ID: ULTANAL WOODO: COMP-ATTR-VA IN STREAM 8 ID: ULTANAL TEXTO: COMP-ATTR-VA IN STREAM 7 ID: ULTANAL YARDO: COMP-ATTR-VA IN STREAM 9 ID: ULTANAL DECOMO2: SENTENCE=MASS-YIELD VARIABLE=YIELD ID1=MIXED</p>
S1	S2	S3																											
1	1	1																											
2	2	2																											
4	4	4																											
7	7	7																											
8	8	8																											
9	9	9																											
14	25	23																											
R-102	R-202	R-302																											

Calculation Design Spec	Block /	Specification in Aspen									
		<p>ID2=O2 IN UOS BLOCK R-202 PLASA: COMP-ATTR-VA IN STREAM 1 ID: ULTANAL PAPA: COMP-ATTR-VA IN STREAM 2 ID: ULTANAL BIOA: COMP-ATTR-VA IN STREAM 4 ID: ULTANAL WOODA: COMP-ATTR-VA IN STREAM 8 ID: ULTANAL TEXTA: COMP-ATTR-VA IN STREAM 7 ID: ULTANAL YARDA: COMP-ATTR-VA IN STREAM 9 ID: ULTANAL DECOMASH: SENTENCE=MASS-YIELD VARIABLE=YIELD ID1=NCPSD ID2=ASH IN UOS BLOCK R-202</p> <p>FORTTRAN STATEMENTS: TOTAL = YARD+WOOD+TEXTIL+BIOWASTE+PAPER+PLAST C1 = PLASC*PLAST/100 C2 = PAPC*PAPER/100 C3 = BIOC*BIOWASTE/100 C4 = WOODC*WOOD/100 C5 = TEXTC*TEXTIL/100 C6 = YARDC*YARD/100 H1 = PLASH*PLAST/100 H2 = PAPH*PAPER/100 H3 = BIOH*BIOWASTE/100 H4 = WOODH*WOOD/100 H5 = TEXTH*TEXTIL/100 H6 = YARDH*YARD/100 N1 = PLASN*PLAST/100 N2 = PAPN*PAPER/100 N3 = BION*BIOWASTE/100 N4 = WOODN*WOOD/100 N5 = TEXTN*TEXTIL/100 N6 = YARDN*YARD/100 S1 = PLASS*PLAST/100 S2 = PAPS*PAPER/100 S3 = BIOS*BIOWASTE/100 S4 = WOODS*WOOD/100 S5 = TEXTS*TEXTIL/100 S6 = YARDS*YARD/100 O1 = PLASO*PLAST/100 O2 = PAPO*PAPER/100 O3 = BIOO*BIOWASTE/100 O4 = WOODO*WOOD/100 O5 = TEXTO*TEXTIL/100 O6 = YARDO*YARD/100 A1 = PLASA*PLAST/100 A2 = PAPA*PAPER/100 A3 = BIOA*BIOWASTE/100 A4 = WOODA*WOOD/100 A5 = TEXTA*TEXTIL/100 A6 = YARDA*YARD/100</p> <p>DECOMC = ((C1+C2+C3+C4+C5+C6) / TOTAL) DECOMH2 = ((H1+H2+H3+H4+H5+H6) / TOTAL) DECOMN2 = ((N1+N2+N3+N4+N5+N6) / TOTAL) DECOMS = ((S1+S2+S3+S4+S5+S6) / TOTAL) DECOMO2 = ((O1+O2+O3+O4+O5+O6) / TOTAL) DECOMASH = ((A1+A2+A3+A4+A5+A6) / TOTAL)</p>									
<p><u>ACTI-CAL</u></p> <p>Stream equivalence</p> <table border="1"> <thead> <tr> <th>S1</th> <th>S2</th> <th>S3</th> </tr> </thead> <tbody> <tr> <td>17</td> <td>28</td> <td>26</td> </tr> <tr> <td>28</td> <td>40</td> <td>38</td> </tr> </tbody> </table>	S1	S2	S3	17	28	26	28	40	38		<p>SAMPLED VARIABLES: FEED1: TOTAL MASSFLOW IN STREAM 28 FEED2: TOTAL MASSFLOW IN STREAM 28 FEED3: TOTAL MASSFLOW IN STREAM 28 CARBONAC: TOTAL MASSFLOW IN STREAM 40</p> <p>FORTTRAN STATEMENTS: CARBONAC= 0.0005*(FEED1+FEED2+FEED3)</p>
S1	S2	S3									
17	28	26									
28	40	38									
<p><u>AMMO-CAL</u></p> <p>Stream equivalence</p> <table border="1"> <thead> <tr> <th>S1</th> <th>S2</th> <th>S3</th> </tr> </thead> <tbody> <tr> <td>17</td> <td>33</td> <td>31</td> </tr> <tr> <td>23</td> <td>35</td> <td>33</td> </tr> </tbody> </table>	S1	S2	S3	17	33	31	23	35	33		<p>SAMPLED VARIABLES: AMMONIA: NH3 MOLEFLOW IN STREAM 35 NO: NO MOLEFLOW IN STREAM 33</p> <p>FORTTRAN STATEMENTS: AMMONIA=0.5*NO</p>
S1	S2	S3									
17	33	31									
23	35	33									

