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EXPERIMENTAL STUDY OF THE OPERATING CONDITIONS IMPACT ON FUEL BLENDS CO-GASIFICATION: ENVIRONMENTAL AND SOCIO-ECONOMIC ASSESSMENT

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Experimental study of the operating conditions impact on fuel blends co-gasification: environmental and socio-economic assessment

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Your talent determines what you can do

Your motivation determines how much you are willing to do

Your attitude determines how well you do it."

Lou Holtz.

ABSTRACT

Biomass is currently seen as a promising renewable energy source, vast and commonly produced worldwide, which can be sustainably utilized in the production of fuels and electric energy adding no carbon dioxide to the environment. As a path to maximize biomass energy efficiency, the mixture with other sources of residues such as municipal solid waste has proved to be of great interest. Although there are several processes through which this purpose can be attained, thermal conversion is the most talented featuring higher efficiencies and environmental profits. From all the methodologies included in thermal procedures, gasification has unveiled its potential and strengthened a solid position in what regards the conversion of residues. This is not only due to the valuable products obtained but also to the contribution to prevent the complete depletion of non-renewable sources of energy, alleviating the effects of their utilization.

Based on these motivations, the goal of the present thesis was to assess the environmental impacts of municipal solid wastes and biomass gasification in order to understand the position of this technique in the panorama of the thermal treatment of solid residues. To do that, a complete life cycle assessment was performed for the incineration, gasification and plasma gasification of municipal solid wastes using CML 2001 methodology, which evaluates eleven environmental impact categories. Also, it was possible to conduct a case-study for the gasification of biomass within the framework of a LIFE+ project (Ecorkwaste), in this case, a different approach being utilized. Socio-economic studies regarding the viability of this project and also of the innovative two-stage plasma gasification technique were conducted, to enforce a more cohesive and integrated assessment, rather than taking into account only the environmental impacts. To assess this, main economic indicators such as net present value, internal rate of return and payback period were estimated, as well dedicated hybrid importance-fulfilment matrixes were developed to account for the environmental, technical, economic and social aspects related to the techniques.

As main conclusions, incineration and two-stage plasma gasification depicted a sustainable profile, all the impact categories presenting negative results (meaning environmental credits), opposite to what was seen for regular gasification. In fact, although regular gasification revealed environmental burdens for global warming potential, abiotic depletion potential (fossil), ozone depletion potential and terrestrial ecotoxicity potential, it has also shown the best results for eutrophication potential, acidification potential, marine aquatic ecotoxicity potential and human toxicity potential when compared to the other techniques. Regarding efficiency, two-stage plasma gasification presented the best performance, the estimate of the electricity produced from the waste generated *per capita* showing a fair coverage of the electrical demand in distinct world areas. However, incineration and regular gasification also offered a realistic compromise between the environmental and the welfare aspects. Relative to the socio-economic approach of the two-stage plasma gasification technique, important remarks may be stressed: the environmental domain has shown to be the most important, followed by the technical and the economic spheres, whereas the social field was the less impacting under the utilized approach. Two main indicators were seen as the big drivers for this conclusion: the reduction of municipal solid waste landfill and the waste management sustainability increase.

RESUMO

A biomassa é atualmente vista como uma promissora fonte de energia renovável, ampla e comumente produzida em todo o mundo, que pode ser utilizada de forma sustentável na produção de combustíveis e energia elétrica, sem adicionar dióxido de carbono ao meio ambiente. Como forma de maximizar a eficiência energética da biomassa, a mistura com outras fontes de resíduos sólidos urbanos tem-se mostrado de grande interesse. Embora existam vários processos através dos quais essa finalidade possa ser alcançada, a conversão térmica é a mais auspiciosa, com maior eficiência e ganhos ambientais. De todas as metodologias incluídas nos procedimentos térmicos, a gaseificação revelou o seu potencial e estabeleceu uma posição sólida no que se refere à conversão de resíduos. Isto não se deve apenas ao valor dos produtos obtidos, mas também ao seu contributo no sentido de impedir a completa depleção de fontes de energia não renováveis, aliviando os efeitos da sua utilização.

Com base nestas motivações, o objetivo da presente tese foi avaliar os impactos ambientais da gaseificação de biomassa e resíduos sólidos urbanos, a fim de compreender a posição desta técnica no panorama do tratamento térmico de resíduos sólidos. Para isso, foi realizada uma avaliação completa do ciclo de vida para a incineração, gaseificação e gaseificação por plasma de resíduos sólidos urbanos utilizando a metodologia CML 2001, que avalia onze categorias de impacto ambiental. Além disso, foi possível realizar um estudo de caso para a gaseificação da biomassa no âmbito de um projeto LIFE+ (Ecorkwaste), sendo neste caso, utilizada uma abordagem diferente. Estudos socioeconómicos sobre a viabilidade deste projeto e também da inovadora técnica de gaseificação por plasma foram conduzidos para garantir uma avaliação mais coesa e integrada, em vez de considerar apenas os impactos ambientais. Para esta avaliação, os principais indicadores económicos como o valor atualizado líquido, a taxa interna de rentabilidade e o período de retorno foram estimados, bem como foram desenvolvidas matrizes híbridas de cumprimento-importância para estimar os aspetos ambientais, técnicos, económicos e sociais relacionados com estas técnicas.

Como principais conclusões, a incineração e a gaseificação por plasma exibiram um perfil de sustentabilidade, todas as categorias de impacto apresentando resultados negativos (ou seja, créditos ambientais), em oposição ao que foi visto na gaseificação regular. De facto, embora a gaseificação regular tenha revelado encargos ambientais para o potencial de aquecimento global, potencial de depleção abiótico (fóssil), potencial de destruição de ozono e potencial de ecotoxicidade terrestre, também demonstrou os melhores resultados para o potencial de eutrofização, potencial de acidificação, potencial de ecotoxicidade aquática marinha e toxicidade humana potencial, quando comparada com as outras técnicas. Quanto à eficiência, a gaseificação por plasma apresentou o melhor desempenho, a estimativa da eletricidade produzida a partir dos resíduos gerados *per capita*, mostrando uma boa relação com a procura elétrica em distintas áreas do mundo. No entanto, a incineração e a gaseificação regular também ofereceram um compromisso realista entre os aspetos ambientais e de bem-estar. Em relação à abordagem socioeconómica da técnica de gaseificação por plasma, observações importantes devem ser enfatizadas: o domínio ambiental mostrou ser o mais importante, seguido pelas áreas técnica e económica, enquanto o campo social foi o menos impactante na abordagem utilizada. Dois indicadores principais foram vistos como os grandes impulsionadores para esta conclusão: a redução do aterro de resíduos sólidos urbanos e o aumento da sustentabilidade da gestão de resíduos.

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Ana Ramos.

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ABBREVIATIONS

ADP – abiotic depletion potential

ANN – artificial neural networks

AP – acidification potential

APC - air pollution control

ASR – automotive shredder residues

BC – black carbon

BFB - bubbling fluidized beds

C&I – commercial and industrial

CAPEX – capital expenditures

CBF – circular fluidized bed

CCE - carbon conversion efficiency

CE – circular economy

CED – cumulative energy demand

CFB - circulating fluidized beds

CFD – computational fluid dynamics

CGE – cold gas efficiency

CH_4 – methane

CHP – combined heat and power

CO – carbon monoxide

CO_2 – carbon dioxide

DCB – dichlorobenzene

DEM - Discrete Element Method

DNS - Direct Numerical Simulation

EF – ecological footprint

EP – eutrophication potential

ER – equivalence ratio

EU - European Union

EU–28 – European Union (28 countries)

FAETP – freshwater aquatic ecotoxicity potential

FE – freshwater eutrophication

FRS – fossil resources scarcity

GWP – global warming potential

H_2 – hydrogen

H_2S – hydrogen sulfide

HCl - hydrochloric acid

HCN – hydrogen cyanide

HDPE – high density polyethylene

HHV – higher heating value

HM – heavy metals

HTP – human toxicity potential

IRR – internal rate of return

ISO – international standard organization

LCA – life cycle assessment

LCC – life cycle cost

LCI – life cycle inventory

LCIA – life cycle impact assessment

LES - Large Eddy Simulation

LHV – lower heating value

M € - million euro

MAETP – marine aquatic ecotoxicity potential

ME – marine eutrophication

MSW - municipal solid waste

N_2 - nitrogen

NGO – non-governmental organization

NH_3 - ammonia

NMVOC – non-methane organic volatile compounds

NO – nitrogen oxide

NOx – nitrogen oxides

NPV – net present value

ODP – ozone depletion potential

OPEX – operational expenditures

PAH - polycyclic aromatic hydrocarbons

PBP – payback period

PCDD/F - polychlorinated dioxins and furans

PE - polyethylene

PET – polyethylene terephthalate

PM – particulate matter

PO_4 - phosphate

POCP – photochemical ozone creation potential

PS - polystyrene

PVC – polyvinylchloride

R114 – dichlorotetrafluoromethane

RANS - Reynolds-averaged Navier-Stokes

RDF – refuse derived fuel

SBR - steam-to-biomass ratio

SETAC – Society of environmental toxicology and chemistry

SO_2 – sulphur dioxide

SOx – sulphur oxides

SRF – solid recovered fuel

TA – terrestrial acidification

TETP – terrestrial ecotoxicity potential

WtE – waste-to-energy

Chapter 1 - Introduction

1.1. Relevance and Aims

In the view of circular economy, waste should be considered as resources in order to accomplish a more sustainable society and way of living. The concept of Waste-to-Energy (WtE) is one of the possible approaches to apply so as to convert the residues created on several different sectors into the most valued asset nowadays: energy.

Among all the distinct waste streams, municipal solid waste (MSW) has become a massive issue along the years partly due to the exponential populational growth in the last decades which produces higher amounts of residues day-by-day, and partly due to the technologically advanced society which, by a progressive and fast-passed evolution, generates debris which are more complex and difficult to treat [1-3]. The EU's economy uses 16 tonnes of materials per person per year and produces up to 2.5 billion tonnes of waste every year. On average, only 40% of our solid waste is re-used or recycled, while the rest is sent to landfill or incineration [4]. All the landfilled waste has a huge impact on the environment, causing potential soil, water bodies and air pollution, as well as greenhouse gas emissions that contribute to climate change. Also, significant material losses are seen, which is a particular problem for EU, highly dependent on imported raw materials. Although it has been decreasing in the last decade, waste disposal in landfills is still the most common option for waste management in most countries of the EU [5]. Landfill is the oldest form of waste treatment and comparative studies of the several possible means of waste management have shown that landfilling is the cheapest option in terms of exploitation and capital costs [6]. However, landfills cause a large impact on the environment and public health, as well as the present and future land uses may become limited and devalued if the landfill activity increases. To tackle this issue, the European Union has established well-defined waste management policies, preconizing preventive as well as reducing measures, aiming to take control over the increasing amount of solid residues nowadays [7]. Environmental regulations and directives claim for sustainable solutions to this problem, regarding the implementation of new technologies besides using the existing ones, to assure environmental quality and aiding to meet the set goals [8-12].

The EU's Seventh Environment Action Programme (also known as General Union Environment Action Programme to 2020) has identified the following EU priority objectives, among others: to safeguard the Union's citizens from environment-related pressures and risks to health and well-being, and to maximize the benefits of EU's environment legislation by improving implementation [13]. In that sense, the aim of Landfill Waste Directive (1999/31/EC) is to prevent or reduce as far as possible the negative effects on the environment from the landfilling of waste, by introducing stringent technical requirements for waste and landfills [4]. Moreover, the Waste Framework Directive (Directive 2008/98/EC) is the roadmap that the European Community should follow in order to reduce the environmental and health impacts of waste. As stated in the Waste Framework Directive, the first objective of any waste policy should be to minimize the negative effects of the generation and management of waste on human health and the environment [14]. This Directive specifies that the hierarchy shall apply as a priority order in waste prevention and management: prevention first, followed by preparing for re-use, recycling, energy recovery, and disposal as the less recommended waste management option. So, the member states shall take appropriate measures to encourage the prevention or reduction of waste production and its harmfulness. This may be potentially achieved recovering waste by means of recycling, re-use or by the use of waste as a source of energy for instance [15]. Besides, in 2014 the European Commission amended several waste directives in order to review the EU's waste management targets, to limit energy recovery to non-recyclable materials and also to limit landfilling to non-recoverable waste [16].

This being said, it is essential to focus the research on the development of new environmentally friendly technologies and solutions, in order to minimize waste disposal in landfills and its effects on human health and the environment. Furthermore, the roadmap to a resource efficient Europe sets out a framework for the design and implementation of future actions that supports the shift towards sustainable growth via a resource efficient and low-carbon economy [15]. Turning waste into a resource is one key to a circular economy and the following milestone has been set: "By 2020, waste is managed as a resource. Waste generated per capita is in absolute decline. Recycling and re-use of waste are economically attractive options for public and private actors due to widespread separate collection and the development of functional markets for secondary raw materials. More materials, including materials having a significant impact on the environment and critical raw materials, are recycled. Waste legislation is fully implemented. Illegal shipments of waste have been eradicated. Energy recovery is limited to non-recyclable materials, landfilling is virtually eliminated and high-quality recycling is ensured" [17].

As the experimental studies for enhancing these techniques are highly resource- and time-demanding, simulation tools have become very convenient to predict the optimal parameters and the heating content of the final products, as confirmed by the growing number of related literature [18]. Computational methods reduce the time needed to design and implement each experiment, by using mathematical approaches and developing specific codes regarding the type of feedstock, the operational conditions of the technique itself and the characterization of the final products, among other parameters.

In order to assess the environmental performance of the WtE techniques, tools such as the life cycle assessment (LCA) methodology are very useful. LCA compiles and appraises the potential inputs, outputs and environmental impacts of the system through its life cycle [19], enabling the identification of the most jeopardizing processes and the opportunity to intervene in them, as well as highlighting the environmentally beneficial procedures. This is ever more required as it is important to estimate the gaseous emissions or the landfilling of the residual solid portion (among other) of these techniques [20, 21], promoting the compliance with the EU regulations. LCA also allows to account for the recovery of valuable materials, as the sub-products achieved for the WtE. These products may be used as raw materials, decreasing the environmental burdens associated to the thermal techniques [22, 23] and preventing the use of natural resources. Raw materials availability for the European industry system is becoming more problematic as shown by a recent report published by the European Commission [24], identifying a periodically updated list of critical raw materials, a major part of them being present in the products attained from the treatment of municipal solid waste through WtE, such as the natural ores composing the fossil fuels' share in electricity. The sustainable management of waste is, thus, important to prevent the loss of these materials and to mitigate the growing shortage of resources.

All the new knowledge about the possible waste management options raises issues regarding the social acceptance of the renewable energy technologies at urban, regional or even national scale [25]. Some of the main constrains associated with a new WtE facility are related to air pollution, soil and water contamination, noise and smell, social disamenity, unaesthetically landscapes and land use changes [26]. So, rather than presenting only the environmental results, the social and economic aspects of every waste management strategy also constitute important factors to take into account [27]. The life cycle cost (LCC) analysis and a socio-economic methodology reinforce the advantages of the WtE assessment, also aiding in the decision-making process.

Based on these motivations, the goal of the present thesis was to investigate the impacts of gasification-based technologies as waste-to-energy schemes, for the management of municipal solid waste, biomass streams or mixtures of these in order to implement the principles of sustainability and circular economy. All the work was developed in an attempt to achieve the most efficient and environment-friendly process, nevertheless the technical, economic and social spheres were also taken into account.

1.2. Outline

This thesis is organized in seven chapters. Chapter 2 presents a bibliographic review of the co-gasification of biomass and wastes, including pre-treatment processes, effect of the operational conditions, synergistic mechanisms among the co-fuels and recent advances in the technique. Chapter 3 compiles the main publications on numerical modelling of gasification since the beginning of the century, distinguishing kinetic models, thermodynamic equilibrium models, computational fluid dynamic models (CFD) and artificial neural network models (ANN). Both chapters helped to recognize the research gaps in this area so that an aligned strategy could be set for the subsequent part of the thesis.

Chapters 4 and 5 describe the life cycle assessment of waste-to-energy techniques at low and high temperatures, respectively. In Chapter 4, the environmental impacts of both incineration and regular gasification are evaluated for the treatment of municipal solid wastes, being then compared. Also, the environmental assessment of a case study for a biomass gasification plant is presented. In Chapter 5, a parallel assessment is performed for two-stage plasma gasification of municipal solid wastes, the results being later compared to the low temperature techniques. Also, an estimate of the electricity production from the waste generated *per capita*, using the thermal techniques assessed is performed.

Chapter 6 presents the socio-economic feasibility study for both regular gasification of biomass and two-stage plasma gasification of municipal solid wastes. This was done by means of a hybrid fulfilment-importance matrix specifically developed for each case. The life cycle cost analysis of both techniques is also detailed.

Chapter 7 comprises a global review of the work and the main conclusions. It also addresses possible work that can be considered in the future.

Chapter 2 – State of the Art

The content of this chapter may be cited as: Ramos, A., E. Monteiro, V. Silva and A. Rouboa (2018). "Co-gasification and recent developments on waste-to-energy conversion: A review." Renewable and Sustainable Energy Reviews **81**: 380-398.

2.1. Gasification as a Waste-to-Energy technique

In order to comply with the comfort and wealth needs of the nowadays' society, the growing energetic demand is mainly attained through the use of fossil fuels [28]. This constitutes an environmental concern since the extraction and transformation of fossil fuels depletes the planet's natural reservoirs, also generating greenhouse gases which are toxic and harmful to living beings, as well as detrimental to the built environment and heritage. The conversion of distinct feedstocks such as waste, biomass or even their blends is a possible alternative to these situations, sustainably generating energy from materials that are prone to disposal [29-32].

Innovative methodologies are being proposed which integrate several sectors and possibilities [33-36]. However, thermochemical methods still provide a promising double-benefit approach for this issue: they reduce the disposal of residues, while taking advantage of their calorific content and emitting lower noxious substances [37-42]. Among the conventional thermochemical methodologies, gasification is one of the most well-known waste-to-energy techniques [39, 42-55]. Gasification involves the exposure of residues to high temperatures, which break down molecules into their elements in an oxygen-deprived atmosphere, producing a final gas composed of H_2, CO, CO_2 and short-branched hydrocarbons (as well as ash and char) which may be subsequently used for the production of power, chemicals, hydrogen and liquid fuels [54, 56]. The energy recovered through this process is higher than that of other thermochemical techniques such as combustion and pyrolysis [57].

More specifically, gasification is the thermochemical conversion of carbon-based feedstock into a combustible gas through the controlled supply of a gasification agent [58, 59] changing the chemical structure of the fuel particles due to the high temperatures (> 700ºC) reached in the process [60]. The main sequence of events is: i) pyrolysis/devolatilization at low temperature, where thermal cracking reactions, mass and heat transfer phenomena are responsible for the production of liquid and gaseous fractions as well as tar; ii) decomposition of these products by additional heat supply (either catered by combustion inside the reactor or by external sources), giving rise to a gaseous mixture of smaller molecules; iii) char gasification, resulting in the producer gas (composed of CO, CO_2, H_2 and light hydrocarbons) [61]. This technique produces syngas with higher commercial value, that may later be used as a feedstock for the chemical industry, or as a fuel for efficient production of electricity and/or heat [47, 62-66]. This gas is mainly composed of CO, CO_2, H_2, H_2O and CH_4, but also contains trace amounts of some other hydrocarbons, inert gases (from the gasification agent – air, oxygen, steam, CO_2 or mixtures of these) and contaminants (small char particles), and is accompanied by ashes and tars formed in gasification [64].

The first commercial gasifier for solid fuels was established in 1839 and later adapted for industrial purposes. Automotive applications demanded new energy production structures and solutions that promoted the use of compact gasifiers, also massively used during World War II due to the shortage of petroleum. After this period, liquid fuels became available again and gasification as a means to produce fuels declined until an energy crisis settled. Later, around 1970, small-scale reactors for wood and charcoal appeared and preconized coal gasification for heat and electricity production [67]. Among the internationally known environmental concerns raised in the 1990's, renewable energies took the spotlight and alternative fuels such as biomass and wastes became an option for gasification feedstocks [68, 69].

Sansaniwal et al. [53] published a recent review on biomass gasification, in which each type of gasification reactor was scrutinized, explaining the kinetics involved in each stage as well as highlighting gasification advantages, major drawbacks and barriers. The authors compiled previous studies and performed a roadmap concerning the actual state of biomass gasification, its technological advances as well as its foreseen perspectives in terms of syngas quality and future applications. Siedlecki and de Jong [70] tackled syngas cleaning issues aiming to achieve a final product suitable for the required purpose and within the legal limits of emissions and environmental charges. Different bed materials and experimental conditions were tested as well as distinct feedstocks, from woody and agricultural residues to energy crops, while syngas production and quality were monitored throughout the experiment. Other studies also report strategies for a cleaner syngas and high-performance gasification [55]. Parthasarathy and Narayanan [39] carried out a review on the major works on biomass steam gasification and the parameters influencing hydrogen production in the process, namely biomass type, particle size, temperature, steam-to-biomass ratio (SBR), catalyst action and sorbent-to-biomass ratio. The authors concluded that the hydrogen content varied based on biomass composition, with smaller biomass particles enhancing H_2 (hydrogen) yield due to larger surface area, promoting faster gasification reactions and higher carbon conversion efficiency (CCE). H_2 production was also seen to be upshifted due to the presence of steam and catalysts, and

CCE was improved by higher temperatures. The variation of the experimental parameters had already been reviewed by Guell et al. [51], fluidized beds being identified as appealing for several reasons such as wide particle size range, suitable average working temperatures and the possibility of adapting to the most adequate cleaning processes. Temperature was also assessed and was concluded to be a crucial factor determining gasification performance. Alauddin et al. [44] also reviewed biomass gasification in fluidized beds showing their versatility through an ability to relate the optimization of specific parameters to the desired final output, whether it was syngas composition, syngas yield, syngas lower heating value (LHV), tar and char content, carbon conversion or cold gas efficiency (CGE).