Calculation Design Spec	Block /	Specification in Aspen														
<u>LIME-CAL</u> Stream equivalence <table border="1"> <tr><td>S1</td><td>S2</td><td>S3</td></tr> <tr><td>17</td><td>28</td><td>26</td></tr> <tr><td>26</td><td>38</td><td>36</td></tr> </table>	S1	S2	S3	17	28	26	26	38	36		SAMPLED VARIABLES: LIME: CA(OH)2 MASSFLOW IN STREAM 38 FEED1: TOTAL MASSFLOW IN STREAM 28 FEED2: TOTAL MASSFLOW IN STREAM 28 FEED3: TOTAL MASSFLOW IN STREAM 28 FORTRAN STATEMENTS: LIME= 0.0065*(FEED1+FEED2+FEED3)					
S1	S2	S3														
17	28	26														
26	38	36														
<u>AIRG-CAL</u> Stream equivalence <table border="1"> <tr><td>S2</td><td>S3</td></tr> <tr><td>30</td><td>28</td></tr> <tr><td>31</td><td>29</td></tr> </table>	S2	S3	30	28	31	29		SAMPLED VARIABLES: MC: C MOLEFLOW IN STREAM 30 MH2: H2 MOLEFLOW IN STREAM 30 MO2: O2 MOLEFLOW IN STREAM 30 MAIR: TOTAL MOLEFLOW IN STREAM 31 FORTRAN STATEMENTS: MAIR = (0.4*(MC+(0.5*MH2)-MO2))/0.21								
S2	S3															
30	28															
31	29															
<u>AIRC-CAL</u> Stream equivalence <table border="1"> <tr><td>S1</td><td>S2</td><td>S3</td></tr> <tr><td>20</td><td>32</td><td>30</td></tr> <tr><td>16</td><td colspan="2">Syngas</td></tr> </table>	S1	S2	S3	20	32	30	16	Syngas			SAMPLED VARIABLES: MC: C MOLEFLOW IN STREAM SYNGAS MH2: H2 MOLEFLOW IN STREAM SYNGAS MO2: O2 MOLEFLOW IN STREAM SYNGAS MAIR: TOTAL MOLEFLOW IN STREAM 32 MCO: CO MOLEFLOW IN STREAM SYNGAS MCH4: CH4 MOLEFLOW IN STREAM SYNGAS MC6H6O: C6H6O MOLEFLOW IN STREAM SYNGAS MC6H6: C6H6 MOLEFLOW IN STREAM SYNGAS FORTRAN STATEMENTS: MAIR = (1.2*(MC+MCO+MCH4+MC6H6O+MC6H6+(0.5*MH2)-MO2))/0.21					
S1	S2	S3														
20	32	30														
16	Syngas															
<u>FE-CAL</u> Stream equivalence <table border="1"> <tr><td>S2</td><td>S3</td></tr> <tr><td>5</td><td>5</td></tr> <tr><td>11</td><td>-</td></tr> <tr><td>12</td><td>10</td></tr> <tr><td>S-202</td><td>S-301</td></tr> </table>	S2	S3	5	5	11	-	12	10	S-202	S-301		SAMPLED VARIABLES: FINEFE: IRON MASSFLOW IN STREAM 11 FEIN: IRON MASSFLOW IN STREAM 5 COARSEFE: IRON MASSFLOW IN STREAM 12 RECUP: SENTENCE=FRAC VARIABLE=FRACS ELEMENT=2 ID1=CIPSD ID2=13 IN UOS BLOCK S-202 FORTRAN STATEMENTS: RECUP = ((FEIN*0.895)-FINEFE)/COARSEFE				
S2	S3															
5	5															
11	-															
12	10															
S-202	S-301															
<u>NOFE-CAL</u> Stream equivalence <table border="1"> <tr><td>S2</td><td>S3</td></tr> <tr><td>6</td><td>6</td></tr> <tr><td>11</td><td>-</td></tr> <tr><td>14</td><td>12</td></tr> <tr><td>S-203</td><td>S-302</td></tr> </table>	S2	S3	6	6	11	-	14	12	S-203	S-302		SAMPLED VARIABLES: NONFEIN: ALUMINUMMASSFLOW IN STREAM 6 FINENONF: ALUMINUMMASSFLOW IN STREAM 11 COARSENO: ALUMINUMMASSFLOW IN STREAM 14 RECUP2: SENTENCE=FRAC VARIABLE=FRACS ELEMENT=3 ID1=CIPSD ID2=15 IN UOS BLOCK S-203 FORTRAN STATEMENTS: RECUP2 = ((NONFEIN*0.828)-FINENONF)/COARSENO				
S2	S3															
6	6															
11	-															
14	12															
S-203	S-302															
<u>NIR-CAL</u> Stream equivalence <table border="1"> <tr><td>S2</td><td>S3</td></tr> <tr><td>1</td><td>1</td></tr> <tr><td>2</td><td>2</td></tr> <tr><td>11</td><td>-</td></tr> <tr><td>17</td><td>15</td></tr> <tr><td>18</td><td>16</td></tr> <tr><td>S-204</td><td>S-303</td></tr> </table>	S2	S3	1	1	2	2	11	-	17	15	18	16	S-204	S-303		SAMPLED VARIABLES: RECUP3: SENTENCE=FRAC VARIABLE=FRACS ELEMENT=2 ID1=NCPSD ID2=19 IN UOS BLOCK S-204 RECUP4: SENTENCE=FRAC VARIABLE=FRACS ELEMENT=1 ID1=NCPSD ID2=19 IN UOS BLOCK S-204 FINEPAP: PAPER MASSFLOW IN STREAM 11 FINEPLAS: PLASTICSMASSFLOW IN STREAM 11 HEAVYPAP: PAPER MASSFLOW IN STREAM 17 HEAVYPLA: PLASTICSMASSFLOW IN STREAM 17 PAPERIN: PAPER MASSFLOW IN STREAM 2 PLASTIN: PLASTICSMASSFLOW IN STREAM 1 LIGHTPAP: PAPER MASSFLOW IN STREAM 18 LIGHTPLA: PLASTICSMASSFLOW IN STREAM 18 FORTRAN STATEMENTS: RECUP3 = ((PAPERIN*0.311)-FINEPAP-HEAVYPAP)/LIGHTPAP RECUP4 = ((PLASTIN*0.206)-FINEPLAS-HEAVYPLA)/LIGHTPLA
S2	S3															
1	1															
2	2															
11	-															
17	15															
18	16															
S-204	S-303															

Calculation Design Spec	Block /	Specification in Aspen									
DS-1 Stream equivalence		MANIPULATED VARIABLE MASSFLOW IN STREAM 42 DESIGN SPECIFICATION EXPRESSION SPECIFICATION: STREAM-VAR STREAM=43 VARIABLE=TEMP UNITS=C TARGET: 420 TOLERANCE: 0.5									
<table border="1"> <thead> <tr> <th>S1</th> <th>S2</th> <th>S3</th> </tr> </thead> <tbody> <tr> <td>30</td> <td>42</td> <td>40</td> </tr> <tr> <td>31</td> <td>43</td> <td>41</td> </tr> </tbody> </table>	S1	S2	S3	30	42	40	31	43	41		
S1	S2	S3									
30	42	40									
31	43	41									

Specification details of equipment included in scenarios simulation is shown in Table B. 4 for scenario 1 and Table B. 5 for scenarios 2 and 3. Specification include conditions impose in the simulation, the reactions involve in the equipment simulated and the type of equipment selected to simulate the processes that compose the scenarios.

Table B. 4. Scenario 1 equipment specifications and details simulated in Aspen

Process/equipment	Aspen Plus V11 Identification	Specification in Aspen														
Drying	ID: R-101 Type: Stoichiometric reactor	Temperature: 150°C Pressure: 1.013 bar <table border="1"> <thead> <tr> <th>Reaction</th> <th>Fractional conversion</th> </tr> </thead> <tbody> <tr> <td>$PLASTICS \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$</td> <td>% Moisture Plastic</td> </tr> <tr> <td>$PAPER \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$</td> <td>% Moisture Paper</td> </tr> <tr> <td>$BIOWAST \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$</td> <td>% Moisture Biowaste</td> </tr> <tr> <td>$TEXTILES \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$</td> <td>% Moisture Textiles</td> </tr> <tr> <td>$WOOD \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$</td> <td>% Moisture wood</td> </tr> <tr> <td>$YARDWASTE \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$</td> <td>% Moisture Yardwaste</td> </tr> </tbody> </table>	Reaction	Fractional conversion	$PLASTICS \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$	% Moisture Plastic	$PAPER \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$	% Moisture Paper	$BIOWAST \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$	% Moisture Biowaste	$TEXTILES \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$	% Moisture Textiles	$WOOD \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$	% Moisture wood	$YARDWASTE \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$	% Moisture Yardwaste
Reaction	Fractional conversion															
$PLASTICS \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$	% Moisture Plastic															
$PAPER \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$	% Moisture Paper															
$BIOWAST \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$	% Moisture Biowaste															
$TEXTILES \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$	% Moisture Textiles															
$WOOD \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$	% Moisture wood															
$YARDWASTE \rightarrow \left(\frac{1}{MW_{H_2O}}\right) H_2O$	% Moisture Yardwaste															
Inert separation	ID: CY-101 Type: Stream split	Conventional solids split fraction: 1														
Steam separator	ID: D-101 Type: separator	Mixed H ₂ O split fraction: 1														
Decomposition	ID: R-102 Type: Yield reactor	Temperature: 450°C Pressure: 1.013 bar Components yield according to calculator DECO-CAL														
Pyrolysis	ID: R-103 Type: Gibbs reactor	Phase equilibrium and chemical equilibrium at 1.013 bar and 450°C														
Ash separation	ID: D-102 Type: separator	Non-conventional solid ash split fraction: 1														
Combustion	ID: R-104 Type: Gibbs reactor	Phase equilibrium and chemical equilibrium at 1.013 bar and 850°C														
Selective non-catalytic reduction	ID: R-105 Type: Stoichiometric reactor	Temperature: 850°C Pressure: 1.013 bar Reactions: $2NO + 2NH_3 + \frac{1}{2}O_2 \rightarrow 2N_2 + 3H_2O$ $2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$														

Process/equipment	Aspen Plus V11 Identification	Specification in Aspen
Boiler-1	ID: E-101 Type: Heater	Outlet temperature: 150°C Pressure: 1.013 bar
Boiler-2	ID: E-102 Type: Heater	Pressure: 52.8 bar Temperature: 420°C Specification varying water mass flow to absorb all heat delivered by Boiler-1 (DS-1)
Turbine	ID: C-101 Type: compressor	Model: Turbine Isentropic type Discharge pressure: 0.15 bar(a)
Dry spray	ID: R-106 Type: Stoichiometric reactor	Temperature: 150°C Pressure: 1.013 bar Reactions: $SO_2 + Ca(OH)_2 \rightarrow H_2O + CaSO_3 \cdot 1/2(H_2O)$
Activated carbon injection	ID: M-103 Type: Mixer	
Baghouse filter	ID: F-101 Type: Stream separator	Conventional solid split fraction: 1 Non-conventional solid split fraction: 1