Besides flexibility, other advantages of biomass gasification may be found for specific cases, namely in remote areas [47] or for dedicated purposes [42, 52]. Umberto Arena [45] conducted similar studies but using MSW as feedstock, reinforcing the environmentally-friendly character shown by gasification, since it meets the legal limits for emissions and reduces landfill disposal of this type of residue, greatly contributing to the abatement policies for climate change. The author also points out some technological challenges such as reducing the cost of the syngas cleaning process or even improving energy conversion efficiencies to meet strategic market conditions in order to promote the technique as a direct competitor of conventional combustion systems. This has also been stated by Kumar et al. [42]. Ahmad et al. [43] evaluated the different types of biomass gasifiers and the most suitable operational parameters for each as well as the economic aspects of the process. Gasifier design and operational settings were suggested as the main contributors to calculate gasification costs. Gasification economic viability has also been assessed in other works [47, 52]. Some simulation tools were also evaluated for attaining optimal experimental conditions, their inputs proving to be useful in the parametrization study.

2.2. Feedstock pre-processing and feeding

Biomass chemical energy derives from the sun (through photosynthesis process), cellulose, hemicelluloses and lignin constituting its major components, although minor fractions of organic extractives and inorganic minerals are also present [71-73]. Cellulose is a polysaccharide with both crystalline and amorphous structures in its composition, while hemicellulose is a mixture of several monosaccharides with a basic structure and lignin is a three-dimensional polyphenolic substance composed of a multitude of branched phenylpropane units [74]. With such distinct compositions, the thermal decomposition characteristics, reactions and mechanisms of each of the major biomass components are expected to differ greatly [71, 74]. As a result of its varieties and biological diversity, biomass can be roughly categorized as mentioned on Table 1 [73]. A more detailed description can be found elsewhere [68].

Table 1 - Biomass varieties and examples.

Biomass Category	Variety and biological diversity
Wood and woody biomass	Stems, branches, leaves, bushes, chips, lumps, pellets, briquettes, sawdust, sawmill…
Herbaceous and agricultural biomass	Grasses, flowers, straws, stalks, fruits, fibers, shells, husks, pits…
Aquatic biomass	Marine or freshwater algae, macroalgae, microalgae, seaweed, lake weed, water hyacinth…
Animal and human wastes	Bones, meat-bone meal, chicken litter, animal manure, sponges….
Contaminated biomass and industrial wastes	MSW, demolition wood, refuse derived fuel, sewage sludge, hospital waste, paperboard, fiberboard, plywood, wood pallets and boxes…
Biomass blends	Blends from the above varieties

Biomass quantitative composition depends greatly on its species and origin [75]. Similarly, wastes can also be classified according to its provenance, as depicted in Table 2 [62].

Table 2 - Wastes major groups and origins.

Fuel type	Origin	Diversity
MSW	Households, small businesses and public institutions	Paper, cardboard, metals, textiles, organics, wood…
Commercial & Industrial waste (C&I)	Commerce and industries	Packaging, paper, metals, tires, textiles, biomass…
Refuse derived fuel (RDF)	Processing of MSW or C&I	Recyclables, non-combustibles…
Solid recovered fuel (SRF)	Higher quality RDF	Less contaminated recyclables and non-combustibles…
Automotive shredder residue (ASR)	Complex mixture of several residues	Rubber, foam, glass, wood, paper, leather, textile, sand, metals….

Both biomass and MSW can be perceived as mixtures of different residues, thus it is no surprise that elements of different size, shape and composition can be present. Actually, the most significant disadvantage regarding MSW utilization as a possible gasification fuel is its heterogeneity (accounting for a low volumetric energy density), which reduces WtE efficiency as well as the profitability of the process since pre-treatment steps are required and transportation is less competitive. Biomass and wastes represent irregular fuels in terms of their physical characteristics, namely their unorganized structure and shape, which can be a source of instability in the gasifier. Among the thermal conversion processes, gasification requires specific fuel characteristics (as low heating value, ash and moisture contents, among others) and oversight of the sub-process steps so that the produced syngas is clean and can comply with the foreseen utilizations. If waste and biomass are used as feedstock for gasification without any selection or homogenizing process, the quality of the final product as well as the operating conditions can be compromised [76, 77]. In order to surpass these issues, biomass and wastes must be converted into more uniform blends, and this is accomplished using processing techniques such as shredding, screening, sorting, drying, and torrefying, pelletizing or briquetting, so as to achieve an improved feedstock that can overcome the raw material handling difficulties [74, 78-80], as can be seen in Table 3. In the case of MSW a commonly applied processing technique is conversion to RDF, accounting for higher calorific value, lower pollutant emissions, lower ash content and easier storage, handling and transportation [81].

Table 3 - Pre-processing techniques for biomass and wastes.

Concerns	Feedstock	Pre-treatment	Refs.
Particle size	Agricultural and forestry wastes	Sorting, milling, crushing, grinding, sieving	[77, 82, 83]
	Waste tire and/or pine wastes		[84, 85]
	Lignite and forestry wastes		[86-88]
	Agricultural and plastic wastes		[89-91]
	Wood	Torrefaction	[92-95]
	Forestry wastes	Shredding	[96, 97]
	Waste tires, agricultural wastes		[98]
	Wastes and paper sludge	Crushing, grinding, sieving	[38, 99-101]
	Bagasse and sewage sludge		[102]
	Agricultural, forestry and plastic wastes	Pulverizing/smashing and sieving	[103-105]
Moisture content	Agro-industrial and forestry wastes	Drying	[82, 84, 86, 88, 89, 96, 97, 102, 104-109]
	Agricultural residues		[83, 98, 110]
	Wastes and paper sludge		[38, 99-101]
	Agricultural and plastic wastes		[84, 85, 91]
	Lignite and corncob		[111]
	Agricultural residues	Torrefaction	[79]
Density	Forestry and other wastes	Pelletization	[74, 110]
	Wood, straw and grass	Torrefaction and pelletization	[93, 112]
Heterogeneity	Forestry wastes, microalgae, oil palm fiber, and sawdust	Torrefaction	[74]
	MSW	Shredding	[62]
	MSW, RDF and wood	Riffling, milling and sieving	[109]
	Lignite and corncob	Milling and sieving	[111]
	Wood and plastics	Pelletization	[78]

Torrefaction is a thermochemical decomposition process where residues are processed at low temperatures in an inert gas environment near atmospheric pressure ending up with different properties than the raw material, becoming suitable for feedstock on combustion or gasification processes [112]. A recent work by Kuo et al. [113] compares H_2 production in the steam gasification of raw oil palm to torrefied oil palm and reports, at maximum steam-to-carbon ratio, hydrogen yield enhancement of *circa* 30g/kg fuel for the pre-treated samples.

As previously referred, uneven shape and size can be overcome with pretreatments that transform these raw materials into more homogeneous and uniform gasification feedstocks. Pelletization consists in a mechanical process that compacts biomass or wastes into uniformly sized particles with pellet or briquette shape, raising its density and lowering the moisture content [74]. These processed forms of waste result in higher calorific value, more homogeneous physical and chemical compositions, lower pollutant emissions, lower ash content, reduced excess air requirements during combustion and finally easier storage, handling and transportation giving access to a more affordable subsequent thermal conversion [62, 112, 114, 115].

Besides biomass and wastes origin, which contributes largely to their composition, moisture content is other of the chief factors governing gasification economic and energetic viability as it will define the amount of energy spent on drying the feedstock. Usually, moisture contents below 15% are reasonable, maintaining bed temperatures moderately stable but this depends on the type of gasifier utilized [64, 106, 116]. Variations in bed temperature can lead to fluctuations on syngas composition, compromising syngas quality and therefore its final applications. Generally, reduction of biomass moisture content aids at increasing energy efficiency, improving syngas quality and lowering conversion emissions [107]. Nevertheless, Hu et al. [117] and Dominguez et al. [118] reported increasing H_2 yields in wet MSW gasification for increasing moisture contents (up to 40%), possibly due to the *in situ* steam reforming of the volatile compounds which promotes hydrogen formation reactions. Both studies refer decreasing light hydrocarbons and CO yields with increasing moisture.

Upon heating, biomass releases its water content, absorbing some of the heat liberated from the chemical reactions in the gasifier [119]. LHV and higher heating value (HHV) are parameters used to describe heat production of a unit quantity of fuel during complete combustion, defining the energy chemically bound in the fuel. Figure 1 shows a negative correlation between the heating values of biomass and its moisture content, LHV approximating zero for a moisture content of 87% [67].

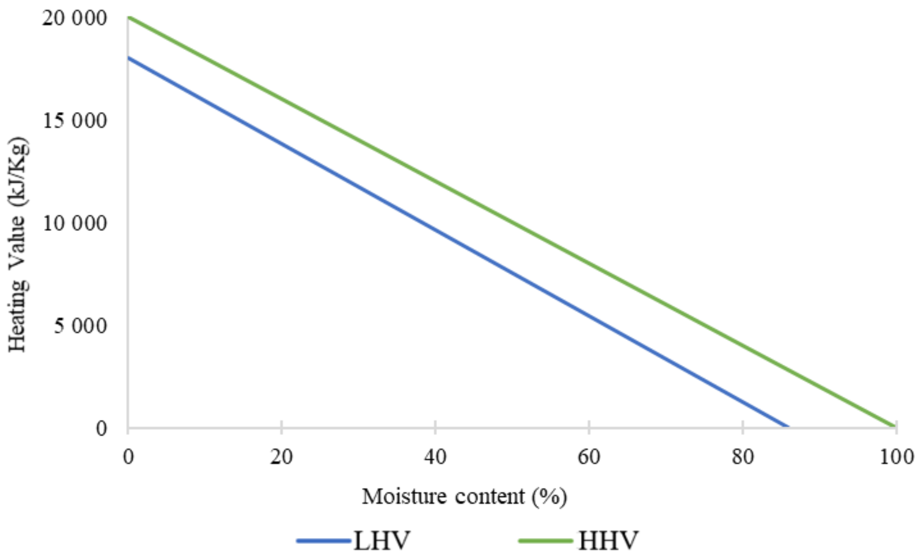

Figure 1 - Dependence of heating values on biomass moisture content.

Similarly, MSW shows the same tendency as depicted in Figure 2, where various organic wastes and their relative heating values are represented. There is a clear trend towards higher heating values, for materials with lower moisture contents [120].

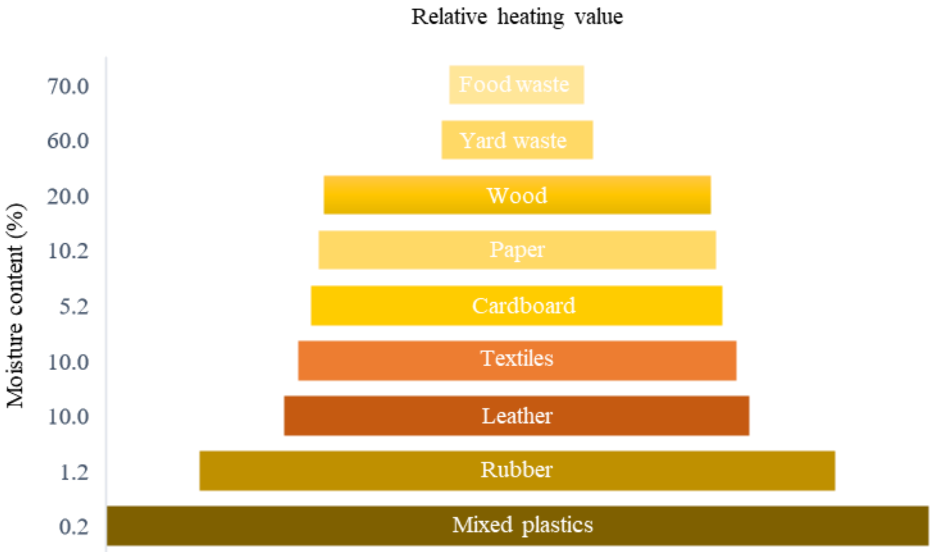

Figure 2 - Effect of moisture on heating value of MSW materials.

These findings confirm moisture content as one of the weak points of utilizing raw biomass and wastes as a fuel for WtE conversion. For the gasification process, higher moisture contents lead to reduced efficiencies, accounting for low CO (carbon monoxide) and H_2 production. Aside from the naturally occurring moisture in biomass and wastes, sometimes storage and transportation can raise this value, diminishing even more their native energy contents.

After this first approach, it is necessary to evaluate the mixing ratios which will be fed in the gasifier in order to achieve the final products with the desired composition. Depending on the type of biomass and waste utilized and furthermore their proportions, the fuel blend will follow different co-gasification mechanisms which afford distinct featured syngas. Also, along with the fuel pre-treatment before gasification, maintaining an adequate operability of the gasifier (to prevent agglomeration of bed material or ash clogging) and promoting residues removal (to preclude hardware erosion and corrosion) [121, 122] are also adequate procedures to take into account.

2.3. Gasification principles

Gasification is a known technology that has recently progressed to feedstocks like biomass and other solid wastes [68], in the view of a more environment-concerned society and preventing the depletion of fossil fuel reserves worldwide [69]. Indeed, gasification has been gaining notoriety due to the high efficiencies afforded [77] when compared to other thermochemical techniques and also to the increasing environmental restrictions imposed by governments and international agencies, which make it a prominent and viable technology as a cleaner alternative solution for waste treatment with energy recovery [45, 123]. Some of the advantages that gasification presents over traditional combustion are especially related to the potential of settling the adequate operating conditions of the specific reactors. The final product may be used in different applications, at the cost of only a fraction of the stoichiometric amount of oxygen (when compared to other methods), which limits the formation of dioxins, SO_2 (sulphur dioxide) and NO_x (nitrogen oxides) [62]. Recently, Sansaniwal et al. [53] published an in-depth review of biomass gasification, concerning technological developments (as well as hurdling to their dissemination), in which the authors underline all the advantages afforded by this conversion technique.

Biomass gasification occurs through a sequence of phenomena from drying, pyrolysis, oxidation and reduction [45, 124], involving the reactions presented in Table 4. Drying occurs at 100-200 ºC and the moisture content of biomass is reduced to <5%. Pyrolysis (or devolatilization) consists mainly in the thermal decomposition of biomass in the absence of oxygen or air, being the volatile matter reduced, which releases hydrocarbon gases and (if condensation at low temperatures occurs) liquid tars. Oxidation is the reaction between solid carbonized biomass and oxygen in the air, resulting in the formation of CO_2 (carbon dioxide). The hydrogen present in biomass is also oxidized generating water. CO may be generated if oxygen is present in sub-stoichiometric quantities and carbon is partially oxidized. Reduction occurs between 800-1000 ºC, in the absence or sub-stoichiometric presence of oxygen. The main reactions occurring during gasification are mostly endothermic, as follows [49, 53, 125].

Table 4 - Gasification reactions and related formation enthalpy.

<table>
<tr><th colspan="2">Oxidation Reaction</th></tr>
<tr><th>Volatiles</th><th>Char</th></tr>
<tr><td>$CO + {}^{1}/_{2}\,O_2 \rightarrow CO_2 \quad \Delta H = -283\ kJ/mol$
$H_2 + {}^{1}/_{2}\,O_2 \rightarrow H_2O \quad \Delta H = -242\ kJ/mol$</td><td>$C + {}^{1}/_{2}\,O_2 \rightarrow CO \quad \Delta H = -111\ kJ/mol$
$C + O_2 \rightarrow CO_2 \quad \Delta H = -394\ kJ/mol$</td></tr>
<tr><th colspan="2">Boudouard Reaction</th></tr>
<tr><td colspan="2">$C + CO_2 \leftrightarrow 2CO \quad \Delta H = -172\ kJ/mol$</td></tr>
<tr><th colspan="2">Water-Gas Reaction</th></tr>
<tr><th>Primary</th><th>Secondary</th></tr>
<tr><td>$C + H_2O \leftrightarrow CO + H_2 \quad \Delta H = -131\ kJ/mol$</td><td>$C + 2H_2O \leftrightarrow CO_2 + 2H_2 \ \Delta H = -90\ kJ/mol$</td></tr>
<tr><th colspan="2">Methanation Reaction</th></tr>
<tr><td colspan="2">$C + 2H_2 \leftrightarrow CH_4 \quad \Delta H = -75\ kJ/mol$</td></tr>
<tr><th colspan="2">Water-Gas Shift Reaction</th></tr>
<tr><td colspan="2">$CO_2 + H_2 \leftrightarrow CO + H_2O \quad \Delta H = -41\ kJ/mol$</td></tr>
<tr><th colspan="2">Steam Reforming Reaction</th></tr>
<tr><td colspan="2">$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad \Delta H = 206\ kJ/mol$
$C_nH_m + nH_2O \leftrightarrow nCO + \frac{(n+m)}{2}H_2$</td></tr>
<tr><th colspan="2">Dry Reforming Reaction</th></tr>
<tr><td colspan="2">$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2 \quad \Delta H = 247\ kJ/mol$
$C_nH_m + nCO_2 \leftrightarrow nCO + \frac{m}{2}H_2$</td></tr>
</table>

In fact, pyrolysis can be seen in two ways: as a thermal conversion process itself or as one of the first steps of gasification, in which case it may be called devolatilization. In this circumstance, it is important to examine carefully this step once it dictates the beginning of the thermal decomposition for any chosen fuel. Different kinetic models were proposed in order to describe possible mechanisms through which pyrolysis of biomass occurs [71]. Sharypov et al. [126] demonstrated that mixtures of several types of biomass and synthetic polymers could be converted by pyrolysis although distinct thermal evolution of the products was achieved for different biomass/plastic blending ratios. Couhert et al. [127] tried to understand this fact performing studies on biomass flash pyrolysis, in an attempt to predict the final composition of the produced gas, taking into account the initially selected biomass contents in cellulose, hemicelluloses and lignin. Major conclusions support that although celluloses from different origins produce similar gas yields (oppositely to what happens for hemicelluloses and lignins) they show different thermal behaviors during pyrolysis. This suggests it is impossible to predict gas yield for biomass during pyrolysis based on the knowledge of its composition on cellulose, hemicelluloses and lignin. In another experiment [128], the same authors confirmed that accurate predictions were impossible to make once pyrolysis would not follow an additivity law in what concerns the yields of these components. Possible explanations were given, mainly relying on their self-interaction during pyrolysis and also on the influence that minerals exert on pyrolysis reactions, favoring the production of CO_2 and lowering CO and CH_4 (methane) contents. Albeit more research is of foremost importance, a few correlations between the structural composition of biomass and some features of the produced gas are already known, more specifically that cellulose contributes to the volatile fraction and lignin to char, while hemicelluloses subscribe to both [129, 130]. A thorough understanding of the decomposition profile of biomass components and their contribution to volatile yield and composition and to char formation would subserve the knowledge of how blends of biomass and wastes perform under thermal conversion processes.

With so much reactions and possible mechanisms involved, it is reasonable that the overall conversion is severely influenced by fuel properties and operating conditions like the gasifying agent, gasification temperature and pressure, type of gasifier used and biomass feedstock [44, 45, 51, 63, 64, 131]. The influence of these parameters in the gasification process will be discussed in the next chapter.

2.3.1. Gasifier type

Several classes of gasifiers exist [45], but generally three main categories to classify them are utilized, according to some technical and operational features (Table 5) [51, 53, 62, 132]: fixed-bed, fluidized-bed and entrained-bed.

Table 5 - Major gasifier types and some related observations.

Gasifier Type	Sub-type	Temperature	Flows		Remarks
			Fuel	**Oxidant**	
Fixed Bed	Updraft	1000 ºC	downward	upward	Simple and robust, fuel size and moisture content restrictions
	Downdraft		downward	downward	
Fluidized Bed	Bubbling	800-850 ºC	upward	upward	Relatively low cost, ease of operation, good scale-up potential
	Circulating		upward	upward	
Entrained Bed	---	1200-1500 ºC	downward	downward	Higher costs, complex, fuel size restrictions, suitable for high capacities

Fluidized beds are the most commonly used gasifiers for biomass and wastes since they tolerate a wider particle size range, which is crucial for this kind of residues [62, 70, 133] depicting a flexible and robust technology [134]. So, in the view of a more comprehensive study, a brief description of the two main types of fluidized beds is due, namely bubbling fluidized beds (BFB) and circulating fluidized beds (CFB). BFB are suitable for a broad range of particle sizes and provide higher heat transfer rates, enabling homogeneous producer gas with low tar content. However, low solid conversion and reduced gasification efficiency limit their use for some syngas applications. CFB obviates these limitations assuring longer solid residence time, making use of a circulating loop. In this gasifier, a turbulent flow regime is triggered by the high fluidization velocity entraining the fuel particles, which are repeatedly stirred. This high stream recirculating behavior promotes a thorough mixing of the fuel particles improving heat and mass transfer, which results in a syngas with enhanced quality [45, 53].