Table B. 5. Scenarios 2 and 3 equipment specifications details simulated in Aspen

Process/equipment	Process/equipment Aspen Plus V11	Specification in Aspen
Primary shredding	ID scenario 2: CR-201 ID scenario 3: CR-301 Type: Crusher	Crusher type: Gyratory Breakage function: US Bureau of Mines (Aspen built-in information) Maximum particle diameter: 150 mm
Screening*	ID scenario 2: S-201 Type: Screen	Screen function: Ideal Cut size for 50% value of grade efficiency curve: 25 mm
Magnetic separator	ID scenario 2: S-202 ID scenario 3: S-301 Type: Separator	Iron split fraction calculated with calculator block FE-CAL according to material recovery percentage presented in chapter 3)
Eddy current separator	ID scenario 2: S-203 ID scenario 3: S-302 Type: Separator	Aluminium split fraction calculated with calculator block NOFE-CAL according to material recovery percentage presented in chapter 3)
Air classifier	ID scenario 2: A-201 ID scenario 3: A-301 Type: classifier	Method: PLITT classification function (Aspen built-in model for classifiers performance correlation developed by Canadian Institute of Mining, Metallurgy and Petroleum CIM) Classification characteristic: particle density Cut density: 2600 kg/m ³ (Value according to incoming glass density reported at Aspen Plus properties) Separation sharpness: 0.8
Near infrared technology	ID scenario 2: S-204 ID scenario 3: S-303 Type: Separator	Paper split fraction calculated with calculator block NIR-CAL according to material recovery percentage presented in chapter 3) Plastic split fraction calculated with calculator block NIR-CAL according to material recovery percentage presented in chapter 3)
Secondary shredding	ID scenario 2: CR-202 ID scenario 3: CR-302 Type: Crusher	Crusher type: Gyratory Breakage function: US Bureau of Mines (Aspen built-in information) Maximum particle diameter: 100 mm
Drying	ID scenario 2: R-201 ID scenario 3: R-301 Type: Stoichiometric reactor	Temperature: 150°C Pressure: 1.013 bar Same reactions as drying process in scenario 2 (R-101)
Inert separation	ID scenario 2: CY-201 ID scenario 3: CY-301	Conventional solids split fraction: 1

Process/equipment	Process/equipment Aspen Plus V11	Specification in Aspen
	Type: Stream split	
Steam separator	ID scenario 2: D-201 ID scenario 3: D-202 Type: separator	Mixed H ₂ O split fraction: 1
Decomposition	ID scenario 2: R-202 ID scenario 3: R-302 Type: Yield reactor	Temperature: 450 °C Pressure: 1.013 bar Components yield according to calculator DECO-CAL
Pyrolysis	ID: R-103 Type: Gibbs reactor	Phase equilibrium and chemical equilibrium at 1.013 bar and 450°C
Ash separation	ID: D-102 Type: separator	Non-conventional solid ash split fraction: 1
Gasification	ID scenario 2: R-204 ID scenario 3: R-304 Type: Gibbs reactor	Phase equilibrium and chemical equilibrium at 1.013 bar and 900°C
Combustion	ID scenario 2: R-205 ID scenario 3: R-305 Type: Gibbs reactor	Phase equilibrium and chemical equilibrium at 1.013 bar and 1000°C
Selective non-catalytic reduction	ID scenario 2: R-206 ID scenario 3: R-306 Type: Stoichiometric reactor	Temperature: 1000°C Pressure: 1.013 bar Reactions: $2NO + 2NH_3 + \frac{1}{2}O_2 \rightarrow 2N_2 + 3H_2O$ $2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$
Boiler-1	ID scenario 2: E-201 ID scenario 3: E-301 Type: Heater	Outlet temperature: 140°C Pressure: 1.013 bar
Boiler-2	ID scenario 2: E-202 ID scenario 3: E-302 Type: Heater	Pressure: 52.8 bar Temperature: 420°C Specification varying water mass flow to absorb all heat delivered by Boiler-1 (DS-1)
Turbine	ID scenario 2: C-201 ID scenario 3: C-301 Type: compressor	Model: Turbine Isentropic type Discharge pressure: 0.15 bar(a)
Dry spray	ID scenario 2: R-207 ID scenario 3: R-307 Type: Stoichiometric reactor	Temperature: 140°C Pressure: 1.013 bar Reactions: $SO_2 + Ca(OH)_2 \rightarrow H_2O + CaSO_3 \cdot 1/2(H_2O)$
Activated carbon injection	ID scenario 2: M-203 ID scenario 3: M-303 Type: Mixer	
Baghouse filter	ID scenario 2: F-201 ID scenario 3: F-301 Type: Stream separator	Conventional solid split fraction: 1 Non-conventional solid split fraction: 1

*Screening process/equipment is exclusively for scenario 2.