Distinct operability conditions, together with imposed restrictions and allowances for each type of reactor lead to different energy requirements and promote syngas with diverse characteristics [131], since the way fuel and oxidizing agent come into contact is an important basis for syngas generation. This is easily explained by the occurrence of the involved reactions, which take place in diverse reactor zones, in the presence/absence of determined reagents and inducing different process temperatures. Therefore, the choice of a particular gasifier will request a specific combination of variables from the feedstock properties to the intended producer gas features [135]. Fluidized beds represent an attractive technology for the relatively low cost, ease of construction and operation, scale-up potential, as well as the high efficiencies attained [44, 54, 68, 80, 124, 136]. Nevertheless, the syngas obtained through this type of gasification is poor and requires intensive additional cleaning [51, 54] concerning tars formation and hydrocarbon reforming, once this type of gasifiers works below the biomass ash melting point (approximately 600-900 ºC).

Although it is complicated to put away all the other variables and compare the effect of the gasifier type by itself for a given biomass residue, there are some reports through which a few conclusions on this influence can be drawn (for instance comparing [137] to [116] or [138] for rice husk; [114] to [77] for grapevine pruning and sawdust wastes; [139] to [140] and [141] for wood sawdust). In the case of co-gasification of biomass and wastes, this is a much more complex task once a direct conclusion isolating the gasifier type from all the other affecting parameters (even for similar fuel blends) is almost impossible to reach, due to the myriad of blending ratio possibilities and most importantly to the synergy that combined fuels may present, which makes it harder to understand the gasifier contribution alone. Despite this, based on the available literature on biomass/waste co-gasification, a general comparison of fluidized and fixed beds reveals some interesting aspects, namely:

- the performance of fixed bed gasifiers seems to be more dependent on the biomass/waste ratio, 70-80% of biomass being the maximum allowed in the blends, aiming to avoid agglomeration and blockage problems in the equipment [87, 96, 142, 143].
- fluidized beds are also influenced by the fuels ratio but their results depend majorly on the gasifier temperature, 800-900ºC presenting the best gas yields and energy conversion [78, 103, 144].

2.3.2. Gasification bed material

Regarding the bed material it has a crucial role in fluidized beds since heat storage and transfer are important fluid phenomena depending on it. The heat produced during exothermic reactions is accumulated in the fluidized bed material and then becomes available for processes that require heat input. Bed materials can be inert or show catalytic activity during gasification process, in which case they can contribute to improved quality syngas achievement and/or tar abatement [78, 90, 145-147]. Ruoppolo et al. [78] reported the gasification of biomass/plastic pellets in a catalytic fluidized bed gasifier, to produce

H_2-rich syngas, using quartzite sand and a Ni-based catalyst. They concluded that the catalyst promoted H_2 formation, while drastically reducing methane concentration and slightly increasing CO_2 production. Miccio et al. [148] tested different catalysts in a fluidized bed gasifier for biomass conversion and confirmed that the Ni-based option showed the largest effectiveness in enhancing the H_2 yield as well as in tar reduction, allied to a better mechanical resistance. Chin et al. [90] also verified that the presence of a Ni-based catalyst promoted smaller activation energies in the co-firing of mixtures of rubber seed shell and plastic, when compared to gasification in the absence of this catalyst.

Bed material can also interact with the fuel in an undesirable way, changing its physical properties and leading to agglomeration, especially in the case of biomass as its conversion releases alkali compounds which, when in contact with silica bed material, generate alkali-silicates [54]. In this case, natural rock bed materials (dolomite, olivine, limestone, etc.) could be used instead of silica as they represent an affordable and easily accessible mean, albeit their lower mechanical strength can cause attrition [80, 149, 150]. Some alternative synthetic bed materials (for instance alumina) can substitute the former ones, with the disadvantage of being more expensive. In cases where this substitution is not possible, namely due the mechanical resistance issue, in-bed additives like kaolin, calcium oxide or carbonite and bauxite can help to reduce agglomeration [70, 151]. In-bed additives are also a good option to achieve tar reduction, as shown in Figure 3, where $Y_{\text{tar relative}}$ (%) represents the relation between tar production in each test to tar production in the absence of catalyst (referred as 100%). de Andrés et al. [145] concluded that, for the applied conditions, dolomite was the most active catalyst in tar removal from sewage sludge gasification, while olivine afforded the least significant result. Pinto et al. [147] also confirmed that dolomite afforded the best results on their co-gasification experiments with SRF and different types of biomass. Among other tested catalysts, the use of dolomite in optimized experimental conditions presented lower tar and H_2S contents, as well as an increase in gas yield.

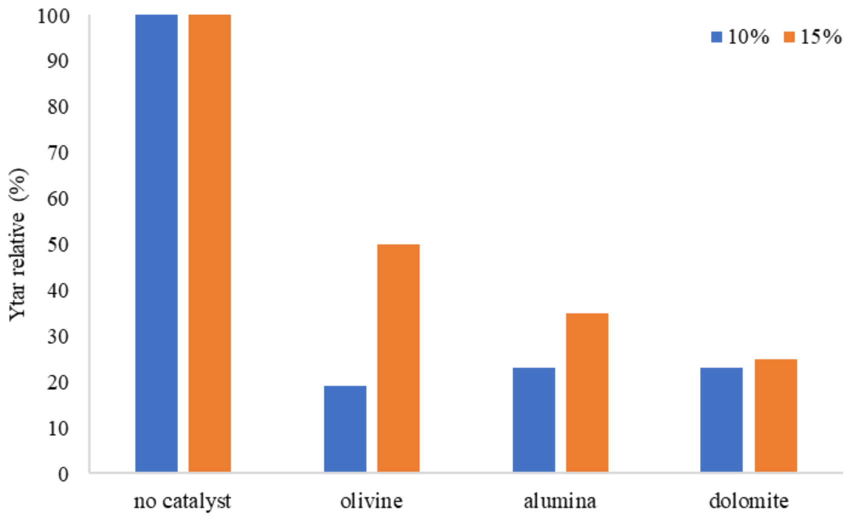

Figure 3 - Tar production for different amounts of catalysts [145].

Catalysts like Ni-based, iron-based, calcined dolomites and magnesites, zeolites and olivine act *in situ*, promoting chemical reactions that alter syngas composition and heating value [146, 152].

2.4. Synergistic effects

Several experimental studies on gasification of pure biomass [44, 51, 54, 64, 70, 124, 135, 153-155] and less on wastes [45, 125, 156, 157] have been conducted but reports on co-gasification of both are scarce. Probably this is due to a deprived knowledge of the whole process, namely the inputs introduced by the new blend concerning thermal behavior and kinetics of the decomposition, since a mixture of different chemical and physical compositions can be attained and it is difficult to predict and to interpret such characteristics. The diversity found in the properties of this new combined fuel, its blending ratio and possible interactive effects during co-gasification are still a matter of research, as will be referred throughout this chapter.

Synergistic effects can be perceived when the co-conversion products show improved results as compared to the ones achieved from the weighted average yields of the individual fuel components. Although not truly understood there are several mechanisms through which synergy can occur, therefore a more detailed discussion of events happening on the phases governing biomass conversion will be carried out, in an attempt to elucidate some less ascertained questions.

2.4.1. Blending ratio effect on syngas characteristics

As expected, different gasification fuels feature different syngas compositions. Hence, when mixing two (or more) feedstocks in different proportions, distinct characteristics and distribution of the components are expected in the producer gas. As already stated, blending biomass and wastes seems to afford higher yields of volatile products thus, the energy content of the produced syngas is expected to be higher than for biomass gasification alone.

Synergy amongst solid fuels is still a matter of controversy as some authors point out synergetic results and others do not show interactive effects. Among the co-conversion studies that resulted in no synergy are the ones held by Seidelt et al. [158] and Lin et al. [159] which conducted experiments on the degradation of tires composed of different rubber mixtures and were able to conclude that their behavior was the superposition of the thermal profiles of their main components, with no significant influence of the tire additives normally used. Deng et al. [160] performed co-pyrolysis of medical wastes at different mixing ratios and found no interaction between the components of some of the tested mixtures containing catheter. Regarding co-gasification, Straka and Bičáková [161] studied lignite and waste plastic mixtures with 10% to 20% of plastics in the blend, in a laboratory gasification unit under atmospheric pressure. A hydrogen-rich gas with HHV and other key properties fully comparable to lignite alone was achieved, depicting no synergy.

Oppositely, reports on the co-conversion of biomass and waste tires [85, 108] suggested synergy between the residues leading to an upgraded bio-oil as product, with lower amount of aldehydes and phenolic compounds, accounting for a more stable oil. This fact is explained by the higher contents of carbon and lower of oxygen and volatile matter present in the mixture. Also, the producer gas had higher H_2, lower hydrocarbons, CO_2 and CO yields as well as higher heating values. There are some other studies reporting interaction between different solid residues, exposed below.

Alvarez et al. [87] investigated the addition of plastics to wood sawdust in a two-stage pyrolysis/gasification experiment, in the presence/absence of a Ni-based catalyst. Results show that the gaseous content increases with increasing plastic fraction (being the maximum achieved for a mixture of 80% biomass and 20% polypropylene, in both cases) and for char and liquid contents, the reverse tendency is followed. The catalyst effect is more pronounced in the gas yield, showing that this additive plays an important role when more plastic is present in the blends. Regarding the plastic type, in the absence of catalyst, the high-density polyethylene (HDPE) produced the highest gaseous content and the smallest liquid and tar contents and, in the presence of catalyst, polypropylene performed accordingly. Other research groups [103, 126, 162] reported enhanced syngas obtainment and improved formation of gaseous products for raising plastic contents in biomass/plastic blends. A possible explanation relies on the easy and fast degradation of plastic products at high temperatures, when compared to biomass alone. The olefinic products from their thermal decomposition, together with some products from the biomass depolimerization can justify the increase on liquid fractions achieved, highlighting that the product distribution strongly depends on the biomass/plastic ratio. More recently, Yang et al. [82] also investigated the interaction between plastic residues and biomass conducting co-gasification of high-calorific-value plastics and rice straw in a carbon dioxide atmosphere. They verified a synergistic effect once the mixture performance was higher than the linear sum of the parent fuels, effects being strengthened for higher plastic ratios in the blend. Tavares et al. [163] also report synergistic effects on the co-gasification of polyethylene terephthalate (PET) and vine pruning, results showing that higher PET contents lead to a high quality syngas (LHV = 9.2 MJ/Nm^3), H_2 yields raising with PET share (Figure 4). Inversely, Oyedun et al. [164, 165] conducted experiments on the co-pyrolysis of polystyrene (PS) and bamboo, and found that increasing the plastic percentage in the blends would require more energy to complete pyrolysis, being this effect more pronounced in the case where no pre-mixing of the feedstock components is previously made.

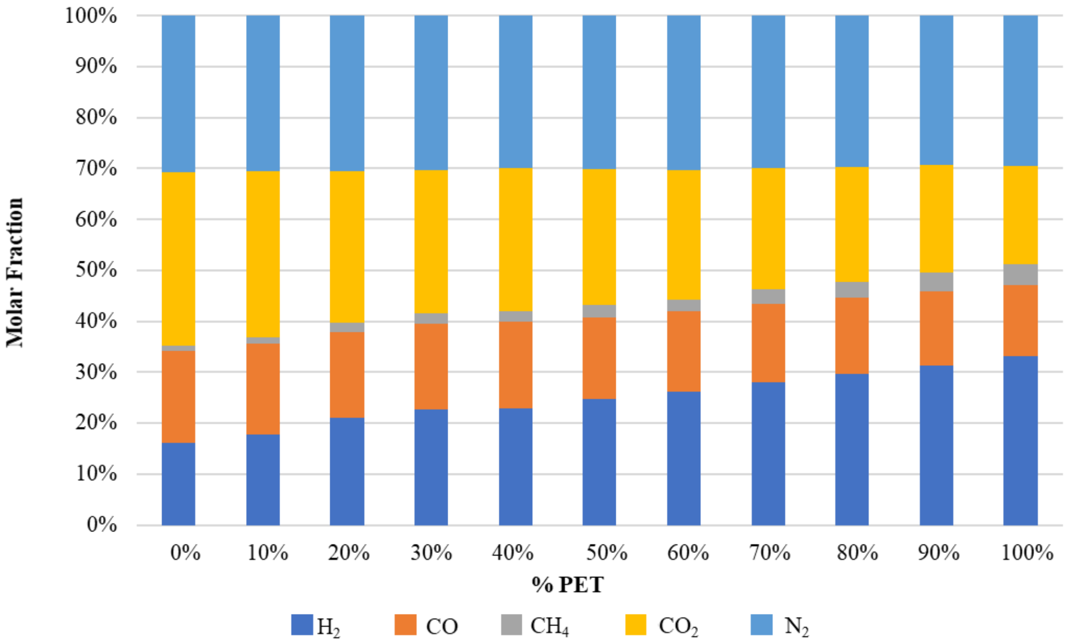

Figure 4 - The effect of PET fraction (in a PET-biomass blend) in syngas composition [163].

Kern et al. [166] co-gasified lignite with polyethylene (PE) in a dual fluidized bed pilot plant, with olivine as bed material. A range of different combination ratios (from 0% to 100% lignite) was tested and they showed improved syngas quality and reduced tar content even for low concentrations of lignite (33%), compared to single PE. A synergistic effect was encountered with higher CGE than for the sum of the contributing fuels. Saw and Pang [167] described interaction between lignite and wood, in a co-gasification experiment in a bubbling fluidized bed. Different ratios of each component were tested, the optimum blend consisting of 40% lignite and 60% pine sawdust. Producer gas yield and composition depicted non-linear correlations, tar yield and concentration being reduced with increasing lignite fractions.

Peng et al. [96] studied the thermal behavior of forestry waste and wet sewage sludge suggesting that their decomposition would be improved when adding biomass, parallel to what Zhang et al. [168] found for similar studies with sewage sludge and rice straw blends. Also, a marked decrease in the gas yield accompanied by an increase in the liquid yield when raising the sludge content was achieved. Variations on the wet sewage sludge content in the blends gave rise to different syngas composition (from 0% to 50% higher H_2 and CO concentrations were achieved, with decreasing CO_2 content; from 50% to 100% the opposite trends were revealed due to the drastic decrease in organic matter and carbon content feeding). Some authors [142, 143] established that for woody biomass/sewage sludge blends, sludge content should not surpass 30% (w/w) in order to minimize problems caused by ash (blocking the gasifier). Raising the sludge content led to reduced total fuel gas percentage and LHV, mainly due to the CO and H_2 content decrease in the blends. Torquato et al. [102] demonstrated that increasing bagasse content allows to augment the calorific value of the bagasse/sewage sludge blends, due to the volatile organic content, which in turn increases the HHV. For higher sewage sludge content, less energy was generated accounting for a temperature reduction inside the gasifier. Fang et al. [101] found an optimal 50:50 ratio for blends of paper sludge and MSW, as these presented the minimum activation energy value. Jeguirim et al. [110] observed that the 50:50 ratios for spent ground coffee and sawdust depicted higher volatile matter and lower moisture contents, presenting superior syngas quality features.

2.4.2. Possible mechanisms for synergy

Despite the debate about the influence of synergy effect during co-conversion, the major supported trend seems to be the catalytic effect. All the other possible explanations are assembled together and by now designated “other mechanisms”.

The catalytic effect of alkali and alkaline earth metals on pyrolysis and gasification of carbon has long been known [169, 170], sodium and potassium playing the major roles among these metals [75, 171, 172]. Actually, McKendry [173] reported the alkali metal content for some biomass materials (willow, cereal straw, bagasse and switchgrass amongst others) and it can be concluded that this parameter (in terms of sodium and potassium oxides) falls into roughly 4% to 16% of the total composition, for the selected biomass types. This alkali content affords higher surface area and porosity to biomass-char enhancing its gasification reactivity [174] and promoting catalytic activity when blended with other wastes [38, 98]. Given that biomass has a high content of these components and a significant amount of oxygen, it is known to be even more reactive than coal [175] once its char is continuously consumed during gasification leaving only trace residues at the end. Thus, it is somehow expected that co-gasification with other fuels will benefit from these features. Some authors stress that alkali elements potentiate agglomeration especially when chlorine is also present [70, 80, 136] compromising the operability of the gasifier, but measures to counteract this effect have already been established [80].

Lahijani et al. [98] found that 50:50 blending ratios of palm empty fruit bunch or almond shell and tire improved the conversion rate 10 and 5-times respectively, compared to pure tire residues. Treating biomass chars with acid to suppress the metal content afforded reduced gasification reactivities when compared to untreated biomass chars, proving that the alkali metals present in biomass samples promoted the reactivity of the blends, acting as catalysts. Such reduction was even higher in the case of empty fruit bunch, in agreement with its higher potassium content. Silva et al. [89] proceeded on the opposite way to attest the catalytic effect of potassium on sugarcane industry wastes. Potassium-enriched bagasse was obtained doping demineralized bagasse and thermal data suggested synergistic effects through catalysis to explain the higher reactivities found, when compared to the regular samples and their blends. Hu et al. [100] concluded that to some extent better combustibility results for paper mill sludge and MSW were achieved due to the combination of minerals in paper sludge and alkali metal in MSW, which gave rise to low melting point materials, easy to volatilize while promoting decomposition and combustion indirectly. Zhang et al. [176] performed co-liquefaction of secondary pulp/paper-mill sludge and waste newspaper in the presence of several catalysts and some synergistic effects were observed at various mixing ratios, possibly due to the inherent catalyzing potential of alkali and alkaline earth metals in paper sludge.

An additional advantage accomplished when performing co-gasification of biomass is the possible abatement of harmful substances containing sulfur and nitrogen, once the alkali and alkaline earth metals can form sulfates and capture these species. An example of literature reporting this double effect of alkali metals in biomass is given by Lin et al. [38], who studied the pyrolysis behavior and kinetics of oil-palm solid wastes, paper sludge and their blends. Evidences showed that increasing the oil-palm wastes ratio in the blends released greater amounts of volatiles from the organic matter, raising their reactivity. The authors explained these findings based on two events: the hydrogenation role of oil-palm wastes, and the secondary decomposition plus new char gasification promoted by the alkali and alkaline earth metallic species. Later, Lin and co-workers [99] performed more investigations on this matter and found that noxious emissions (SO_2, NO and CO_2) were reduced mainly through the influence of alkali and alkaline earth metals. At no extra cost, phenomena like slagging, corrosion and fouling also declined.

As stated earlier, besides the catalytic effects shown by mineral matter, synergy can occur through other ways. Despite the case of biomass and wastes is still insufficiently discussed in literature and much research is needed to disclose possible enlightenments on these interactions, it is known that in the co-conversion of biomass and coal two recognizable events support synergy: i) increased volatile matter yields with decrease in char yields; ii) and overall decrease in pollutant species [177]. Though thermal profiles of coal and the majority of residues are quite different, in the view of some resemblances between their carbonaceous structure and also their common counterpart in the herein mentioned co-conversion (biomass), some parallelism might be assumed and similar basis to interpret synergism might be taken as a starting point, regardless of all other potential hypothesis. Therefore, some reported biomass-waste studies [84, 85, 87, 101, 102, 104, 105, 108, 110, 178] may fall into this category.

Several authors investigated the co-pyrolysis of biomass and plastics reporting higher carbon and hydrogen contents, lower oxygen content and higher heating value [178], improved bio-oil yield and composition [179], as well as higher bio-oil heating value [97], higher amounts of liquid products and higher calorific value for the chars than for biomass alone [84], lower energy requirements [164] and lower activation energies [82, 83]. This synergetic effect led to a more stable oil and could be attributed to the hydrogen transfer from the cracking of polymer chains to biomass-derived radicals during thermal decomposition, which stabilized the formed radicals and improved condensable fractions, resulting in higher oil yields too. Reports on biomass and waste tire co-pyrolysis [85, 105, 108] revealed positive synergistic effects in bio-oil yields due to the radical interactions occurring between waste tires and biomass pyrolysis products, the production of water molecules being reported elsewhere to be due to biomass decomposition [180] and the increment in the oil proportion being a result of the hydrogen transfer from the polymer to biomass-derived radicals among the organic vapors [181]. For increasing tire masses, increased HHV of the produced oil was achieved, ameliorating the results obtained for biomass alone. Authors were also able to show that the addition of biomass inhibited the formation of polycyclic aromatic hydrocarbons (PAHs), compared to tire pyrolysis alone. Ahmed et al. [162] reported enhanced syngas, hydrogen and hydrocarbon yields as well as higher energy yield and thermal efficiency when adding woodchips to polyethylene. Somehow, this can be explained by the plastics acting as a hydrogen donor to radicals generated from biomass pyrolysis, which are then stabilized as well as the total hydrocarbons production increases. On the other hand, biomass char may contribute to the adsorption of volatiles from polyethylene, promoting hydrogen formation. Moghadam et al. [103] confirmed this trend and observed improved syngas production and conversion rates for increased polyethylene fraction in mixtures with palm kernel shell. As polyethylene contains higher volatile matter and lower ash content than biomass, its degradation at elevated temperatures is easier and faster than the degradation of biomass. Zhang et al. [104] investigated the fast co-pyrolysis of corn stalk and food waste, in the presence of a zeolite catalyst. Parameters like hydrogen to carbon effective ratio, yield of total organic products and the aromatics content revealed an apparent synergistic effect, once all had a non-linear increase during the process. Two main reasons for these events were the oxygen deliver by food waste for the conversion of corn stalk and, furthermore, the chain scission and cracking of long-chain organic matter in food waste due to the oxygenated compounds in the pyrolysis vapors released from biomass. Comparatively, Jeguirim et al. [110] found higher reactivity for blends of spent ground coffee and biomass when compared to each of its components, since parameters like apparent activation energy among others could not be expressed as the addition of parameters for each residue. Alvarez et al. [87] attributed enhanced gaseous content and hydrogen yield found in the co-gasification of polyethylene and biomass to synergetic effects between intermediate species formed in secondary cracking reactions generated via co-pyrolysis. This was also explained by Pinto et al. [144] who confirmed the formation of small molecular fractions through bond breaking in olefinic polymers. Çepeliogullar and Putun [91] stressed that higher temperatures and energies were necessary towards the decomposition of the biomass/PET mixtures than for the biomass/polyvinyl chloride (PVC) counterparts. A possible explanation is the aromatic ring present in PET’s structure, which raises the energy barrier to start pyrolysis.

From this list of reported works one can observe that synergy seems to be ruled by two major events: interactions among the pyrolytic vapor molecules denoting synergetic effect through radical processes, and hydrogen transfer from the polymer to biomass-derived radicals, stabilizing the formed radicals and improving products’ features.

2.5. Co-gasification products

Despite all the environmental advantages accomplished by the co-gasification of biomass and waste this process is not free from side products, some of them presenting harmful properties for animals, humans and the environment itself. As shown in previous sections, the producer gas composition is thoroughly influenced by feedstock type and origin, the type of gasifier and the operating conditions utilized. Thus, as secondary products the pollutants emitted during the process are also influenced by these parameters, for instance, hydrochloric acid, sulfur and nitrogen species, among others [182, 183].

2.5.1. Gaseous products

Wastes containing PVC are an important source of hydrochloric acid (HCl), since during combustion a big part of the chlorine is volatilized being released as HCl and also partly converted to chlorine, as in the case of co-firing MSW [184], both pernicious and corrosion-promoters. Chlorine is known to be the major contributor to the formation of polychlorinated dioxins and furans (PCDD/Fs) [185]. One of the measures to abate these emissions is the addition of calcium-based compounds, which are then calcined to porous forms capturing HCl by conversion into calcium chloride. Other concerning species are sulfur oxides (SOx), which are formed through the oxidization of sulfur containing compounds and contribute to acid rain problems. Sulfur levels on the feedstock may influence the content of hydrogen sulfide, depending on the gasification temperature and on the parent sulfur form on the feedstock (organic/inorganic) [186]. Similar techniques can be used to reduce their emissions, trapping them with calcium oxide resulting in calcium sulphate [187], sometimes leading to a chlorine and sulfur competition towards the calcium species. Other drawback of SO_x capture in the gaseous emissions is a possible increase of sulfates in the fly ashes, overtaking the regulated limits for these compounds [188]. Nitrogen species majorly produced during biomass gasification include NH_3 (ammonia), N_2 (nitrogen), NO_x and HCN (hydrogen cyanide), their concentrations and evolution depending on temperature and on the original nitrogen form in biomass [189]. Reports on nitrogen conversion during biomass and wastes gasification show that approximately 60% (average value) of the initial amount of N is converted to NH_3, the remaining part being converted to HCN and N_2 [133]. As NH_3 and HCN can be considered intermediates for nitrogen oxide species formation, this will be of major importance when considering NO_x reduction, using techniques such as oxygen limitation or de-NO_x, which permit reductions in the order of 50-80% [189-191]. In a recent study, Akkache et al. [192] found that adequately mixing the types of fuels for co-gasification can limit ammonia release as well as increasing the heating value of the obtained producer gas. Engvall et al. [193] approached some of these issues on a review work.

Particulate matter (PM) comprehends dust particles with different aerodynamic diameter, considering their distinct health effects. This way, PM_{10} and $PM_{2.5}$ (particles with diameters smaller than 10μm and 2.5μm, respectively) are the most referred PM categories, the first reaching bronchi and lungs, and the latter being able to penetrate into the gas exchange regions of these organs. There is a more severe PM category comprising ultrafine particles (diameters <0.1μm), which go as far as causing plaque deposits in the arteries, enabling atherosclerosis and cardiovascular problems [194]. In gasification processes, PM can originate from inorganic compounds, residual solid carbonaceous material and sometimes from elutriated bed material and catalysts. Besides the health concerns raised by PM emissions, restricted values for this co-product are allowed depending on the syngas final utilization as well as attempting to avoid problems like fouling, corrosion and erosion of the equipment [195, 196]. Several methodologies exist aiming to reduce or remove particulate matter from the producer gas, hot gas cleanup promoting increased efficiencies and enhanced syngas conversions, with particle removals that can go from 90% to above 99.5% [182, 196]. Also, the use of cyclone separators, recirculation of the bed material and barrier filters are suggested as possible techniques targeting PM removal [42].

2.5.2. Ashes

Ashes are formed during the thermal conversion of solid fuels and consist mostly of inorganic matter and impurities, its composition depending on factors like fuel type, origin and characteristics as well as the applied operating conditions. Biomass ash formation occurs mainly through vaporization, condensation and coagulation, in which the alkali metals and chlorides form different leachable fractions and a residue fraction composed of silicates and other species insoluble in mineral acids [197], which can difficult the co-gasification with wastes. Slagging and agglomeration are the two main obstacles posed by ashes, lowering the efficiency of the process as well as compromising the operability of the equipment [198, 199]. In this sense it is of great importance to reduce their formation and remove them from the system, which could be attained by using alternative bed materials and/or additives that increase their melting temperature, more expensive techniques such as preliminary leaching of ash-forming compounds from the feedstock, changing the combustor design [200] or even adjusting the type of blend when possible [192].

As a sub-product of thermal co-conversion, biomass ashes can be reused in applications such as soil amendment and fertilization, construction materials, adsorbents or production of ceramic materials [201, 202]. When utilized in soils, biomass ashes will regenerate the nutrients and main elements that had once been consumed for the growth of its parent biomass species [203, 204]. Civil engineering materials used in construction like cements and resembling products can be manufactured through the use of fly ash, which can act as an aggregate and as a cementitious component, altering their rheological characteristics and influencing their cost and energy consumption [204]. Also, bottom ashes are mainly composed of sand, which makes them easily usable in applications such as road construction and asphalt paving [202]. Biomass ashes have also been used in the manufacturing of minerals and ceramics [205-208].

Despite all these possibilities of ash reutilization, the environmental impacts of its production are still a matter of concern, once biomass ashes can pose serious air, water, soil and plant contamination problems on a scale-up scenario, due to the high water-soluble fraction [209]. Therefore, taking in consideration the high concentrations of heavy metals (HM), PCDD/Fs and PAHs adequate disposal methods should be established and controlled, in such a way that legal requirements are met for ashes and also for leachates [204, 210].

2.5.3. Simultaneous pollutants

Among what is released in the form of syngas and in the form of ashes, there are compounds present in both type of emissions, such as PCDD/Fs, PAHs and heavy metals, for instance. These compounds can reach humans through several exposure means like contacting with contaminated elements such as air, food (fish, vegetables, etc…) and water.

PCDD/Fs are a wide group of molecules with two aromatic rings and chlorine atoms at different positions, highly resistant to chemical degradation which augments exponentially their toxicity both for humans and environment. They can result from the waste used as fuel or from other occurring reactions during (co-)gasification, mainly under two proposed pathways: through small organic compounds acting as their precursors or through the oxidative breakdown of residual carbonaceous material [211]. In the case of fly ashes, both requirements are met adding also the presence of chlorine and metal ions, all together supporting PCDD/Fs formation. Reductive techniques such as using air pollution control devices [212] and controlling the amount of oxygen present can limit the formation of these species, furthermore oxygen-free atmospheres preventing dioxin formation [213].

PAHs are molecules with two or more fused aromatic rings, a structure that confers them native toxicity, with some of them reporting carcinogenic and mutagenic effects [214, 215]. Although the mechanism for their formation is not completely known, somehow it is shown to be related to soot nucleation and H-abstraction/acetylene-addition routes [216, 217]. PAH yields from biomass pyrolysis are dependent on the nature of the substrate but also on the conversion operational conditions such as temperature, residence time and thermal cracking reactions occurring in the reactor [218, 219]. Limiting the amount of PAHs present in fly ashes resulting from biomass gasification can be accomplished by burning them in a circular fluidized bed (CFB), a reduction efficiency of 99% being attained in some cases [210], leaving the ashes free of toxic organic substances so that they can be used as soil amendments or fertilizers.

Heavy metals comprise a vast group of elements (like As, Cd, Co, Cu, Cr, Hg, Mn, Ni, Pb and Zn) some of them essential to the human body normal functioning but very toxic if overexposure occurs. Probably the most noted heavy metals are mercury (Hg) and lead (Pb), since they are xenobiotic, owning no beneficial effect to human body but exerting highly harmful effects when accumulated in organs and tissues [220]. Heavy metals can follow distinct routes within the gasification process, depending on their chemical and physical properties but also on the presence of other pollutants: remaining in the bottom ash, being retained in the fly ash or vaporized and entrained with the raw gas like in the case of co-conversion of sewage sludge or MSW [221], wood waste, sewage and paper sludge, and manure [222]. This partition was studied for some metals and it could be seen that speciation occurs differently according to the element, under reductive and oxidative atmospheres [221]. Biomass or waste type along with operation conditions such as particle size, type of reactor and furnace temperature also influence metal partitioning [222]. In respect to control strategies, these are not straightforward each metal form requiring distinct abatement techniques, but some are coincident with the ones described for particulate removal, referring to metals in the bottom and fly ashes.

2.5.4. Tar

Tars are complex mixtures of single and multiple ring aromatic compounds and other hydrocarbons that originate from the breakdown of the complex polymers constituting biomass (cellulose, hemicellulose and lignin) [223] through a mechanism composed of three parallel reactions [224]. According to their properties and typical components, tars can be classified into different categories that further help to interpret their subsequent behavior and decomposition [225], like the ability to condense in the lines and equipment components compromising gasifier operability and syngas quality [183].

Biomass tars' likelihood to condense and adsorb can lead them to undergo polymerization reactions originating larger fragments that, when in contact with porous carbon can take part of the chemical bonds, disabling desorption. This can cause severe damages to equipment and installations, as well as implicate the performance of the overall process. The type and amount of inorganic matter present in the feedstock also contributes to the total yield of biomass tars formed, as components like alkali and alkaline earth metals can promote catalytic activity in reactions of cracking or reforming tars [226]. Biomass is prone to develop high release of tars on gasification, once it depicts high contents of hydrogen, oxygen and volatiles presenting several polar groups that raise the water solubility of the produced tars, making it necessary to use treatment procedures before its release in the environment. Besides biomass composition, several other factors may contribute to the formation of tars, such as type of gasifier, type of utilized fuel, particle size, temperature, gasifying agent and residence time, among others [44, 63, 64, 227]. When the combination of all these parameters is not sufficiently optimized or controlled, tar formation will be difficult to regulate, its final abatement showing vital importance for the process efficiency. The choice of the cleanup method depends on the type of end-use that the producer gas is destined to, e.g. direct combustion may take advantage of the presence of a certain amount of tar that can be converted into other compounds in opposition to synthetic fuel production, that request a cleaner syngas [45].

Two different approaches can be used regarding tars cleanup: primary methods (inside the gasifier) and secondary methods (syngas cleaning). In the case of primary methods, they include all the measures taken in the gasification step to prevent tar formation or convert it inside the gasifier by adjusting the experimental conditions (operating parameters, bed additives, catalysts, etc…) in order to potentiate a cleaner product [146, 223, 228]. In what concerns secondary methods, two categories are set: physical methods in which clean-up elements as cyclones, filters, separators, precipitators or scrubbers are introduced in the system [64, 229] and chemical methods as cracking reactions [122, 230]. Wet scrubbing techniques, in which a liquid media is utilized to capture tars, can be recirculated in the gasifier enabling their energy recovering [231]. Sansaniwal et al. also reviewed this thematic in one of their works [53]. As secondary methods tend to be more complex and expensive, development of primary methods is gaining notoriety for its efficiency and due to the ease of optimizing gasification conditions, most of the times eliminating the need for downstream cleanup [150, 232], although both can be combined to achieve better results in some cases [233, 234]. In fluidized gasifiers, one of the big allies in this matter is in fact bed material. Its action goes behind the heat transfer playing an important role on produced tar yields, promoting tar cracking and reducing solid agglomeration [70, 146, 235].

Afterwards, if aiming to avoid or eliminate tar production so that the obtained syngas is as clean as possible and presents high heating value, it is of utmost importance to keep in mind factors such as economic viability and environmental concern when selecting the cleanup options.

2.6. Recent developments on thermal conversion of residues

In the light of the gathered knowledge, some hiatus on the conversion of different residues had been identified, namely regarding the best operational practices and system design, in order to optimize results for a blended fuel. In the last years, recent publications intended to clarify these matters, endeavoring to understand how to adequate these features according to the issued samples. Table 6 describes the progress of the scarce literature on the co-gasification of biomass and wastes since the beginning of the century.

Table 6 - Progress on biomass and waste co-gasification literature.

Reference	Year	Feedstock	Reactor	Bed material	Gasifying agent	Temperature	Gas quality
[133]	2001	Demolition residues, woody biomass	Fluidized bed	Sand	Air	800-860 ºC	2-5 MJ/m^3
[111]	2008	Corncob, lignite	Fixed bed	---	---	300 – 600 ºC	---
[236]	2011	Wood chips, pig manure	Fluidized bed	Sand, Ni catalyst	Steam	530-700 ºC	14 MJ/m^3
[162]	2011	Wood chips, polyethylene	---	---	Steam	900 ºC	22-43 MJ/kg*
[78]	2012	Woody biomass, plastic	Fluidized bed	Sand, Ni catalyst	Steam	780 ºC	18.5–22 MJ/kg
[96]	2012	Forestry waste, sewage sludge	Fixed bed	---	Steam	700–900 ºC	11.3-15.0 MJ/m^3
[143]	2012	Woody biomass, sewage sludge	Fixed bed	---	Air	550-850 ºC	2.5-5.5 MJ/kg
[98]	2013	Agricultural residues, tire	---	Natural catalysts	CO_2	850-1000 ºC	14-19 MJ/kg*
[166]	2013	Lignite, polyethylene	Fluidized bed	Olivine	Steam	850 ºC	19 MJ/kg
[167]	2013	Wood, lignite	Fluidized bed	Sand	Steam	800-850 ºC	14.4-17.3 MJ/kg
[86]	2014	Pine sawdust, lignite	Fixed bed	---	N_2	400-900 ºC	---
[87]	2014	Wood saw dust, plastic mixtures	Fixed bed	Ni catalyst	Steam	600-800 ºC	---
[161]	2014	Lignite, plastic waste	Fluidized bed	---	Steam, CO_2	900 ºC	11 MJ/m^3
[108]	2014	Biomass, waste tires	Fixed bed	---	---	700 ºC	20.5 MJ/kg
[103]	2014	Palm kernel shell, polyethylene	Fluidized bed	Dolomite	Steam	650-800 ºC	25-46 MJ/kg*
[142]	2015	Woody biomass, sewage sludge	Fixed bed	---	Air	550-950 ºC	4.5 MJ/m^3
[237]	2016	Biomass, glycerol	Fluidized bed	---	Steam, air	400-950 ºC	8.9 MJ/m^3
[238]	2017	Coal, biomass	Entrained bed	---	Air, oxygen, steam	1227 ºC	12 MJ/kg
[239]	2017	Biomass, HDPE	Fluidized bed	Ni catalyst	Steam	710 ºC	19.8-43.1 MJ/kg*
[240]	2017	Biomass, coal	Entrained bed	---	Oxygen	1000 ºC	---
[241]	2017	Biomass, RDF	Fluidized bed	---	Air	725-875 ºC	---
[242]	2017	Coal, biomass	Entrained bed	---	Oxygen	1100-1400 ºC	12.74-14.26 MJ/kg

[243]	2017	MSW, coal	Fluidized bed	Activated carbon	---	800 ºC	12.2 MJ/m^3
[244]	2018	Sewage sludge, biomass	Fluidized bed	---	Oxygen	---	---
[163]	2018	PET, biomass	Fluidized bed	---	Air, oxygen, steam	400-1200 ºC	9.2 MJ/m^3
[245]	2018	MSW, biomass	Fixed bed	---	Air	700-900 ºC	16.49-21.08 MJ/kg*
[246]	2018	Coke, biomass	TGA analyzer	---	Steam, CO$_2$	1300 ºC	14.62-35.52 MJ/kg*
[247]	2018	Biomass, coal	Entrained bed	Alumina	He-O$_2$	1500 ºC	---
[248]	2018	Coal, microalgae	---	---	Steam	700 ºC	---
[249]	2018	Biomass, polymeric wastes	Fixed bed	---	Air	---	---
[250]	2018	Coal, mud	Fluidized bed	---	Air, steam	1500 ºC	---
[251]	2019	PS, paper	Fluidized bed	Ca, Mg catalyst	CO$_2$	700-900 ºC	---
[252]	2019	Sludge, RDF	Fluidized bed	---	Oxygen	750-800 ºC	6.51 MJ/Nm^3
[253]	2019	Coal, biomass	Fixed bed	---	Air	500-700 ºC	---
[254]	2019	Sewage sludge, biomass	Entrained bed	Ash	CO$_2$	800 ºC	---
[255]	2019	Biomass, RDF	Fluidized bed	---	Air	700-940 ºC	6 MJ/m^3
[256]	2019	Biomass, PE	Fluidized bed	Silica sand, olivine, zeolites	Steam	850 ºC	15-44.2 MJ/kg*

*LHV from the parent compounds

As can be seen from Table 6, the scientific production of papers reporting co-gasification of biomass and waste in the last two decades started as a sparse event but has been quickly raising more and more attention, especially over the last couple of years. Some studies lack details on experimental conditions or syngas quality and, other than these, there are more publications investigating pyrolysis or kinetic behavior of the fuel counterparts and their resulting blends, contributing to the knowledge herein presented mostly by thermogravimetric analysis and computer modelling.

In a recent work, Ahmad et al. [43] assessed the performance of biomass gasification highlighting the characteristics of various types of gasifiers under different operational conditions, optimizing gasification through the use of computational models and evaluating their economic viability. The most important parameters affecting syngas quality identified for biomass gasification were temperature, ER and the presence of a catalyst. Gasifier design and process parameters settled the hydrogen production cost through this method, pointing gasification as the most economic process after supercritical water partial oxidation. Hazrat et al. [257] also addressed some issues, reviewing the most suitable WtE techniques for turning plastic residues and their blends into fuel, referring to the final use as the conditioning factor. Gasification has been shown to be more versatile, the choice of the catalyst and the reactor type being pointed as major parameters for successful conversion.

Kawamoto and Lu [258] developed a novel Ni-based catalyst in order to assure a final syngas with at least 50% H_2 content, which simultaneously limited the tar yield effectively. For this purpose, they used a minimum of 20% (v/v) NiO supported in silica, granting a better H_2 production through the gasification of a mixed feedstock of wood, refuse paper and plastic residues, in a bench-scale gasification unit. The catalyst performance was compared to an alloy-type catalyst, controlling parameters like steam to carbon and equivalence ratios, as well as temperature and pressure so that the only variable would be the tested catalyst. Meanwhile, to prevent Ni-based catalysts' toxicity, Miccio et al. [152] aimed at developing a safer catalyst resourcing to iron, once its benefits on tar reforming and cracking advocate better performances. The $Fe(NO_3)_3$ catalyst was prepared over an alumina base and utilised in the gasification of spruce wood, in a bubbling fluidized bed. This new catalyst depicted no activity loss during 100 minute-time runs, as well as higher H_2 production and lower tar concentration when compared to alumina alone. Optimizing the gas velocity improved even more the hydrogen yield.

Onwudili [259] performed supercritical water gasification of several different samples (RDF, MSW, plastics, textile waste and biogenic residues) and their mixtures comparing the results in the presence and in the absence of a Ru-based catalyst. Using the catalyst, carbon efficiencies were up to 83% higher and HHV augmented at least two-fold, when compared to the experiment without this additive. Also, in the presence of the catalyst, CH_4, H_2 and CO_2 became the predominant gaseous products for all the samples enabling methanation, steam reforming and possible direct hydrogenolysis of C-C bonds. Udomsirichakorn and Salam [55] reviewed the use of CaO as a catalyst in biomass steam gasification with CO_2 capture and went further, explaining CaO-based chemical looping gasification. This technique consists in continuously producing hydrogen in a fluidized bed in the presence of CaO and steam, *in situ* CO_2 capture converting CaO into $CaCO_3$, which is then calcinated in the regenerator. CaO is then released and cycled back to the gasifier in a looping process that, besides precluding CaO deactivation, also provides additional heat for the gasification step. These efficiency and sustainable features reveal this technique as a promising contribution to the renewable production of hydrogen from biomass. Li et al. [260] developed and tested a new type of tri-metallic catalyst (alumina supported nano-NiLaFe) in steam-gasification of palm oil wastes for hydrogen-rich gas production. When compared to calcined dolomite, NiLaFe afforded higher gas yield, hydrogen concentration and lower CO_2 content, as well as 99% tar removal for specified operational conditions.