B.3 Aspen Plus V11 simulation results

Table B. 6. Aspen Plus V11 mass balance for scenario 1 - Part 1

Stream Name	Units	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
Temperature	C	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	150.0	150.0	150.0	150.0	150.0	450.0	339.0	450.0	450.0	450.0	25.0	850.0	835.9	
Pressure	bar	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Mass Flows	kg/hr	113.6	155.7	85.0	464.0	18.5	2.1	104.1	24.6	9.8	977.4	105.6	871.8	360.4	511.4	511.4	871.8	871.8	52.9	818.9	4562.3	5381.2	5539.7	
PLASTICS	kg/hr	113.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	113.4	0.0	113.4	0.0	113.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PAPER	kg/hr	0.0	155.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	139.8	0.0	139.8	0.0	139.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SILICA	kg/hr	0.0	0.0	85.0	0.0	0.0	0.0	0.0	0.0	0.0	85.0	85.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	85.0
BIOWASTE	kg/hr	0.0	0.0	0.0	464.0	0.0	0.0	0.0	0.0	0.0	139.2	0.0	139.2	0.0	139.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IRON	kg/hr	0.0	0.0	0.0	0.0	18.5	0.0	0.0	0.0	0.0	18.5	18.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.5
ALUMINUM	kg/hr	0.0	0.0	0.0	0.0	0.0	2.1	0.0	0.0	0.0	2.1	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1
TEXTILES	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	104.1	0.0	0.0	93.7	0.0	93.7	0.0	93.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WOOD	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.6	0.0	21.6	0.0	21.6	0.0	21.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
YARDWAST	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.8	3.7	0.0	3.7	0.0	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H2O	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	360.4	0.0	360.4	360.4	0.0	0.0	360.4	283.1	0.0	283.1	0.0	692.3	692.3	
O2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	141.9	141.9	0.0	0.0	0.0	1062.6	175.5	175.5	
N2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	3.0	3.0	0.0	3.0	3499.7	3502.6	3502.6	
H2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	37.1	37.1	14.9	0.0	14.9	0.0	0.0	0.0	
ASH	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	52.9	52.9	52.9	52.9	0.0	0.0	0.0	52.9	
CO2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	281.0	0.0	281.0	0.0	1007.6	1007.6	
CO	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.8	0.0	10.8	0.0	0.0	0.0	
CH4	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	122.7	0.0	122.7	0.0	0.0	0.0	
SO2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	3.0	
H2S	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.0	1.6	0.0	0.0	0.0	
C	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	275.0	275.0	101.8	0.0	101.8	0.0	0.0	0.0	
S	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	1.5	0.0	0.0	0.0	0.0	0.0	0.0	
C6H6	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
NO2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
C6H6O	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
NO	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2
NH3	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CA(OH)2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
CALCI-01	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Table B. 7. Aspen Plus V11 mass balance for scenario 1 - Part 2

Stream Name	Units	23	24	25	26	27	28	29	30	31	32	FLUEGAS	MSW	SOLIDS
Temperature	C	25.0	850.0	150.0	25.0	150.0	25.0	150.0	25.0	420.0	56.3	150.0	25.0	150.0
Pressure	bar	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	52.8	0.2	1.0	1.0	1.0
Mass Flows	kg/hr	87.7	5627.3	5627.3	7.0	5634.3	0.4	5634.7	1537.4	1537.4	1537.4	5470.2	977.4	164.5
PLASTICS	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	113.6	0.0
PAPER	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	155.7	0.0
SILICA	kg/hr	0.0	85.0	85.0	0.0	85.0	0.0	85.0	0.0	0.0	0.0	0.0	85.0	85.0

Stream Name	Units	23	24	25	26	27	28	29	30	31	32	FLUEGAS	MSW	SOLIDS
BIOWASTE	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	464.0	0.0
IRON	kg/hr	0.0	18.5	18.5	0.0	18.5	0.0	18.5	0.0	0.0	0.0	0.0	18.5	18.5
ALUMINUM	kg/hr	0.0	2.1	2.1	0.0	2.1	0.0	2.1	0.0	0.0	0.0	0.0	2.1	2.1
TEXTILES	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	104.1	0.0
WOOD	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.6	0.0
YARDWAST	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.8	0.0
H2O	kg/hr	76.0	768.4	768.4	0.0	768.8	0.0	768.8	1537.4	1537.4	1537.4	768.8	0.0	0.0
O2	kg/hr	0.0	175.5	175.5	0.0	175.5	0.0	175.5	0.0	0.0	0.0	175.5	0.0	0.0
N2	kg/hr	0.0	3502.7	3502.7	0.0	3502.7	0.0	3502.7	0.0	0.0	0.0	3502.7	0.0	0.0
H2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ASH	kg/hr	0.0	52.9	52.9	0.0	52.9	0.0	52.9	0.0	0.0	0.0	0.0	0.0	52.9
CO2	kg/hr	0.0	1007.6	1007.6	0.0	1007.6	0.0	1007.6	0.0	0.0	0.0	1007.6	0.0	0.0
CO	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CH4	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SO2	kg/hr	0.0	3.0	3.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0
H2S	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C	kg/hr	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.0	0.0	0.0	0.0	0.0	0.4
S	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C6H6	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NO2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C6H6O	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NO	kg/hr	0.0	0.1	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0
NH3	kg/hr	11.7	11.6	11.6	0.0	11.6	0.0	11.6	0.0	0.0	0.0	11.6	0.0	0.0
CA(OH)2	kg/hr	0.0	0.0	0.0	7.0	3.7	0.0	3.7	0.0	0.0	0.0	3.7	0.0	0.0
CALCI-01	kg/hr	0.0	0.0	0.0	0.0	5.7	0.0	5.7	0.0	0.0	0.0	0.0	0.0	5.7