In the view of the technology evolution in co-conversion of biomass and wastes, Jaojaruek et al. [261] counterweight a single stage, a conventional two-stage and an innovative two-stage air/gas supply in the downward gasification system of wood. For the latter approach, air was supplied at combustion zone of the gasifier, while premixed air/bypass gas was introduced through the pyrolysis zone. The authors report higher producer gas quality, improved HHV and tar content in the newly developed system. Park et al. [262] performed two-stage gasification on HDPE and biomass blends, comprising an oxidative pyrolysis reactor followed by a thermal plasma reactor. They found that, for higher biomass fractions, enhanced CO_2 yields were produced and reversely, increasing the HDPE fraction allowed for higher content in hydrocarbons. In the thermal plasma reactor these were converted into CO and H_2, improving the concentration and production yield of syngas. Gómez-Barea [263] proposed a different approach with the development of a three-stage gasification process, aiming at maximizing char conversion and avoiding complex tar cleaning. The newly designed system is based on a fluidized bed gasifier and consists in a devolatilization step, followed by non-catalytic air/steam reforming and chemical filtering of the gas with simultaneous char gasification. Tar was seen as an opportunity to increase the heating value of the producer gas, and hence converted instead of removed from the system. When compared to a regular single stage fluidized bed, this three-stage system depicts 14% higher gasification efficiency, 39% increase in char conversion and 3100-fold lower tar content on the produced gas. Kuo et al. [113] propose a heat recovering unit to enhance the system energetic efficiency in a steam biomass gasification. This was done by coupling a combustor at the end of the gasifier, enabling the recovery of the residual char heat.

In a different perspective, Huang et al. [264] presented the microwave co-pyrolysis of sewage water and rice straw, reporting an increase in the calorific value for biomass contents of 30%-40%. Also a maximum temperature in the hoven was found for blends containing only 20% rice straw, which points to a potential new thermal treatment for sewage sludge. More work needs to be done but so far, as some physicochemical parameters in the blends were similar to the ones depicted by anthracite coal, the authors foresee a possible co-conversion with this fuel or even its replacement is some utilizations. Later, Beneroso et al. [265] developed a new microwave heating process to produce high-quality syngas from biowaste, avoiding tars production. Initialy, pyrolysis of the biowaste was induced in the presence of char and a first fraction of syngas was obtained. Then, this char was used as fixed-bed material in a second step where thermal cracking of tars occurs and additional syngas is produced up to a total biomass conversion of 54%. This way, no catalysts or gasifying agents are needed and tar production is lowered. Recently, Junoh and Ani [266] reported a relatively new method using laser for the thermal treatment of solid and gas-phase of biomass processing. This constitutes a very promising technique regarding the field of nanotechnology, once carbon nanoparticles can be synthesized from the producer gas, ensuring sustainability of the natural resources. This way, biomass reinforces its versatility, another important asset being added to the list of possible materials achieved from its thermal treatment. More contributions on laser pyrolysis are needed, to optimize the proposed technology and broaden its scope.

In an attempt to approximate laboratory experiments to the waste real mixtures, Baloch et al. [267] co-gasified a ternary mixture of biomass (rice straw) and waste (PVC and PE) in a bench-scale experimental unit investigating the effect of the operational parameters on the producer gas obtained. Their major findings were: as the temperature was raised, increased syngas yield, H_2 and CO content as well as LHV were obtained; increasing the plastic ratio in the blend enabled higher H_2 as well; the ternary blend with 20% biomass, 40% PE and 40% PVC allowed the maximum results. Synergy between the single fuels was attributed to the volatile-char interaction and mineral catalytic effects. This study showed that, optimizing the system design and the experimental parameters applied, it is possible to handle residues with varying composition to adequately produce high-quality syngas. Tai and Chen [268] also studied the thermal conversion of ternary mixtures of waste and biomass, assessing their physical and chemical properties and modelling pyrolysis kinetics. When compared to the individual feedstocks lower activation energies were observed for the blends, possibly due to the potassium present in biomass, which catalyzed pyrolysis reaction. As all the three materials are common wastes, frequently discarded in significant amounts, this co-pyrolysis experiment depicts noteworthy results and deserves progressive upscale work.

As shown, progressive research either on catalysts production, bed material developments, technology assembly or cleaning techniques is continuously reported, aiding to clarify the existing questions and fill some of the identified gaps on the co-conversion of residues.

2.7. Partial conclusions

This review has explored the current status of biomass and waste co-conversion, highlighting the complementarities of the fuels and reducing drawbacks from individual utilizations. An overview of the actual energy production, utilization and environmental shortcomings was given, contextualizing the need for alternative solutions such as waste-to-energy approaches. From the exposed, relevance should be given to the greenhouse gas emissions reduction attained by this strategy, major contribution due to the use of biomass as a carbon-neutral fuel.

Gasification stands out as an auspicious technique for solid waste conversion, complying with international policies of residues reduction and disposal, arising as the most favorable thermal conversion technique for this purpose. Pre-processing treatments of the raw biomass and waste together with the optimization of the operational conditions had shown to be of great importance in order to maximize conversion efficiency, viability and profitability. Within all the pre-treatment processes, drying appeared to be the prevailing as generally this kind of residues presents high moisture contents, compromising efficiency. Particle size is also a major concern in this WtE technique, procedures such as sorting, milling, crushing, grinding and sieving being reported as the most commonly used to overcome this problem. Among the possible gasification reactors, fluidized beds evidence proper suitability for a co-fuel such as biomass and waste permitting a broader particle size range and resulting in higher efficiencies. Concerning bed materials, natural rocks like dolomite and olivine constitute a reasonably priced option but, when attrition becomes a matter, the recommended materials are silica or alumina, although being more expensive.

Co-gasification of biomass and several different types of wastes frequently revealed synergetic effect, as the final products showed enhanced properties or higher conversion rates, when compared to each of the fuels by themselves or to their additive results. Causes for that concurrent behavior had been stated, as well as its possible mechanisms deepened and explained. The most evident explanations rely on the interactions of molecules during pyrolysis and on the hydrogen transfer from waste polymers to biomass derivatives. Also, pollutant emissions were considered and evaluated, and abatement measures for each of the identified compounds were suggested, along with possibilities for the reutilization and valorization of some of them.

The continuous progress and enhancement of knowledge in this area is an important way of addressing the environmental and sustainability questions. As a hot-topic on WtE methodologies, new research on (co-)gasification is being successively published reporting recent developments and discoveries, whose interpretation and implementation can help to evidence even more its feasibility and efficiency.

This chapter enabled to confirm the highly positive effect of substituting fossil-based fuels for greener options, in terms of replacing less environment-friendly processes of obtaining and using energy. Furthermore, making use of the constantly growing produced residues allows a reduction of deleterious landfilling and open-dumps, so far considered as waste disposal sites. This empowers the pursuit of sustainability conditions aiming to accomplish environmental goals imposed by the European Union and other governmental agencies.

Chapter 3 – Numerical Approaches

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3.1. Computational methods

Performing gasification experiments can be easily foreseen as a high-cost and thoroughly time- and resources-consuming task. Thus, the development of numerical models to predict and adjust all the experimental variables is the best method to optimize the performance of the conversion plants [269, 270]. The optimization of the operational variables resumes the experimental work and ensures greater efficiency for the process. In effect, a reliable mathematical model should provide a set of optimum operating conditions, designate the system hazards and limitations saving the system itself from being exposed to dangerous conditions, predict gasification experiments and outputs for a set of variable operational conditions including different feedstocks, help to understand and explain the experimental results and be suitable for scale-up experiments [56]. The possibility of building up such advanced calculations and complex numerical simulations is only available due to the emergent progress of the computational assets and programming in the last decades.

Gasification modeling may be achieved through different strategies, namely kinetic models, thermodynamic equilibrium models, computational fluid dynamics and artificial neural networks. Nowadays, fluidization modeling is considered in a comprehensive multiphase gas-particle dynamic and has evolved over the years, anchored in the fast advancements in computing systems and information technologies [135, 271-273]. In fact, Singh et al. [272] propose a CFD framework for fluidized beds and present the interrelation between models for gasification and other physical and chemical interactions in the thermochemical conversion of fuels, while Loha et al. [271] go deeper and discuss the hydrodynamics of the bed, highlighting the Euler-Euler and Euler-Lagrange models. These are two of the major numerical methods described in literature concerning gasification simulation, a scale-based categorization for the most well-known model approaches used for the assessment of fluidized beds being suggested elsewhere [274]. The Euler-Euler approach considers the different phases as inter-penetrating media, applying conservation laws to each of them in order to achieve a similar set of equations for all. These equations are further ameliorated with empirical information, whereas mass and momentum conservation equations are solved for each phase separately [61, 65, 270, 275, 276]. Regarding the Eulerian-Lagrangian approach, a large number of particles are tracked in order to describe their behavior along the trajectory through the calculated flow field. The fluid phase is treated as a continuum, with time-averaged Navier-Stokes equations being applied to calculate mass, momentum and energy variables [271, 277].

There are some reports on gasification modelling, namely concerning biomass [43, 66, 124, 278-289] and several residues [65, 270, 273, 275]. Ahmad et al. [43] had already evaluated some simulation tools for biomass gasification, their inputs proving useful in the parametrization studies. Baruah and Baruah [46] conducted a thorough review on biomass gasification computational models, categorizing the assessed works according to criteria such as gasifier type, feedstock origin, model assumptions and the operational parameters applied. Equilibrium, kinetic and artificial neural network modeling were reported as the main approaches in the case of biomass gasification, the incorporation of empirical parameters or correlations from experimental works leading to more accurate models. Che et al. [48] even compared two of the most well-known simulation software, concluding that an integrated solution would perform better than each of them alone in the case of biomass gasification. As fluidized beds are the most utilized in industrial gasification plants, Goméz-Barea and Leckner [50] examined biomass modeling in that type of reactor, reporting strong correlation between numerical and experimental results for most of the evaluated works, despite several different models, assumptions and phenomena being applied. Tang et al. [290] simulated the thermal characteristics of natural coke gasification in a fluidized bed, adapting the model in accordance with the features that required optimization. The authors found very good agreement between the numerical results and the experimental results reported in the literature, enabling the applicability of the developed model to further design, optimization and scale-up of the process. Improved achievements were attained in terms of char distribution and syngas composition, a final product with lower CO_2 content and higher combustible fraction being obtained. Loha et al. [271] also studied the modeling of fluidized beds, describing distinct approaches ranging from the equilibrium model to the two-phase flow model and even to the more complex Euler-Euler and Euler-Lagrange models. The authors concluded that the equilibrium model is the more affordable model among all of them and does not depend on the gasifier type, which makes it very useful for preliminary results; the kinetic model includes the hydrodynamics of the bed, the two-phase model being the simplest, but not solving some of the equations involved in gasification; in the Euler-Euler approach, both gas and solid phases are treated as inter-continuum media, governing equations for each phase being solved separately, and it is less expensive than the Euler-Lagrange approach; the Euler-Lagrange model is applicable to large-scale systems within less time than the others but does not treat both phases individually. La Villetta et al. [291] highlighted the stoichiometric method for biomass gasification, stressing its reduced computational time and its suitability for parametric studies. Parameters such as biomass moisture content, equivalence ratio (ER), pressure and gasifying agent are discussed, providing conclusions regarding their effect on final syngas quality. As general inferences, the authors found that higher moisture content, higher ER and pressure values decreased syngas LHV and CGE, while higher oxygen levels promoted these efficiency parameters. More recently Ismail et al. modelled the gasification of coffee husks [292] and agro-industrial residues [293] in a fluidized bed, using an Eulerian-Eulerian approach, while Monteiro et al. simulated the gasification of different Portuguese biomasses [294, 295]. Tavares et al. [296] report an advanced gasification model for municipal solid waste using a thermodynamic equilibrium model, whereas Ismail et al. [297] resourced to a multi-fluid Eulerian model incorporating the kinetic theory of granular flow to model forest residues.

Regarding the co-gasification of biomass and wastes, even less work is available, highlights being given by Ong et al. [142] and also by Oyedun et al. [164, 165]. Authors such as Emami-Taba et al. [49] state that the fraction of each feedstock in the tested blends greatly influences the other experimental parameters and the final syngas quality, given that mixtures tend to present synergistic behavior, enhanced results being obtained when compared to the gasification of each of the fuels by itself. Tavares et al. [163] confirm this, reporting the co-gasification of PET microplastics with biomass using a thermodynamic equilibrium model. Ong et al. [117] developed numerical models for each of the four zones concerned in the co-gasification of sewage sludge and biomass in a fixed bed downdraft gasifier (drying, pyrolysis, combustion and reduction), merging them afterwards into a unique model that aimed to reproduce the global performance of the system. Syngas composition and cold gas efficiency under different biomass/sludge blends were chosen as indicators for the proficiency of the gasifier. Results proved to be highly accurate when validated against experimental data, once deviations under 10% between the mathematical and the gasifier's values were achieved. In turn, Oyedun et al. [138, 139] modelled biomass and plastic waste, aiming to study the overall energy usage reduction provided by the synergistic effects encountered amid the feedstocks. Two approaches were used to access features such as mass loss, volatiles evolution and overall energy during co-pyrolysis of the tested blends, one with and the other without pre-mixing the fuels. Synergistic effects were confirmed by the energy reduction in both methodologies, the pre-mixed co-fuel depicting a higher energy decrease in favor of the interaction among biomass and plastics, also depending on the blending ratio used. Xu et al. [298] modelled a bubbling fluidized bed gasifier making use of the two phases flow model where the reactor is divided in two phases: the emulsion and the bubble phase. The chemical scheme included the devolatilization, homogeneous and heterogeneous reactions. The authors quantified the gasification reactivities of char from pure and blended substrates. These data were used as input parameters in the developed model. The major drawback relies on the fact that the model assumes very simple hydrodynamics features. The model was developed under the Matlab® framework and was validated under experimental data gathered in a 50-kW bubbling fluidized bed gasifier using coal pellets and blended biomasses.

Although there are several developments concerning the use of advanced numerical methods to predict the main responses of a gasification process, when the simulation process implies blended substrates the research efforts are still in an early stage.

3.1.1. Kinetic models

Kinetic models describe the kinetic aspects of the conversion mechanisms along the gasifier in a very accurate perspective which makes them computationally exhaustive, although inexpensive [142, 293, 299-302]. Based on reactor hydrodynamics and geometry, these models present growing sophistication from zero-dimensional (stirred tank) to one-dimensional (plug flow), two-dimensional or three-dimensional, more kinetic and hydrodynamic details being required for highy-detailed systems [46]. Fiaschi and Michelini [302] developed a one-dimension biphasic kinetic model for biomass gasification based on a zero-dimensional model. The authors concluded that mass transfer initially prevails over the effects of surface reaction kinetics, which gradually tend to dominate when the temperature stabilizes. Halama and Spliethoff [300, 301] presented a three-dimensional model to simulate lignite gasification in an entrained bed, focusing on the comprehensive modeling of char particle reactions. An effectiveness factor approach with intrinsic reaction kinetics was applied in order to account for pore and boundary layer diffusion limitations, a new pore structure model for higher temperatures that describes the surface area, the diameter, the density, the porosity and the mean pore diameter of the particles as a function of reaction regime and char conversion being introduced. In order to simulate the co-gasification of sewage sludge and biomass in a fixed bed, Ong et al. [142] settled a new model based on several kinetic models already published for plain gasification. Relatively high prediction accuracy was achieved after comparing the modeled results with the experimental data, a further study of the operational parameters being held upon this validation. Adeyemi and Janajreh considered that the equilibrium models published so far for the co-gasification of coal and biomass in entrained beds were inconclusive, therefore they suggest a detailed kinetic model, taking into account processes such as moisture release, devolatilization, volatile combustion and char gasification [299]. Results comparable to the experiments were obtained from the model and a sensitivity test was performed to evaluate its robustness with feasible outcomes.

Nevertheless, as mathematical models may always be validated with different experimental data, some cases where the kinetic models' accuracy was arguable were observed by Giltrap et al. [303], who tested a kinetic model for biomass gasification previously developed [304] and found some inconsistencies in the assumptions made, namely the omission of the pyrolysis and cracking reactions, which overpredicted CH_4 and underpredicted H_2. These differences were caused by the assumption that O_2 reacted only with char, disregarding CH_4 combustion. In addition, Jaya et al. [305] needed to introduce some changes to the model developed by Chen in his Ph.D. thesis [306], since this model over-predicted the outlet temperature due to the negligence of CO and H_2 in the pyrolysis gas.

3.1.2. Thermodynamic equilibrium models

The fundamentals of chemical equilibrium are based on the second law of thermodynamics [307]. It is a state where a reacting system is at its most stable composition maximizing the entropy and minimizing the Gibbs free energy. Therefore, a thermodynamic equilibrium model can be formulated using the governing equations and describing the behavior of such state. Thermodynamic equilibrium models have the advantage of predicting the maximum achievable yield of the final product. Although they are simpler, thermodynamic models are not so accurate given that thermodynamic equilibrium would require an infinite time for reactants to convert into products at low gasification temperatures. This hinders the chemical equilibrium and therefore compromises the minimization of the Gibbs free energy [135, 308]. However, thermodynamic models may be more suitable for some applications given they are independent of the gasifier’s design and therefore focus more on other operational parameters since they do not require any knowledge about conversion mechanisms [56, 309]. These may further be classified as stoichiometric or non-stoichiometric, depending on whether they are based on equilibrium constants or Gibbs free energy minimization, respectively [56, 303].

The term non-stoichiometric is due to the absence of any specific chemical reaction, other than the assumed global gasification reaction. This equilibrium modeling technique is also known as “Gibbs free energy minimization approach” since it is based on the direct minimization of the Gibbs free energy of reaction. There is only one input required, the elemental composition, obtainable by ultimate analysis. For this reason, non-stoichiometric models are particularly suitable for cases in which all the possible reactions that can occur in the system are not fully known as is the case of gasification. Some published works that resource to the thermodynamic equilibrium are described in [138, 278, 286, 309-321]. Silva and Rouboa [278, 286] used a thermodynamic dual-stage model to evaluate the effect of oxygen concentration on biomass gasification, concluding that both energy and exergy efficiencies were improved for higher oxygen content. Carbon boundary point and response surface methodology were applied to assess the parametric study of other variables. Drosatos et al. [311] suggest a thermodynamic model to assist in the design of a biomass household boiler, in order to achieve a better and deeper understanding of the expected emission characteristics at the boiler outlet and a better estimation of the heat transfer distribution among all different heat exchanging surfaces. After construction, the boiler was expected to be tested under steady-state nominal operating conditions to identify possible discrepancies. Li et al. [317] developed a non-stoichiometric model to examine the performance of several gasifiers. As carbon conversion is usually controlled by non-equilibrium factors and therefore has to be considered based on a kinetic model or an empirical basis, a kinetically-modified equilibrium model had to be proposed. Except for CH_4, model predictions compared fairly with measured gas compositions and good estimates were achieved for carbon conversion efficiencies. This type of approach was also reported by Mendiburu et al. [321] for biomass gasification in a fixed reactor. The authors used a non-stoichiometric equilibrium model involving the minimization of the Gibbs free energy yet also including a kinetic constraint regarding the apparent gasification rate of biomass, enabing efficiency calculation. Good accuracy was achieved for different woody biomass streams.

Although chemical and thermodynamic equilibrium are unattainable inside the gasifier, a reasonable prediction for syngas yield and composition was achieved by Bhavanam and Sastry [310], who used an equilibrium model to compare the gasification of three different streams of solid waste. One of the limitations of the work was the inability to simulate hydrodynamic or geometric parameters such as fluidization velocity or gasifier dimensions. Rodrigues et al. [314] applied a thermodynamic equilibrium model to the co-gasification of coal and biomass aiming to achieve a syngas with enough calorific content for energy production as well as chemical synthesis. The model proved to be suitable for this purpose since its results were highly comparable to experimental and simulated literature values, showing a linear relation to the biomass ratio. Enhanced conversion efficiencies were attained whereas NH_3 and H_2S (hydrogen sulfide) content remained below the recommended limits. Xiang et al. [315] also evaluated the co-gasification of biomass and coal within a thermodynamic equilibrium framework, although presenting a new serial composite process in which the feedstock is first combusted (generating thermal energy) and later gasified (producing combustible gases). Therefore, the model was divided into two submodels, each of them also being subdivided in two stages (pyrolysis and combustion, char gasification and biomass gasification). The overall simulation led to fair results, comparable to those achieved through dual-fluidized beds, with the advantage of reduced tar content given that fewer particles moved on to the gasifier and also the flexibility of being fed by regular or pulverized coal. Jarungthammachote and Dutta [312] used an equilibrium model based on the minimization of the free Gibbs energy to compare conventional and modified-spouted bed gasifiers. Significant deviation from the experimental data was observed, especially for CO and CO_2. The model was thus modified by considering the effect of carbon conversion. Improvements were noted, with closer results to the experimental data. However, the model did not afford accurate results for the spouted bed gasification process, overpredicting the heating content of the syngas produced in this reactor. The authors suggested that perhaps a kinetic model would be more suitable for dealing with this situation. In contrast, Prins et al. [313] compared the thermodynamic efficiency of different gasification systems using a chemical equilibrium model and showed that the presence of kinetically limited gasification reactions negatively influenced the efficiency of the gasifier. In another study [320], the authors had to modify the thermodynamic equilibrium developed in order to predict syngas composition in a fixed bed. The former model was based on an equilibrium constant although mutiplying factors had to be applied to enhance its performance. Following this adaptation, the model was validated with different reported data and the results proved to be accurate. This has also been reported by Huang and Ramaswamy [319] for the same type of reactor. Karmakar and Datta [138] examined the H_2 production from biomass gasification using a thermochemical model for fluidized beds. Higher hydrogen yields were achieved for increasing temperatures and steam content whereas higher quality syngas was achieved only for higher temperatures, which was closely predicted by the model. Zainal et al. [316] even mastered the development of a thermodynamic model for fixed bed gasifiers capable of reasonably predicting the calorific value of the syngas produced, only by knowing the ultimate composition of biomass fed. Its suitability was tested under different biomass streams and comparable results were attained. Besides lab-scale or pilot plants, the thermodynamic equilibrium model also served to evaluate the performance of world-renowned technologies as reported by Yoshida et al. [318].

Tavares et al. [163] adapted a pre-existing thermodynamic model to the gasification of mixtures with PET microplastics and biomass (vine pruning) using the Gibbs free energy minimization principle, under Aspen Plus® environment (Figure 5). Parameters such as ER, SBR, gasification temperature and gasifying agent (air, oxygen and steam) were tested over syngas production. The main conclusions report that for higher syngas quality, enhanced PET content should be present in the blends, also promoting increased LHV. CO production was increased in the presence of steam, while in the presence of oxygen, both CO and H_2 were raised for lower ER values. Low ER, moderate SBR and high temperatures promoted syngas calorific content.

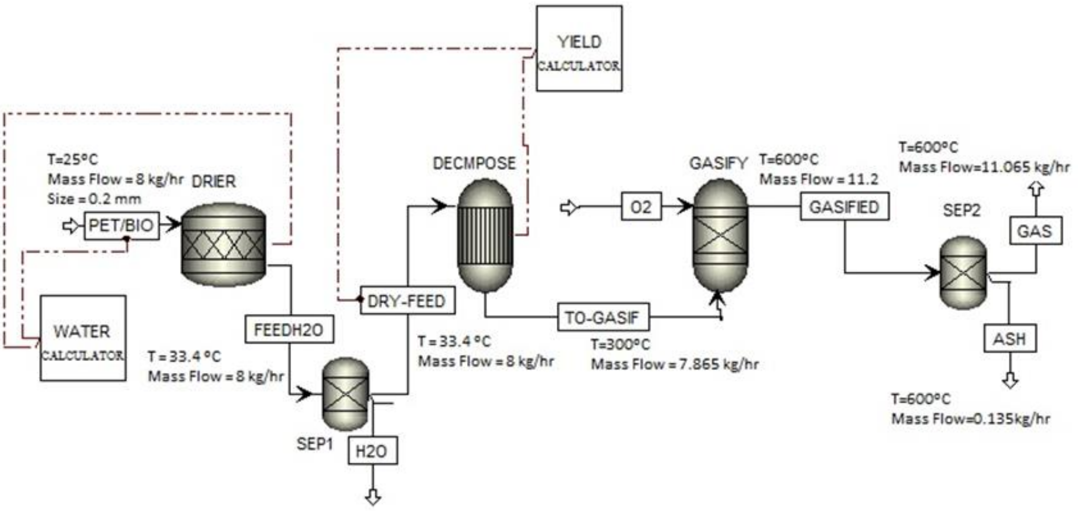

Figure 5 - Schematic representation for PET-biomass gasification modelling [163].

Later, another interesting study demonstrated that the same model could be adapted to simulate MSW treatment through plasma gasification [296]. To achieve that, a plasma torch fed by steam, oxygen or air was added to the gasifier module, to simulate the gasifying agent. A fair agreement between the modelled results and the literature data was accomplished. The parameter variation showed that H_2 production is favored by air and steam atmospheres, as well as high SBR, high ER and low temperatures in the presence of oxygen. Oppositely, high temperatures promote CO production in air and LHV under oxygen atmosphere.

3.1.3. Computational fluid dynamic models

Computational fluid dynamics constitute a solid option for gasification modeling based on the conservation of mass, momentum, species and energy in a defined region [56]. This is especially important in the case of fluidized beds, where pyrolysis has a sensitive role regarding the lower temperature of the gasifier, with deficient heat transfer and high tar production being the main concerns. CFD provide relevant information on temperature contours and species concentration along the reactor which, when combined with profound knowledge of the hydrodynamics of the reactor, may afford a highly accurate prediction on syngas yield. Thus, fluidized beds are often modeled using Eulerian-Lagrangian approaches, the discrete solid phase being treated as particle flow while the gas phase is seen as a continuous medium. Klimanek et al. [322] used the dense discrete phase model to simulate the flow of the particulate phase in a coal fluidized gasifier. The heterogeneous reactions on coal particles surface were modeled using finite rate chemistry, while the homogenous gas phase reactions were modeled using the finite rate and eddy dissipation models. Some issues were observed due to a misconception about the initial gas composition, which had to be tackled by artificially increasing the water-gas shift reaction rate. Furthermore, the applied time step was not ideal for this particular case, leading to inadequate prediction of some gaseous species. Xue and Fox [323] also report a time step adaptation implementation to provide stability to the system and achieve higher efficiency in a biomass gasification study held in a fluidized reactor. Gao et al. [277] used an Euler-Lagrange approach to assess biomass gasification in an entrained reactor, applying a standard k-epsilon model to the continuous phase and a discrete phase model to the biomass particles phase. The finite rate/eddy dissipation model was applied to calculate the reaction rates for homogeneous phase reactions, whereas for heterogeneous phase reactions the intrinsic reaction rate model was utilized. The same regimes, feedstock and reactor type were used by Ku et al. [324], with parameters such as temperature, steam/carbon molar ratio, excess air ratio, biomass type and particle size being examined. Matching trends were seen for numerical and experimental results, good agreement being achieved with data reported in the literature. The same authors later performed a similar study in a fluidized gasifier, the calculated results also comparing well with the experimental data available in the literature [325]. Jeong et al. [326] and Park et al. [327] also reported the use of an Eulerian-Lagrangian model to simulate the gasification of coal in an entrained bed, although resourcing to the steady-state Navier-Stokes equations. The gaseous phase chemical reactions were solved using the finite-rate/eddy-dissipation model while for char gasification reactions the random pore model with bulk and pore diffusion effects was considered. Numerical results were compared to real plant results and reasonable agreement was found. A similar approach was applied by Luan et al. [328] and the authors observed that by changing the water-gas shift reaction rate, different results were seen for syngas composition. However, when distinct fuel distributions were used, no influence on gasification performance was observed.

Although Euler-Lagrange regimes are said to be the most suitable for fluidized beds, there are several works reporting Euler-Euler approaches for this type of reactor. The multiphase flows have been modeled using three approaches known as Euler-Euler (two fluid model), Euler-Lagrange and the Discrete Element Method-CFD method within the Euler-Lagrange approach.

In the Euler-Euler approach, the different phases are considered to be interpenetrating continua. It introduces the notion of phasic volume fraction assumed to be continuous functions of space and time. The conservation laws for each phase are applied obtaining a set of equations with analogous structure for all phases. This set of equations is closed by additional constitutive relations obtained from experimental data or by application of kinetic theory in the case of granular flows [326, 327, 329, 330]. Three different Euler-Euler multiphase models are available: the volume of fluid model, the mixture model and the Eulerian model. The volume of fluid model is a surface-tracking technique designed for two or more immiscible fluids where the position of the interface between the fluids is of interest. Therefore, it is not applicable to fluidized bed gasification scenarios. The mixture model is designed for two or more phases. The mixture model solves the mixture momentum equation and prescribes relative velocities to describe the dispersed phases. It is applicable to particle-laden flows with low loading, bubbly flows, sedimentation, and cyclone separators. Therefore, this model is not applicable to the fluidized bed gasification scenarios either. The Eulerian model is the most complex of the multiphase models. It solves a set of momentum and continuity equations for each phase. Coupling is accomplished through pressure and interphase exchange coefficients and depends on the type of phases involved. In a fluidized bed gasification case, the properties for the granular (gas-solid) flow are obtained from application of kinetic theory. Therefore, the Eulerian multiphase model is the only suitable one for modeling fluidized bed gasification and has been applied to several works on modeling [326, 327, 329-332].

Monteiro et al. reported the gasification of miscanthus [294] and peach stone [295], using a comprehensive two-dimensional model in order to assess the potential of the syngas produced by a semi-industrial gasification plant featuring a bubbling fluidized bed (Figure 6). The main components of the gasification system are: a) feed system; b) gasifier; c) heat exchangers; d) bag filter; e) condenser; f) flare; g) condensate tank; h) vacuum pump; i) air compressor; j) air fan. A Eulerian-Eulerian approach was used to describe the transport of mass exchange, momentum and energy for both solid and gas phases. The results were obtained after comparing both the numerical model and the experimental data for validation, and the simulated syngas composition was found to be in good agreement with the experiment. The effect of changing some operational parameters was evaluated so as to achieve a high-quality syngas. In the case of miscanthus, high temperatures were seen to improve syngas quality and conversion efficiency while reducing tar production, whereas higher equivalence ratios had the opposite effect, with the exception of conversion efficiency. As far as the peach stone study is concerned, lower syngas quality was achieved for higher ER values, whereas increased efficiencies and calorific values were seen for enhanced SBR and moisture contents.

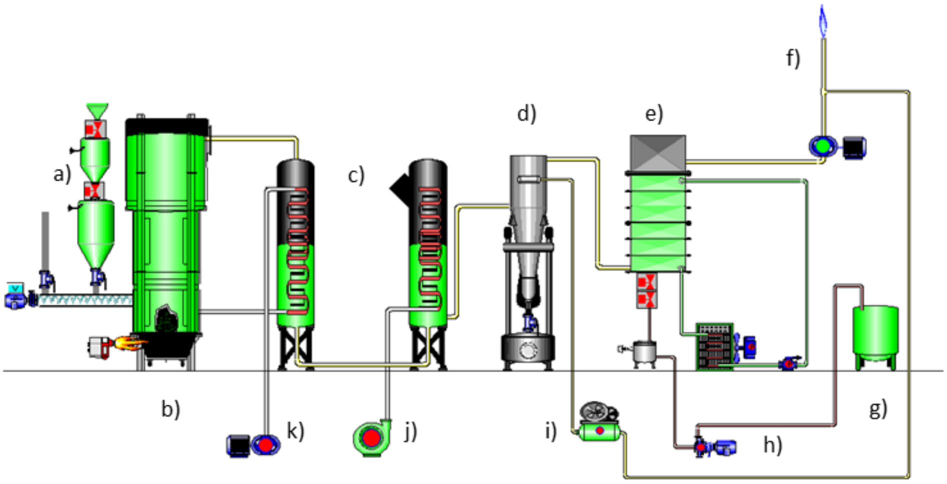

Figure 6 - Schematics of the biomass gasification semi-industrial pilot plant [295].

Armstrong et al. [333] present an Euler-Euler CFD model for the gasification of coal in a fluidized bed. The base model was validated with literature data and later adapted to include different parameters such as bed temperature, bed height, bed material, heat transfer coefficients and pyrolysis details. An interesting finding was that extended simulation times of 400 seconds afforded more stable gaseous compositions than for comparative experimental work and published literature, which held experiments for 100 seconds. This provides solid evidence for the major advantages of simulation works in reducing experimental runs. Couto et al. [270] developed a numerical model for biomass gasification based on kinetic theory of the granular flow using an Eulerian-Eulerian approach, in which three runs were enough to achieve good agreement with experimental results and validate the model. The influence of an oxygen-enriched air atmosphere on gasification temperature, steam to biomass ratio (SBR) and final syngas composition was evaluated, with accurate predictions resulting from the model. A similar study from the same team was published for municipal solid wastes [275]. Reasonable agreement between the modeled and experimental results was achieved although some deviations were identified, probably due to the heterogeneity of the feedstock used, with properties such as elemental composition, density, structure and moisture accounting for these discrepancies. Nevertheless, by modeling pyrolysis in a dedicated way and considering temperature, feeding rate and equivalence ratio it was possible to obtain a syngas composition suitable for chemical synthesis and fuel applications [65]. Regarding moisture content, Ismail et al. [334] verified that this parameter has a negative influence on the conversion efficiency and the calorific content of biomass when simulated with a Euler-Euler homemade code developed for biomass. This effect was seen to decrease for higher equivalence ratios. In a subsequent work, the authors tested the gasification of agro-industrial waste in a pilot-scale plant equipped with a fluidized bed and observed the effect of temperature on syngas composition. Higher temperatures were seen to favor CO content and reduce tar production [293]. Thankachan et al. [335] developed an Euler-Euler model to simulate biomass gasification in a fluidized reactor, resourcing to the standard k-epsilon approach to model the turbulence for each phase and to the kinetic theory of granular flow to model particle motion inside the reactor. The reaction rates of homogeneous reactions and heterogeneous reactions were determined by the Eddy-Dissipation and Arrhenius-Diffusion reaction rates respectively and good agreement was found between experimental and numerical results.

More recently, Ismail et al. [297] developed a completely novel numerical model to simulate the flow inside a plasma gasifier for forest residues. Concepts such as continuity, species transport, heat transfer and turbulence were taken into account, as well as the chemical reactions. Conservative and non-conservative equations were solved using a finite difference and volume method. Drying, pyrolysis, gasification and char combustion were modeled, based on mass balance, momentum and energy balance. The large Eddy simulations and the Reynolds-averaged Navier-Stokes equations method were applied and excellent agreement to literature data was accomplished. As far as the parametric study is concerned, low ER promoted enhanced LHV, high SBR increased the production of H_2 and the efficiency, reducing CO contents and LHV. Temperature had a positive impact on syngas quality.

In the Euler-Lagrange approach, the fluid phase is treated as a continuum by solving the Navier-Stokes equations, while the dispersed phase is solved by tracking a large number of particles, bubbles, or droplets through the considered flow field. In a fluidized bed gasification scenario, the dispersed phase comprises solid particles that can exchange momentum, mass, and energy with the gas phase. This model assumes that the volume fraction of the solid particles is lower than 10-12%, although its mass can be greater than the mass of the gas phase [336]. This model approach is computationally more demanding than the Euler–Euler model but has been used in various works on modeling [337-339]. The Discrete Element Method (DEM) is a numerical method for analyzing the motion of a large number of particulates. DEM tracks the motion of particles by using Newton’s second law based on the Lagrangian approach, and CFD solves the motion of fluid flow based on locally-averaged Navier-Stokes equations. The DEM model has proven to be useful in modeling the behavior of granular particulates, providing a model to describe the fluidized bed when coupled with fluid flow, which has been receiving some attention in various gasification modeling works [321, 337, 340].

A CFD gasification model will not be completed before introducing a chemical kinetic model. It is well known that gasification reactions proceed at a finite rate and that it is generally divided into four steps: drying, pyrolysis, oxidation and reduction. Is also widely known that the drying and pyrolysis phases of biomass are much briefer than the oxidation and reduction phases of the remaining char [56]. Therefore, some models consider that drying and pyrolysis occur instantaneously, and as a result the rate of reaction of the char governs the gasification process. Drying consists of the conversion of biomass moisture to water vapor. This phase is usually modeled together with the pyrolysis phase in a so-called drying and devolatilization model or simply devolatilization model [124, 272, 273, 331, 341]. However, more detailed CFD models do model this gasification phase separately [276, 326, 327, 329, 342]. In this phase, the biomass does not experience any decomposition. The conversion of moisture to steam occurs due to heat transfer between hot gases from the oxidation phase to biomass in the drying phase. Pyrolysis is the thermal decomposition of the biomass in an inert atmosphere [343, 344]. The kinetic mechanism employed of single particle biomass pyrolysis accounts for three parallel primary reactions with the possibility of a tar cracking reaction; that is, the biomass decomposes into gas, tar and char, and vapor tar decomposes to yield further gas. The main product of the tar cracking reaction is light gases, and the amount of char yield is negligible as concluded in experimental studies [336, 345]. The pyrolysis phase is also prone to releasing gases that constitute oxidizing agents such as O_2, H_2O and CO_2 for heterogeneous gasification reactions. The char produced in the pyrolysis phase will be further converted by heterogeneous gasification reactions. Therefore, gasification can be distinguished by three possibilities with different product gas compositions. These are oxygen gasification, steam gasification and carbon dioxide gasification. The kinetic/diffusion surface reaction model is generally implemented to include both diffusion and kinetic effects on the heterogeneous reactions [276, 326, 327, 329, 342]. Homogeneous reactions refer to reactants and products in the same phase. In a gasification scenario, these are reactions in the gas phase. The homogeneous gasification reaction rate coefficients are based on the Arrhenius law.

The conservation equations that are the basis of any CFD model are not sufficient to describe a fluidized bed biomass gasification process. The additional processes considerably influence the dynamics of the reactor system. The CFD governing equations need to be supported with specific physical models or assumptions to completely represent a fluidized bed gasification process. The most relevant additional models include the multiphase models already described above and turbulence. Turbulence has a remarkable influence on heat and mass transfer and hence performs a crucial role in the fluidized bed biomass gasification. Turbulence models are required for most engineering applications, including fluidized bed gasification, since direct numerical simulation is computationally too demanding. Three alternative methods can be employed to perform turbulence flow calculations: Reynolds-averaged Navier-Stokes (RANS), Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS), of which a detailed description can be found in CFD literature. The LES and DNS methods are still too computationally demanding since their application to practical engineering problems remain very limited. Therefore, the turbulence modeling on fluidized bed gasification is limited to the application of RANS. The RANS models employ the Eddy viscosity concept to model the Reynolds stresses terms. Models based on this hypothesis include the mixing length model, Spalart-Allmaras, k-ε, k-w, algebraic stress and Reynolds stress. The standard k-ε model is the turbulence model chosen by several authors due to its suitability for fluidized bed gasification, where the turbulence transfer between phases plays an important role along with the granular temperature model expressing the macroscopic kinetic energy of the random particle motion [276, 324, 326, 327, 329, 330, 342, 346]. However, other turbulence models have been implemented with identical success [337, 347].

3.1.4. Artificial neural network models

The accuracy of the equilibrium models can be improved resourcing to an artificial neural network, which is a relatively new segment of modeling when applied to gasification. ANN refers to the system's ability to learn by itelf from previous experiences, finding patterns in the responses and improving the following outputs, mimicking some human features [56]. ANN does not provide analytical outcomes, only numerical results [46, 56]. Complex features are perceived and replicated from experiment to experiment in order to optimize the set of required parameters or desired outcomes even faster, like syngas composition, for instance [348-350]. Guo et al. [351] carried out an important study which offered some insights on the ANN contribution to gasification systems, after which further works were published either for fixed beds [352, 353], fluidized beds [347, 348, 350, 354, 355], and even for correlating elemental and proximate analyses of feedstock with the estimated LHV of the syngas produced [337].

Baruah and Baruah [353] designed an ANN model to simulate biomass gasification in a fixed bed in order to predict syngas composition using a set of 18 different reported works, with experimental data to train the neural networks. The simulated and experimental gaseous composition of the final product follows a linear regression curve with high concordance between them. The model was also compared to experimental data out of the "training set" and revealed good conformity. However, increasing the database with more experimental results for other biomass species is a promising upgrade to the model, expanding its spectrum of application. The four major syngas components (CO, H_2, CH_4 and CO_2) were accurately predicted and this study is one of the few reports on the contribution of ANN to small-scale gasification. All the tested variables showed a strong influence on the outcomes of the study, although temperature reduction was still the most important variable for CO and H_2 prediction. Puig-Arnavat et al. [348] presented two distinct ANN models for fluidized beds (one for a bubbling bed and the other for a circulating bed) for the preditcion of syngas composition following biomass gasification. High agreement with experimental data was attained in both cases although different variables were seen to have a different influence on each bed. Therefore, biomass composition affects results from the circulating bed more strongly than those from the bubbling bed, whereas equivalence ratio input proves to be the most important variable in the circulating bed than in the bubbling bed. Li et al. [350] also developed an ANN model to assess the gasification of biomass in a fluidized bed, evaluating the importance of some variables such as heating rate and gasifier length on H_2 production and efficiency. Gasifier length has shown to have a direct relation with hydrogen yield as it promotes reaction rates contributing to a more H_2-enriched syngas. The heating rate has also shown to have a significant impact given that higher heating rates endorse higher char conversion and tar cracking rates. Xiao et al. [355] propose an ANN approach to studying municipal solid waste gasification in a fluidized bed, assessing the LHV of the syngas produced as a measure of accuracy. Different waste streams were tested at different temperatures, from paper to kitchen garbage, plastic and textiles. The relative errors of training and validating the model were seen to be lower than 15% and 20% respectively, which grants feasibility to the model. Again, the authors recommend expanding the set of training samples in order to achieve even more accurate results, enabling the method to be applied to a wider range of feedstocks. Pandey et al. [347] also assessed MSW in a fluidized bed through neural networks, using nine input and three output parameters to train the model in order to evaluate LHV and syngas yield. An interesting flowchart of procedures is presented, where the network building is based on a ‘yes or no’ sequence of events. This was proposed as an efficient methodology that allows for the optimization of the architectural model design. Good agreement was observed between the experimental and modelled results and high accuracy levels were attained which indicates that the performance of similar types of gasifiers under similar operational conditions may be predicted. Nonetheless, the model must be adapted whenever the input or output parameters are varied.