Table B. 8. Aspen Plus V11 mass balance for scenario 2 - Part 1

Stream Name	Units	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Temperature	C	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	150.0	150.0
Pressure	bar	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Mass Flows	kg/hr	113.6	155.7	85.0	464.0	18.5	2.1	104.1	24.6	9.8	977.4	170.3	807.1	13.2	793.9	1.4	792.6	45.1	747.4	25.2	722.3	722.3	26.7
PLASTICS	kg/hr	113.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	113.6	19.7	93.9	0.0	93.9	0.0	93.9	0.0	93.9	3.7	90.2	90.0	0.0
PAPER	kg/hr	0.0	155.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	155.7	26.9	128.7	0.0	128.7	0.0	128.7	0.0	128.7	21.5	107.2	96.3	0.0
SILICA	kg/hr	0.0	0.0	85.0	0.0	0.0	0.0	0.0	0.0	0.0	85.0	15.6	69.4	0.0	69.4	0.0	69.4	43.6	25.8	0.0	25.8	25.8	25.8
BIOWASTE	kg/hr	0.0	0.0	0.0	464.0	0.0	0.0	0.0	0.0	0.0	464.0	80.3	383.7	0.0	383.7	0.0	383.7	0.1	383.6	0.0	383.6	115.1	0.0
IRON	kg/hr	0.0	0.0	0.0	0.0	18.5	0.0	0.0	0.0	0.0	18.5	3.4	15.1	13.2	1.9	0.0	1.9	1.2	0.7	0.0	0.7	0.7	0.7
ALUMINUM	kg/hr	0.0	0.0	0.0	0.0	0.0	2.1	0.0	0.0	0.0	2.1	0.4	1.7	0.0	1.7	1.4	0.4	0.2	0.1	0.0	0.1	0.1	0.1
TEXTILES	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	104.1	0.0	0.0	104.1	18.0	86.1	0.0	86.1	0.0	86.1	0.0	86.1	0.0	86.1	77.5	0.0
WOOD	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.6	0.0	24.6	4.3	20.3	0.0	20.3	0.0	20.3	0.0	20.3	0.0	20.3	17.9	0.0
YARDWAST	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.8	9.8	1.7	8.1	0.0	8.1	0.0	8.1	0.0	8.1	0.0	8.1	3.1	0.0

Stream Name	Units	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	
H2O	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	295.8	0.0	
O2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ASH	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CO2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CO	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CH4	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SO2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H2S	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
S	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C6H6	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NO2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C6H6O	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NO	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NH3	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CA(OH)2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CALCI-01	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table B. 9. Aspen Plus V11 mass balance for scenario 2 - Part 2

Stream Name	Units	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Temperature	C	150.0	150.0	150.0	450.0	336.0	450.0	450.0	450.0	25.0	25.0	1000.0	992.2	25.0	1000.0	140.0	25.0	140.0	25.0	140.0	25.0
Pressure	bar	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Mass Flows	kg/hr	695.6	295.8	399.9	399.9	695.6	695.6	42.5	653.1	518.0	4139.1	5310.2	5379.3	76.3	5455.6	5455.6	4.5	5460.2	0.3	5460.5	1819.8
PLASTICS	kg/hr	90.0	0.0	90.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PAPER	kg/hr	96.3	0.0	96.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SILICA	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.8	0.0	25.8	25.8	0.0	25.8	0.0	25.8	0.0
BIOWASTE	kg/hr	115.1	0.0	115.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IRON	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.7	0.7	0.0	0.7	0.0	0.7	0.0
ALUMINUM	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.1	0.0	0.1	0.0
TEXTILES	kg/hr	77.5	0.0	77.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WOOD	kg/hr	17.9	0.0	17.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
YARDWAST	kg/hr	3.1	0.0	3.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H2O	kg/hr	295.8	295.8	0.0	0.0	295.8	227.6	0.0	227.6	0.0	0.0	558.0	558.0	76.0	634.4	634.4	0.0	634.7	0.0	634.7	1819.8
O2	kg/hr	0.0	0.0	0.0	108.0	108.0	0.0	0.0	0.0	120.6	964.1	380.4	380.4	0.0	380.2	380.2	0.0	380.2	0.0	380.2	0.0
N2	kg/hr	0.0	0.0	0.0	2.0	2.0	0.0	0.0	2.0	397.3	3175.0	3573.9	3573.9	0.0	3574.4	3574.4	0.0	3574.4	0.0	3574.4	0.0
H2	kg/hr	0.0	0.0	0.0	29.3	29.3	12.0	0.0	12.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ASH	kg/hr	0.0	0.0	0.0	42.5	42.5	42.5	42.5	0.0	0.0	0.0	0.0	42.5	0.0	42.5	42.5	0.0	42.5	0.0	42.5	0.0
CO2	kg/hr	0.0	0.0	0.0	0.0	0.0	224.9	0.0	224.9	0.0	0.0	794.6	794.6	0.0	794.6	794.6	0.0	794.6	0.0	794.6	0.0
CO	kg/hr	0.0	0.0	0.0	0.0	0.0	8.7	0.0	8.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CH4	kg/hr	0.0	0.0	0.0	0.0	0.0	99.1	0.0	99.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SO2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	2.3	0.0	2.3	2.3	0.0	0.1	0.0	0.1	0.0
H2S	kg/hr	0.0	0.0	0.0	0.0	0.0	1.2	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Stream Name	Units	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
C	kg/hr	0.0	0.0	0.0	216.9	216.9	77.5	0.0	77.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.0
S	kg/hr	0.0	0.0	0.0	1.1	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C6H6	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NO2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C6H6O	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NO	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.5	0.5	0.0	0.5	0.0	0.5	0.0
NH3	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CA(OH)2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.5	2.0	0.0	2.0	0.0
CALCI-01	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.4	0.0	4.4	0.0

Table B. 10. Aspen Plus V11 mass balance for scenario 2 - Part 3

Stream Name	Units	43	44	FLUEGAS	MSW	RDF	SOLIDS	SYNGAS
Temperature	C	420.3	56.3	140.0	25.0	25.0	140.0	900.0
Pressure	bar	52.8	0.2	1.0	1.0	1.0	1.0	1.0
Mass Flows	kg/hr	1819.8	1819.8	5386.6	977.4	722.3	73.9	1171.1
PLASTICS	kg/hr	0.0	0.0	0.0	113.6	90.2	0.0	0.0
PAPER	kg/hr	0.0	0.0	0.0	155.7	107.2	0.0	0.0
SILICA	kg/hr	0.0	0.0	0.0	85.0	25.8	25.8	0.0
BIOWASTE	kg/hr	0.0	0.0	0.0	464.0	383.6	0.0	0.0
IRON	kg/hr	0.0	0.0	0.0	18.5	0.7	0.7	0.0
ALUMINUM	kg/hr	0.0	0.0	0.0	2.1	0.1	0.1	0.0
TEXTILES	kg/hr	0.0	0.0	0.0	104.1	86.1	0.0	0.0
WOOD	kg/hr	0.0	0.0	0.0	24.6	20.3	0.0	0.0
YARDWAST	kg/hr	0.0	0.0	0.0	9.8	8.1	0.0	0.0
H2O	kg/hr	1819.8	1819.8	634.7	0.0	0.0	0.0	152.8
O2	kg/hr	0.0	0.0	380.2	0.0	0.0	0.0	0.0
N2	kg/hr	0.0	0.0	3574.4	0.0	0.0	0.0	399.3
H2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	45.2
ASH	kg/hr	0.0	0.0	0.0	0.0	0.0	42.5	0.0
CO2	kg/hr	0.0	0.0	794.6	0.0	0.0	0.0	183.5
CO	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	388.8
CH4	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.1
SO2	kg/hr	0.0	0.0	0.1	0.0	0.0	0.0	0.0
H2S	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	1.2
C	kg/hr	0.0	0.0	0.0	0.0	0.0	0.3	0.0
S	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C6H6	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NO2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C6H6O	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NO	kg/hr	0.0	0.0	0.5	0.0	0.0	0.0	0.0
NH3	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CA(OH)2	kg/hr	0.0	0.0	2.0	0.0	0.0	0.0	0.0
CALCI-01	kg/hr	0.0	0.0	0.0	0.0	0.0	4.4	0.0

Table B. 11. Aspen Plus V11 mass balance for scenario 3 - Part 1

Stream Name	Units	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Temperature	C	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	150.0	150.0	150.0	150.0
Pressure	bar	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Mass Flows	kg/hr	113.6	155.7	85.0	464.0	18.5	2.1	104.1	24.6	9.8	977.4	16.6	960.8	1.7	959.0	53.9	905.1	71.8	833.4	833.4	33.5	799.9	355.3
PLASTICS	kg/hr	113.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	113.6	0.0	113.6	0.0	113.6	0.0	113.6	23.4	90.2	90.0	0.0	90.0	0.0
PAPER	kg/hr	0.0	155.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	155.7	0.0	155.7	0.0	155.7	0.0	155.6	48.4	107.2	96.3	0.0	96.3	0.0
SILICA	kg/hr	0.0	0.0	85.0	0.0	0.0	0.0	0.0	0.0	0.0	85.0	0.0	85.0	0.0	85.0	52.4	32.6	0.0	32.6	32.6	32.6	0.0	0.0
BIOWASTE	kg/hr	0.0	0.0	0.0	464.0	0.0	0.0	0.0	0.0	0.0	464.0	0.0	464.0	0.0	464.0	0.1	463.9	0.0	463.9	139.2	0.0	139.2	0.0
IRON	kg/hr	0.0	0.0	0.0	0.0	18.5	0.0	0.0	0.0	0.0	18.5	16.6	1.9	0.0	1.9	1.2	0.7	0.0	0.7	0.7	0.7	0.0	0.0
ALUMINUM	kg/hr	0.0	0.0	0.0	0.0	0.0	2.1	0.0	0.0	0.0	2.1	0.0	2.1	1.7	0.4	0.2	0.1	0.0	0.1	0.1	0.1	0.0	0.0
TEXTILES	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	104.1	0.0	0.0	104.1	0.0	104.1	0.0	104.1	0.0	104.1	0.0	104.1	93.7	0.0	93.7	0.0
WOOD	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.6	0.0	24.6	0.0	24.6	0.0	24.6	0.0	24.6	0.0	24.6	21.6	0.0	21.6	0.0
YARDWAST	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.8	9.8	0.0	9.8	0.0	9.8	0.0	9.8	0.0	9.8	3.7	0.0	3.7	0.0
H2O	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	355.3	0.0	355.3	355.3
O2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ASH	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CO2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CO	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CH4	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SO2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H2S	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
S	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C6H6	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NO2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C6H6O	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NO	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NH3	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CA(OH)2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CALCI-01	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table B. 12. Aspen Plus V11 mass balance for scenario 3 - Part 2