All these findings prove that ANN enhances the accuracy of results, with high agreement between experimental and simulated values being attained. However, the neural network method may only be accounted for if there is enough data available to calibrate and evaluate the proposed solution, which requires a set of data similar to the one with which it was trained [56].

3.2. Gasification modelling review

Table 7 presents a thorough review of the main published literature concerning numerical simulation of the gasification process in the last two decades. Works are separated by feedstock and reactor types, stating their flow regimes and the simulation methods.

Table 7 - Major published works for the numerical simulation of gasification.

Feedstock	Reactor	Gasifying agent	Temperature (ºC)	Dimension / numerical method / software	Data agreement	Reference
biomass	**fluidized**	Air, steam, air/steam, O_2, CO_2, steam/O_2	400 – 1200	0D, 1D, 2D, 3D, Euler, Lagrange, Euler-Euler, Euler-Lagrange, ANN, Aspen Plus, ANSYS SIMPLE, FactSAGE, Fluent, MFIX, MatLab	Good, reasonable, satisfactory, fair, acceptable	[50, 61, 66, 199, 270, 276, 278, 280, 286, 287, 293-295, 302, 308, 323, 325, 329, 330, 334, 338, 342, 356-377]
	fixed	Air, steam, air/steam, O_2	400 – 1530	0D,1D, 2D, 3D, Euler-Euler, Euler-Lagrange, Fluent STAR, Aspen Plus, Athen Visual Studio®, ANSYS Fluent, Excel, Engineering Equation Solver (EES®), MS Fire Dynamics Simulator, ODE23,	Good, accurate, reasonable, close, low	[113, 192, 282, 311, 321, 359, 378-394]
	entrained	Air, steam, air/steam	700 – 1400	1D, 2D, Euler, Euler-Euler, Euler-Lagrange, Aspen Plus Fluent, OpenFOAM, PHOENICS	Very good, good, satisfactory	[277, 285, 324, 359, 395-397]
waste	**fluidized**	Air/steam, air, CO_2	500 – 1200	2D, 3D, Aspen Plus, ANSYS Fluent, Euler-Euler	Very good, good, reliable	[65, 274, 275, 398-404]
	fixed	Air	500 – 1000	3D, Aspen Plus, Lagrange, SIMPLE	Good, adequate	[405-409]
	entrained	Air	---	3D, RANS, Lagrange	Fair	[410]
coal	**fluidized**	air, O_2, steam, steam/N_2, steam/air, steam/O_2	750 – 1400	1D, 2D, 3D, Euler, Lagrange, Euler-Euler, Euler-Lagrange, ANSYS Fluent, Barracuda, Fluent, Gambit, Virtual Reactor, MFIX	Good, satisfying, comparable, reasonable	[290, 317, 322, 333, 339, 411-423]
	fixed	Air, steam/O_2	600 – 1500	3D, ANSYS Fluent, Euler-Euler, MFIX	Good, comparable	[424-426]

	entrained	Steam/air, O_2, steam, air, O_2/steam	500 – 2500	2D, 3D, Lagrange, Euler-Euler, Euler-Lagrange, ANSYS Fluent, Aspen Plus, Excel®, OpenFOAM, Visual Basic	Excellent, good, reasonable, comparable	[300, 301, 326-328, 427-447]
Biomass/waste	**fluidized**	Steam, air, O_2	400 – 1200	2D, ANSYS Fluent, Aspen Plus, Euler-Euler	Good, reasonable	[163, 448-450]
	fixed	Air, steam	500 – 1200	SIMPLE, home-made models	Good	[142, 192, 310, 451, 452]
	entrained	Air	1450	Aspen Plus		[453]
Biomass/coal	**fluidized**	Air/steam, steam, air, O_2/steam	700 – 1150	2D, Euler, ANSYS, CODE SATURN, Aspen Plus, MatLab	Good, satisfactory, close, fair, sufficient	[195, 314, 315, 454-459]
	fixed	Air/steam	400 – 1250	Aspen, GASDS	Fair	[460, 461]
	entrained	O_2, steam, Air/steam, air	1000 – 1700	2D, 3D, Lagrange, Euler-Lagrange, ANSYS Fluent, Aspen Plus, ChemCAD, Thermoflex	High, good, reasonable, satisfactory	[238, 299, 314, 462-470]
Waste/coal	**fluidized**	steam	700 – 900	Euler-Euler	Reasonable	[471]
	fixed	---	---	---	---	---
	entrained	O_2, steam	1000 – 1500	0D, Euler-Lagrange, Fluent	Good	[472]
others	**miscellaneous**	O_2, steam, air	500 – 1825	2D, 3D, Lagrange, Euler-Euler, Euler-Lagrange, DEM, ANSYS Fluent, Aspen Plus, ChemCAD Comsol Multiphysics®, Matlab, MTDATA	Very good, good, reasonable, fair	[46, 48, 281, 288, 289, 328, 340, 473-490]

After analyzing Table 7, it may be noted that air, steam, or even a combination of both can possibly be applied as oxidizing agents to all the evaluated feedstocks and type of beds. Furthermore, a huge variety of methods, models and simulation codes may be seen, however broadly speaking, the majority of the cited works are based on kinetic rate models and thermodynamic equilibrium models, while the most common software used to achieve the simulations are Fluent and Aspen Plus.

Regarding the agreement between experimental and numerical data, it can be noted that almost all of the feedstock/gasifier combinations present at least a ‘reasonable’ or ‘satisfactory’ level of concordance, some of them showing ‘very good’ and ‘excellent’ comparisons. La Villetta et al. [291] point out the general assumptions made by the vast majority of stoichiometric models found in literature, which may sometimes be the cause for discrepancies observed between numerical and experimental results. The authors also conduct a chronological description of some relevant stoichiometric methods developed between 1991 and 2015 for biomass gasification. Some interesting remarks to be noticed are taken from Zainal’s model [316] in which H_2 content is seen to increase for higher moisture content in the feedstocks; from Sharma’s model [491], where the calorific content of the syngas produced seems to be improved by the increase of biomass moisture; from Jarungthamachote’s model [320], which after modification predicts reduced yields for H_2; from Huang’s studies [319] which report a first model (neglecting char) that presents higher predictability and a second model (including char) that overpredicts CO and underpredicts CO_2. These are some examples of the incorrect assumptions that are sometimes undertaken when constructing the models and their influence on the final results. Thermodynamic equilibrium provides the maximum yields achievable under equilibrium conditions, and different experimental conditions in the real gasifier or unprecise assumptions in the model may therefore contribute to the unreliability of results. In order to attain more accurate results, Puig-Arnavat et al. [492] included modifications such as semi-empirical correlations in the pyrolysis step, considering heat losses in the system and relating the tar and char content produced to the remaining quantities in the gasifier. Babu and Seth [493] also introduced modifications to the model developed by Giltrap et al. [303] concerning the char reactivity factor in the reduction zone for biomass gasification. They verified that exponentially varying this parameter afforded better agreement with the experimental results than a linear variation. Loha et al. [271] also expose the major assumptions commonly made for equilibrium models, stressing that apart from the molecules containing C, H and O, other elements are disregarded and their balances bypassed. The authors state that equilibrium models always afford methane concentrations lower than the experimental results mainly due to the pyrolysis step which is not accounted for in the model. Hence, distinct modifications to the equilibrium models have been implemented by Li et al. [317, 346] through the introduction of experimental carbon conversion and better agreement with the experimental results was achieved.

Figure 7 depicts a statistical representation of data from Table 7, regarding the distribution of the cited publications in terms of feedstock and type of gasifier bed.

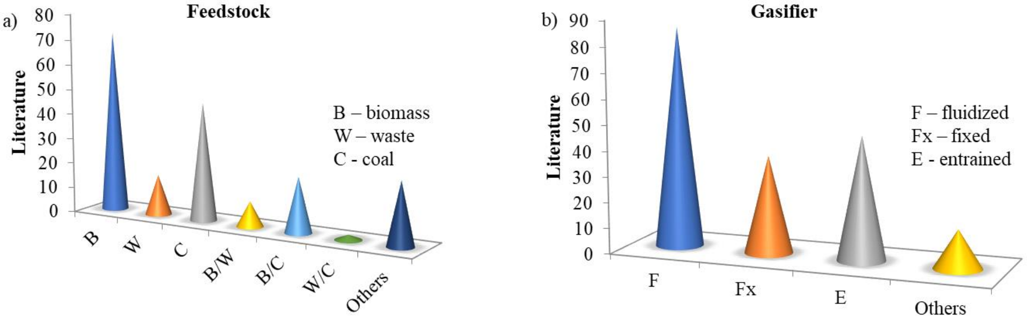

Figure 7 - Statistics of publication of numerical models for gasification studies.

As seen in Figure 7a, the most assessed feedstock within the reviewed papers is biomass (37%) followed by coal (24%), while waste represents only 8% of the share. Indeed, the co-gasification of biomass and coal embodies the co-fuel with the highest share (12%), which indicates that these materials are seen to be the most competitive for gasification purposes, possibly due to their energetic content as suggested elsewhere [49, 314, 494, 495]. In regard to the gasifier type, Figure 7b shows that fluidized beds gather almost half of the share within the cited papers. This is in agreement with the advantages presented in Table 5 and with important reviews previously reported [44, 51, 54].

3.3. Parametric study

Design and operation of the selected gasifier depend greatly on the available residues, since the characteristics of the final product reflect the performance of the system. Therefore, a compromise between the optimal values for several operating parameters must be attained once the ideal situation of optimizing them all simultaneously is almost impossible.

Experimental parameters play a crucial role in syngas yield and quality, a thorough understanding of their variation constituting a very important phase in each modeling study. Therefore, variables such as feedstock properties, feeding flow, oxidizing agent, bed material and reactor geometry among others, should be assessed in order to achieve an optimal combination of factors that allow the maximum performance of the gasification system [272, 325, 327, 414]. Singh et al. [272] reviewed several CFD models for gasification in fluidized beds and concluded that it is very difficult to compare diverse conditions due to the complexity of the process itself. For instance, Gerber et al. [280] found no influence of the bed height on the yield of gaseous products, contrary to what was published by other authors [333]. Deng et al. [496] reported an increase of gaseous fractions except for H_2 and CH_4, different to what was seen in other works [325, 333]. From these findings, it is evident that for a set of distinct conditions, different outcomes will be obtained, which is the reason why parametric studies should be held for the desired feedstock and experimental setup. Nevertheless, some major trends may be identified regarding parameters such as the moisture content present in the fuel, the temperature inside the reactor and the steam concentration throughout the process [32, 56].

3.3.1. Temperature

Temperature is an important operation parameter since it can affect the heating value and producer gas composition, according to the thermodynamics of the reactions involved. Bed temperature has a proportionally inversed influence on the heating value of the produced syngas, as one drops linearly when the other increases [116]. Gasification energy requirements are satisfied by the combustion enthalpy of biomass, higher temperatures improving its combustion, consequently resulting in superior amounts of enriched gas [103, 126, 497, 498]. High bed temperatures also promote carbon conversion and steam cracking, ensuing less char and tar formation [54, 96, 499]. The degree of bed fluidization is directly related to temperature fluctuations in the reactor, these being lower and therefore promoting a more uniform environment for higher fluidization beds. Moghadam et al. [103] investigated the influence of temperature in the co-gasification of biomass and polyethylene and found syngas production was enhanced by higher temperatures, favoring H_2 yield and reducing hydrocarbons and CO_2 contents. The same trends were observed by Peng et al. [96] when investigating the co-gasification of sewage sludge and forestry wastes, reporting increases in H_2 and CO yields, due to the *in situ* steam generated from the moisture content of the sludge, and decreases in CO_2 and hydrocarbons, as well as char and liquid yields when increasing the temperature inside the reactor. Carbon conversion efficiency was also enhanced.

Armstrong et al. [333] report on the temperature effect for the gasification of coal in a fluidized bed, an increase in CO and H_2 being seen for higher temperatures, while CO_2 and H_2O yields decrease, due to the faster consumption of these reactants promoted by the Boudouard reaction and the steam gasification reaction, respectively. This has been corroborated by Ismail and El-Salam [378] in the assessment of biomass high temperature air gasification, by Ali et al. [238] in the co-gasification of coal and bio-waste and by Monteiro et al. [294] who achieved higher quality syngas and enhanced efficiency when higher temperatures were modeled for the gasification of miscanthus (Figure 8).

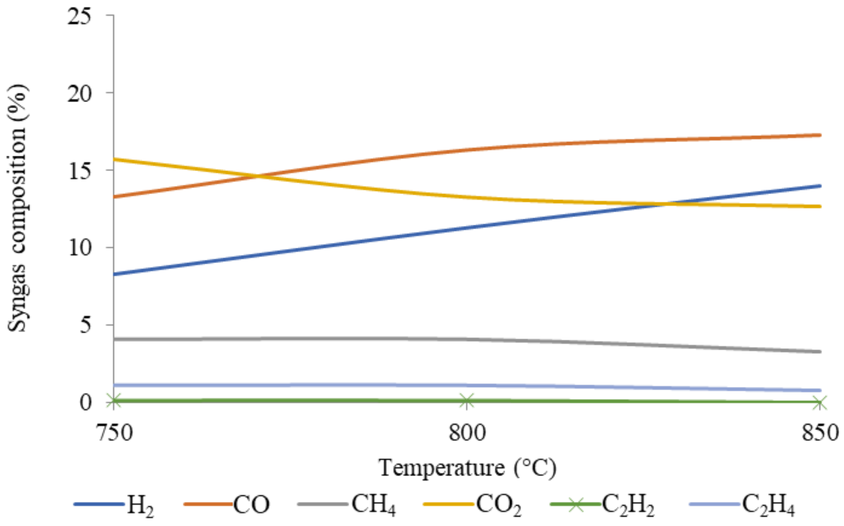

Figure 8 - Effect of temperature on the produced syngas for miscanthus [294].

Zhang et al. [412] confirm the gaseous fraction tendencies and Ku et al. [324, 325] tested different biomass streams and found similar trends regarding H_2 and CO production when high temperatures were applied to the gasifier. The authors suggest the favoring of endothermic char reactions as well as the steam reforming reaction at high temperatures as being the cause for this behavior. It is important to note that while H_2 yields are favored by high temperatures, they are also lowered (to a different extent) by the exothermic water-gas shift, which is also promoted by those temperatures [325]. Concerning the effect of temperature on CO_2 fraction, Xue and Fox [323] came across a different conclusion in the assessment of biomass gasification in polydisperse fluidized beds. The authors refer to an enhancement of CO_2 content when the temperature is raised and explain it through tar cracking, which in the temperature range tested might be completely converted, leaving only inert tar and ash behind due to the oxidation reaction. In contrast, decreasing CO and H_2 yields and enhanced CO_2 content were seen for raised temperatures in the gasification of natural coke [290]. Tang et al. [290] report higher heating values for increased temperatures.

In general, for increasing temperatures the yields of H_2 and CO increase, in addition to higher carbon conversion and producer gas yield, while the yields of CO_2 and hydrocarbons decrease, which affords an upgrade of syngas quality and gasification efficiency. A recent review work by Ahmad et al. confirms this trend [43].

3.3.2. Moisture content

Quaak et al. [67] and Themelis et al. [120] present a very clear perspective on the correlation of heating value and moisture content for biomass and municipal residues, respectively. Both studies reveal the decrease in the relative heating value for feedstocks with higher humidity, which leads to the need for drying these materials before the gasification stage takes place. This might considerably affect the temperature inside the reactor while producing steam that is readily available for other reactions, namely steam reforming reactions which lower the energy conversion efficiency [295, 309, 321]. In a recent Euler-Euler approach, Ismail et al. [334] modelled the gasification of coffee husks in a fluidized bed and reached the same conclusion regarding moisture, the CGE and the HHV of the produced syngas being negatively affected by high moisture content in the feedstock. Monteiro et al. [295] explain that higher moisture content enhances H_2 and reduces CO mostly due to the consumption of this last compound in the water-gas shift reaction, which raises CO_2 and hydrogen, as seen in Figure 9. This was also reported in other published work [321].

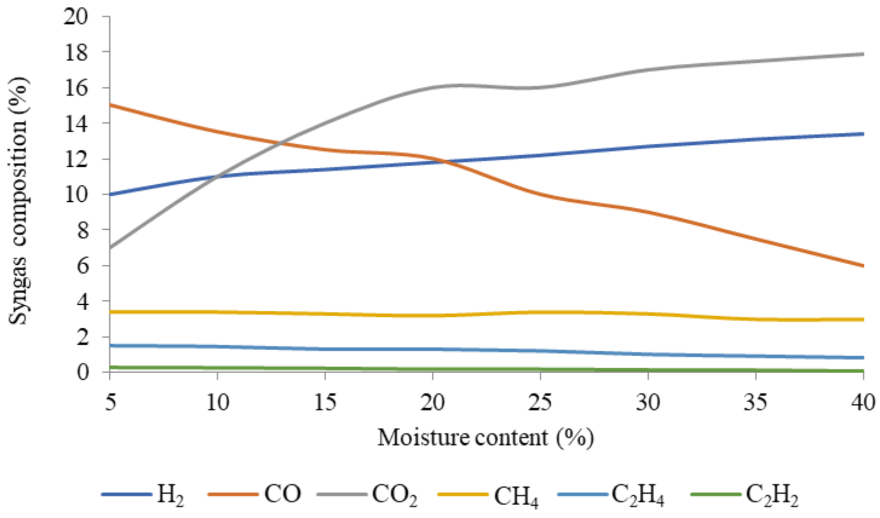

Figure 9 - Effect of moisture content on the produced syngas for peach stone [295].

La Villetta et al. [291] further explain that for high moisture content inside the gasifier, the reduction of CO yield has a greater effect than the gain in H_2 production as the heating value of CO is higher than that of H_2. This leads to a downside balance regarding syngas quality. CO_2 fraction is also seen to drop when moisture levels are higher due to lower available carbon levels [323].

Carbon conversion efficiency has shown to decrease when higher moisture content is present, due to the possibility that after the drying step, more humidity remains in the feedstock, negatively affecting the gasification step which will result in less energy available for endothermic reactions [314, 321].

3.3.3. Gasifying agent

The most common gasifying agents used in biomass gasification are air, steam, oxygen and mixtures of them [51]. An interesting study conducted by Gil et al. [331] compared air, pure steam and steam-oxygen mixtures performance on the gasification of biomass, and conclusions point out that pure steam had a general better performance concerning operational conditions (permitting lower reaction temperatures, for instance) and producer gas composition (presenting superior H_2 yields and LHV values), results confirmed by several other authors [51]. Investigations on each of the gasifying agents alone have also been conducted, some reports deserving a more detailed explanation, as follows.

Air is commonly applied as gasifying agent due to its economical nature, the produced syngas being highly diluted by nitrogen with lower heating value (usually 3.5-7 MJ/m^3) and H_2 contents typical for electricity production or heat generation [53, 229, 331]. Ong et al. [142] tested different air flow rates in the co-gasification of sewage sludge and wood chips and reported higher temperatures inside the reactor, for increasing flows. This was due to the promotion of the exothermic combustion reactions, which released more energy. They also studied the effect of air flow rate in the producer gas composition and found that when this parameter was raised the concentration of CO increased, and the char gasification reactions with CO_2 and steam were favored at higher temperatures. Oppositely, the concentration of H_2 slightly decreased with increasing air flow rates, possibly due to the promotion of the reverse water-gas shift reaction. These results were confirmed by Hernandez et al. [497], who also showed the addition of steam to air raises the quality of the produced gas, improving H_2 and CH_4 contents, with an optimal range of steam-air mixtures balancing this parameter with the gas production and the fuel conversion. This was also reviewed in [43].

Steam utilization for biomass gasification promotes syngas with higher heating value (11-20 MJ/m^3) and H_2 content [39, 51, 113, 146, 260, 497], although more energy is necessary to increase the temperature meanwhile reduced by the endothermic reactions [96]. When more steam is present, the partial pressure inside the gasifier is improved, favoring the water-gas, water gas-shift and steam reforming reactions, enhancing H_2 and CO production while lowering CO_2 yield and tar content [294, 324, 412]. Some authors also suggest that enhanced steam concentrations require part of the heat present in the system, contributing to a temperature drop as well as diluting the syngas produced, lowering H_2 and CO fractions. Nevertheless, as this also favors the exothermic water-gas shift reaction, more H_2 is produced, no significant variations being seen for this compound, the opposite to what is seen for CO [500].