Stream Name	Units	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Temperature	C	150.0	450.0	330.5	450.0	450.0	450.0	25.0	25.0	1000.0	991.6	25.0	1000.0	140.0	25.0	140.0	25.0	140.0	25.0	420.0	56.3
Pressure	bar	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	52.8	0.2
Mass Flows	kg/hr	444.6	444.6	799.9	799.9	49.8	750.1	550.1	4641.1	5941.3	6024.5	76.3	6100.9	6100.9	5.2	6106.1	0.4	6106.5	2039.9	2039.9	2039.9
PLASTICS	kg/hr	90.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PAPER	kg/hr	96.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SILICA	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	32.6	0.0	32.6	32.6	0.0	32.6	0.0	32.6	0.0	0.0	0.0
BIOWASTE	kg/hr	139.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IRON	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.7	0.7	0.0	0.7	0.0	0.7	0.0	0.0	0.0
ALUMINUM	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0
TEXTILES	kg/hr	93.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WOOD	kg/hr	21.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
YARDWAST	kg/hr	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
H2O	kg/hr	0.0	0.0	355.3	265.1	0.0	265.1	0.0	0.0	648.4	648.4	76.0	724.9	724.9	0.0	725.3	0.0	725.3	2039.9	2039.9	2039.9
O2	kg/hr	0.0	116.8	116.8	0.0	0.0	0.0	128.1	1081.0	421.9	421.9	0.0	421.7	421.7	0.0	421.7	0.0	421.7	0.0	0.0	0.0
N2	kg/hr	0.0	3.0	3.0	3.0	0.0	3.0	421.9	3560.1	3984.5	3984.5	0.0	3985.1	3985.1	0.0	3985.1	0.0	3985.1	0.0	0.0	0.0
H2	kg/hr	0.0	32.8	32.8	13.9	0.0	13.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ASH	kg/hr	0.0	49.8	49.8	49.8	49.8	0.0	0.0	0.0	0.0	49.8	0.0	49.8	49.8	0.0	49.8	0.0	49.8	0.0	0.0	0.0
CO2	kg/hr	0.0	0.0	0.0	262.9	0.0	262.9	0.0	0.0	882.9	882.9	0.0	882.9	882.9	0.0	882.9	0.0	882.9	0.0	0.0	0.0
CO	kg/hr	0.0	0.0	0.0	10.1	0.0	10.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CH4	kg/hr	0.0	0.0	0.0	115.0	0.0	115.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SO2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	2.3	0.0	2.3	2.3	0.0	0.1	0.0	0.1	0.0	0.0	0.0
H2S	kg/hr	0.0	0.0	0.0	1.2	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C	kg/hr	0.0	241.0	241.0	78.8	0.0	78.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.0	0.0	0.0
S	kg/hr	0.0	1.2	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C6H6	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NO2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C6H6O	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NO	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	1.2	0.0	0.6	0.6	0.0	0.6	0.0	0.6	0.0	0.0	0.0
NH3	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CA(OH)2	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.2	2.7	0.0	2.7	0.0	0.0	0.0
CALCI-01	kg/hr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.4	0.0	4.4	0.0	0.0	0.0

Table B. 13. Aspen Plus V11 mass balance for scenario 3 - Part 3

Stream Name	Units	FLUEGAS	MSW	RDF	SOLIDS	SYNGAS
Temperature	C	140.0	25.0	25.0	140.0	900.0
Pressure	bar	1.0	1.0	1.0	1.0	1.0
Mass Flows	kg/hr	6018.4	977.4	833.4	88.1	1300.2
PLASTICS	kg/hr	0.0	113.6	90.2	0.0	0.0
PAPER	kg/hr	0.0	155.7	107.2	0.0	0.0
SILICA	kg/hr	0.0	85.0	32.6	32.6	0.0
BIOWASTE	kg/hr	0.0	464.0	463.9	0.0	0.0
IRON	kg/hr	0.0	18.5	0.7	0.7	0.0
ALUMINUM	kg/hr	0.0	2.1	0.1	0.1	0.0
TEXTILES	kg/hr	0.0	104.1	104.1	0.0	0.0
WOOD	kg/hr	0.0	24.6	24.6	0.0	0.0
YARDWAST	kg/hr	0.0	9.8	9.8	0.0	0.0
H2O	kg/hr	725.3	0.0	0.0	0.0	183.4
O2	kg/hr	421.7	0.0	0.0	0.0	0.0
N2	kg/hr	3985.1	0.0	0.0	0.0	425.0
H2	kg/hr	0.0	0.0	0.0	0.0	51.9
ASH	kg/hr	0.0	0.0	0.0	49.8	0.0
CO2	kg/hr	882.9	0.0	0.0	0.0	210.9
CO	kg/hr	0.0	0.0	0.0	0.0	427.6
CH4	kg/hr	0.0	0.0	0.0	0.0	0.1
SO2	kg/hr	0.1	0.0	0.0	0.0	0.0
H2S	kg/hr	0.0	0.0	0.0	0.0	1.2
C	kg/hr	0.0	0.0	0.0	0.4	0.0
S	kg/hr	0.0	0.0	0.0	0.0	0.0
C6H6	kg/hr	0.0	0.0	0.0	0.0	0.0
NO2	kg/hr	0.0	0.0	0.0	0.0	0.0
C6H6O	kg/hr	0.0	0.0	0.0	0.0	0.0
NO	kg/hr	0.6	0.0	0.0	0.0	0.0
NH3	kg/hr	0.0	0.0	0.0	0.0	0.0
CA(OH)2	kg/hr	2.7	0.0	0.0	0.0	0.0
CALCI-01	kg/hr	0.0	0.0	0.0	4.4	0.0