Compared to steam gasification alone, steam-oxygen promotes biomass conversion, accompanied by a CO_2 content increase simultaneously with CO and H_2 content decrease [43, 501]. O_2-enriched air provides syngas with moderate heating value (usually 9-15 MJ/m^3) but has the drawback of being more expensive, once oxygen generators are required. Zhou et al. [137] used oxygen as gasifying agent for biomass gasification and witnessed an uplifted gasification as well as enhanced carbon conversion, confirming a lower LHV for the producer gas. Guo et al. [502] examined the kinetic behavior of biomass under several oxygen concentrations and were able to see significant differences in the composition and distribution of the generated products, as well as increased reaction rates and activation energies for CO and CO_2, when oxygen concentration was raised. H_2 activation energy depicted the opposite trend, diminishing with increased levels of O_2. In general, activation energies were higher for oxygen than for inert atmosphere.

Regarding so many aspects to take into account, a trade-off between gas quality and yield, process efficiency and cost should be reached to optimize the overall process. There are some parameters that elucidate this balance, two of the most used regarding the influence of the gasifying agent being equivalence ratio and steam-to-biomass ratio.

3.3.3.1. Equivalence ratio

Equivalence ratio is defined as the air to biomass weight, in relation to the stoichiometric air to biomass weight needed for complete combustion [54], as shown in Eq. 1. Gasification presents ER values below 1, the optimum range for biomass lying between 0.2 and 0.4, depending on other operation conditions [53, 64, 503] and enabling the generation of tars and char to be controlled [146, 229].

$$ER = \frac{(O_2/m_{biomass})}{(O_2/m_{biomass})_{stoichiometric}} \tag{1}$$

Ismail et al. [334] concluded that increasing ER affords lower H_2 and CO yields due to the oxidation of oxygen, also stated by Rodrigues et al. [314]. This decrease in the hydrogen levels accounts for a reduction in the heating value of the syngas produced, the combination of temperature and ER also promoting lower heating values. In a recent work [381], Jayathilake and Rudra assessed the air-gasification of birchwood in a fixed reactor and found similar trends, except in the case of H_2 which decreased for higher ER values. The authors explained this behavior based on a combined effect of reactions such as char oxidation, Boudouard reaction, dry reforming and steam reforming reactions. This confirms the extreme importance of controlling this parameter in order to achieve a high-quality syngas. Monteiro et al. [295] explain the optimal range of ER values for the gasification of peach stone, where H_2 and CO are seen to increase until moderate ER values to ensure complete gasification, avoiding constraints such as excessive char formation and low heating values for syngas (Figure 10).

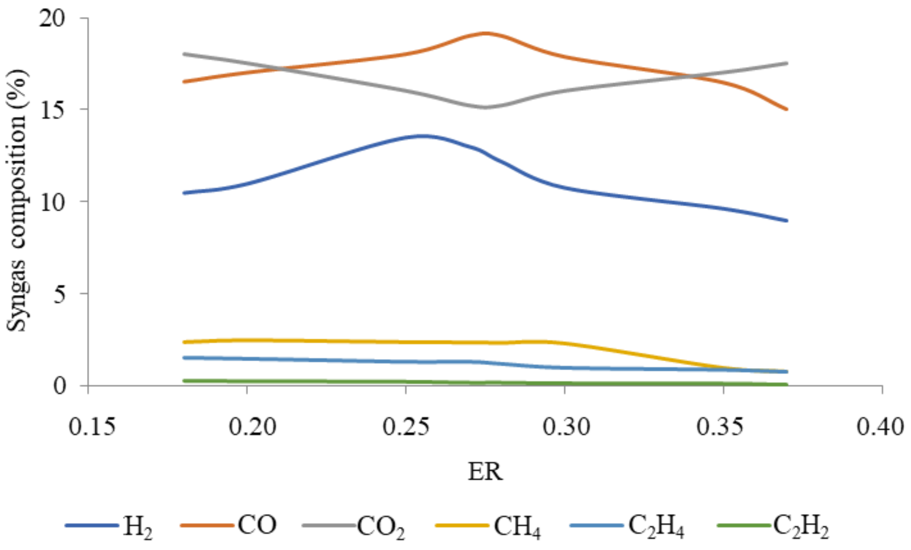

Figure 10 - Effect of equivalence ratio on the produced syngas for peach stone [295].

A negative effect of ER on conversion efficiency and syngas quality is also reported, comparable to other works [291, 294, 381]. This is due to the fact that syngas heating value is a direct function of the combustible fraction [465], which is seen to drop for higher ER values. Higher ER values have also been seen to promote carbon conversion efficiency due to the augmented oxygen availability for combustion, which produces more energy to be used in endothermic reactions [321]. Nevertheless, some authors report reduced heating values and CGE for higher ER due to non-converted solid carbon [314].

3.3.3.2. Steam to biomass ratio

SBR defines the relation between the steam income and the biomass (or any other feedstock) fed to the gasifier [32], as shown in Eq. 2.

$$SBR = \frac{Steam\ mass\ flow}{Biomass\ feed\ rate} \tag{2}$$

Several studies report improved syngas yield, LHV and carbon conversion efficiency when steam is utilized as gasifying agent [103, 331] and higher gaseous content production for increasing SBR [53, 367, 497]. Although a compilation of reports on this topic points to SBR values between 0.3 and 1.0 as the most enhancers towards carbon conversion, cold gas efficiency, hydrogen yield and tar reduction [43, 54], Pindoria et al. [498] found higher H_2 and CO_2 yields as well as lower CO, CH_4 and C_2H_2 contents, for SBR values between 1.35 and 4.04. Above the optimum range gas yield, LHV and carbon conversion efficiency tend to decrease because high amounts of unreacted H_2O will appear in the product gas, causing thermal efficiency to decline significantly.

Tavares et al. [296] report enhanced H_2 and CO_2 fractions and decreasing CO concentrations for higher SBR values when converting MSW (Figure 11), explaining this fact by the water-gas shift reaction, also found by Ku et al. [325] for biomass.

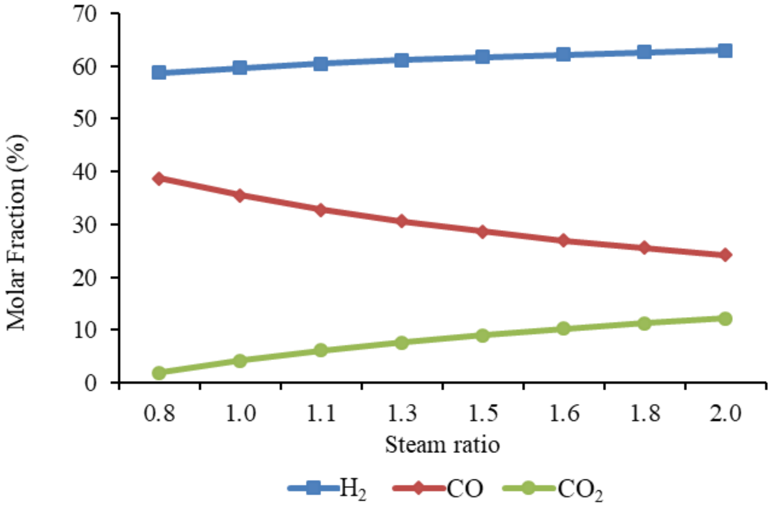

Figure 11 - Effect of steam to feedstock ratio on syngas molar composition [296].

Rodrigues et al. [314] assessed distinct coal-biomass blends and accounted higher CO and lower CO_2 and H_2O content for increasing SBR, pointing to higher heating value in the syngas obtained. Higher SBR have also been reported to promote carbon conversion, decreasing the ash content and improving gas yield. Dou and Song [482] assessed the hydrogen production from the steam gasification of glycerol and show that as the steam ratio is raised, higher conversion and H_2 yields are attained, which has also been stated for other feedstocks [324, 331, 504].

3.3.4. Pressure, particle size and residence time

Regarding pressure, there are two major operating conditions: atmospheric pressure or pressurized regimes, the latter being more efficient but also more expensive. It is known that higher pressures afford lower tar yields and lower volumetric gas flow rates, meaning that a smaller gasifier can be used. As some of the downstream applications for syngas require pressurized conditions (e.g. gas turbines or engines) the necessary technical requirements can be met before that stage, compensating possible operational issues brought by the introduction of high-pressure feeding systems [229]. An extra advantage achieved when operating the gasifier under pressure is the recarbonization of CO_2 enabling its capture. Pressurized systems are viable in large plants but uneconomical at smaller scales. Sharypov et al. [126] studied the influence of pressure applied during pyrolysis on the conversion of wood biomass and plastic mixtures and it was shown that higher pressures led to higher yields of light liquid products.

The reactivity of different types of biomass chars was tested under diverse conditions and evidences on higher pyrolysis pressures leading to lower surface area and therefore less reactive chars were found [499, 505, 506], as shown on Figure 12. A possible explanation for this seems to rely on the fact that high pressures may inhibit the transport effect during pyrolysis, reducing the release of volatile matter. This will cause large deposition on the pore surfaces, creating secondary reactions hence deactivating char.

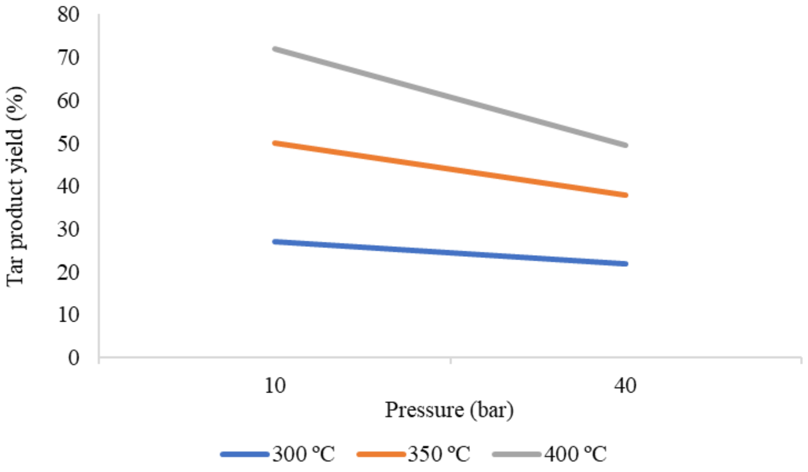

Figure 12 - Effect of pressure on tar yields, for three studied temperatures.

Assuming that higher pyrolysis pressure improves fluidity and mobility of the counter fuel molecules and structure, possibly reducing its porosity, another reactivity decrease can be settled during co-conversion.

In what concerns particle size, it is easily understandable that small-sized particles take advantage of their prone ability to mix with each other and to readily fit any space left. This increases the overall energy efficiency of the gasification process, although their size reduction may constitute an extra cost. Smaller particles enhance hydrogen and dry syngas yields, as well as carbon conversion efficiency [39]. Ahmad et al. [43] emphasize this conclusion, reviewing several works by other authors and presenting also their own experiments. In turn, bigger-sized particles reduce the pre-treatment costs but difficult the feeding, devolatilization and overall performance of the decomposition. Figure 13 shows the evolution on the producer gas composition and the overall conversion for different particle sizes, registering a general decrease in the gaseous content and in the fuel conversion for bigger particles [77].

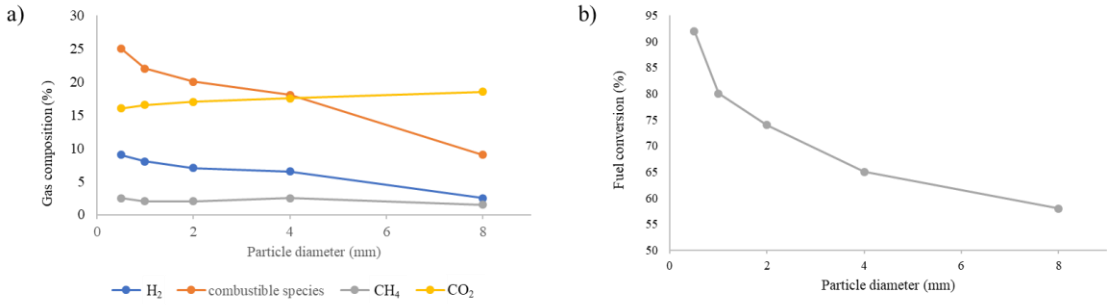

Figure 13 - Effect of fuel particle size on syngas composition and fuel conversion [77].

Particles size is not so relevant in the case of fluidized beds as compared to entrained beds, for instance. This is due to the longer residence times and strong mixing occurring in fluidized beds thus obviating the need of extreme small-sized fuel particles. However, size reduction leads to a more effective mass and heat transfer between the particles due to larger surface areas and lower diffusion resistance coefficients, increasing reaction rates and improving fuel conversion and gasification efficiency [39, 77, 155].

Residence time is the average period for which the fuel particles remain inside the gasifier. This should be long enough so that gasification can proceed adequately, depending on the type of reactor and bed material [157]. In the case of fluidized beds, the residence time is longer for BFB and shorter (few seconds repeating cycles) for CFB [64, 229]. Pinto et al. [146] performed the gasification of lignin pellets in a BFB and verified enhanced gas yields with higher H_2 and CH_4 contents, as well as lower tar contents, for increasing residence times. Hernandez et al. [77], found the same conclusions in the case of an entrained gasifier, as increasing residence time raised not only the yields of H_2, CO_2 and hydrocarbons, but also the producer gas yield and carbon conversion, contributing to higher gasification efficiency. Zhou et al. [507] confirmed these trends for a simulation on a fixed-bed gasifier, when increasing residence time along with temperature in the reactor.

3.4. Partial conclusions

This chapter enabled a large number of papers on the topic of gasification modeling to be gathered in order to understand their position regarding the feedstock used, reactor and major experimental conditions applied. In doing so, a broad panorama of state-of-the-art for numerical models to simulate gasification is presented and some interesting remarks may be identified. These simulations assemble a large amount of data, processing the information in order to simplify and reduce the resources needed to perform experimental runs in real gasification facilities, whether they are lab-scale, pilot-scale or industrial-scale.

Among the possible approaches for studying syngas production from distinct types of feedstocks, kinetic, thermodynamic and computational fluid dynamic models were seen to be preferred, several different software and technologies being applied and numerous mathematical codes developed for specific purposes. It is not unusual that after the proposed employment of a developed model, it is further enhanced according to the simulation results, with the aim of evolving to a better approach. This is carried out namely by reducing or adjusting the assumptions made when first building the mathematical model, by taking into account operational parameters, gasification steps or chemical compounds that were missing, or even by refining the applied equations. This reutilization and adaptation of pre-existing models supports gasification as an auspicious thermal technique as it illustrates the rising need for solutions for problems such as waste treatment techniques, energy production or the synthesis of fuels and chemicals, which are granted by the attainment of an adequate-quality syngas.

From the evaluated feedstocks, biomass and coal were shown to be the top options for gasification fuels, depicting 37% and 24% respectively of the total share. Regarding the gasifier type, fluidized beds are highlighted for being used in almost 50% of the assessments, followed by entrained beds, mostly used for coal gasification. Within a complex process involving several steps, multiple combinations of experimental conditions and therefore many potential problems, fluidized reactors feature a fairly low-cost option and are relatively easy to operate. Furthermore, they present advantages such as good scale-up potential and wider feedstock size possibilities which is especially important in the case of waste and biomass streams.

Computational fluid dynamics models of the fluidized bed gasification process are all based on conservation laws of mass, momentum, energy and species. However, these equations are not sufficient to fully describe a fluidized bed biomass gasification process. The CFD basic governing equations need to be supported with specific physical and chemical models or assumptions to completely represent a fluidized bed gasification process. The most relevant additional models include multiphase models, turbulence and pyrolysis in which the works on modeling generally differ and further developments are needed.

Regarding the agreement between numerical simulations and the experimental results achieved in gasification facilities, the vast majority of the models revealed a high level of agreement, with ‘reasonable’ or ‘satisfactory’ validations being observed only a few times. Such high-graded comparisons afford noticeable reliability in the developed models, emphasizing their capability to resume the optimization of all the necessary operational parameters as well as predicting the experimental results accurately. This fulfills the proposed goal of reducing the time, cost and resources required to perform gasification experiments within adequate conditions so as to achieve syngas with a desired quality for the planned use.

As far as experimental conditions are concerned, only major trends could be identified for some of them, which supports the need to continue developing new models and adapting the existing ones to every situation, since distinct parameters afford completely different outcomes. Operating conditions were explored and major conclusions towards their optimal application and the most significant trends exhibited were pointed, regarding a maximization of the process and results. With regards to the temperature effect, higher bed temperatures promote combustion and carbon conversion, enhancing syngas yields as well as lowering the formation of chars and tars. Relative to the pressure effect, a parallel interpretation can be assumed, once higher pressures reduce char and tar yields, as well as promote CO_2 sequestration. As far as particles size is concerned, size reduction leads to a more effective mass and heat transfer, which increases reaction rates hence enhancing thermal conversion. For selecting the gasifying agent among the various possibilities, a balance between gas quality and yield, process efficiency and cost should be met. Air depicts the most affordable option but compromises syngas quality, steam offers better results but requires more energy to maintain the temperature inside the reactor, steam-oxygen mixtures produce higher yields of CO_2 but reduced contents of H_2

and oxygen-enriched air constitutes an intermediate solution but is far more expensive. Residence time seems to be directly related to the producer gas yields, as longer periods promote H_2 and CO_2 contents, as well as carbon conversion. Possible problems and corrective procedures in terms of design, handling and operating features were also presented.

As populations are growing at a fast pace, higher energy requirements are foreseen as well as more efficient ways to produce it. Gasification embodies a promising technique that accomplishes this need with the benefit of treating waste in a sustainable and effective manner. This chapter depicted an important contribution to the operational knowledge of gasification, featuring the major trends for the main experimental conditions. This enables reuniting the most favorable set of parameters for dedicated feedstocks and equipment, in order to perform more efficient conversions and achieve a higher degree of sustainability. Furthermore, after identifying the most suitable profiles for establishing the gasification experiments, it was possible to perform the following parts of this work, holding the experiments under settings as close as possible to the ideal conditions.

Chapter 4 – Environmental Assessment of Low Temperature Waste-to-Energy Techniques

The content of this chapter may be cited as:

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Ramos, A., Carlos A. Teixeira and A. Rouboa (2018). "Assessment study of an advanced gasification strategy at low temperature for syngas generation." International Journal of Hydrogen Energy **43**: 10155-10166.

Ramos, A., J. Berzosa, F. Clarens, M. Marin and Abel Rouboa (2019). "Environmental and socio-economic assessment of cork waste gasification: life cycle and cost analysis." Accepted for publication in Journal of Cleaner Production. DOI: 10.1016/j.jclepro.2019.119316

4.1. Life cycle assessment

Life cycle assessment is a methodology that enables the quantification of the impacts related to a specific process or combination of processes, for instance waste management [508]. Distinct methodologies are available to characterize the impact categories depending on the assessed topic, CML being one of the most commonly used when environmental assessments are performed [509].

As stated in ISO 14040:2006 [19], life cycle assessment is the compilation and evaluation of potential inputs, outputs and potential environmental impacts of a product, process or service, through its life cycle. Environmental inputs and outputs refer to natural resources, products or energy demand and to emissions and solid waste. The life cycle consists of the technical system of processes and transport routes used at, or needed for, raw materials extraction, production, use, end of life, recycling and final disposal. LCA methodology is comprised of four stages (goal and scope definition, inventory analysis, impact assessment and interpretation), as shown in Figure 14.

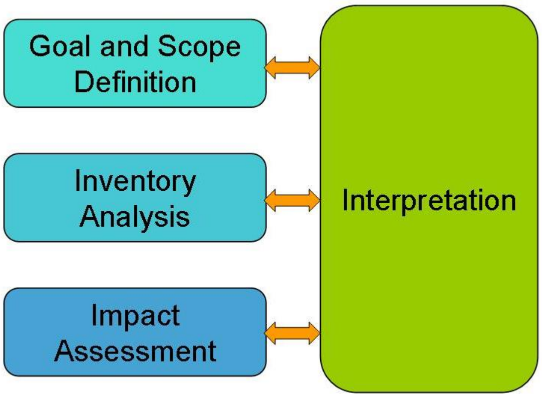

Figure 14 - LCA methodology according to ISO 14040:2006.

The goal and scope definition phase is the first step in an LCA study. This description includes the intended application and audience, the reasons for carrying out the study, and the scope of the study. The scope includes a description of the study limitations, function, functional unit (fu) and boundaries. The allocation approaches, data requirements and quality, the main assumptions, methodology, the interpretation method and the reporting via are also described here. Particular care should be taken when choosing the system boundaries to assure that they are kept throughout the LCA, referring for instance if distribution/transportation, use of fuels, electricity and heat, disposal processes, etc. are included or excluded. Data quality is also a significant feature as it influences the overall uncertainty, system limitations and ultimately the goal. Existing constraints in the data collection should be mentioned in the scope and reported in the final document. Allocation is due when more than one product/service is achieved through the system.

In the Life Cycle Inventory (LCI) analysis an inventory of the input/output data is collected and interpreted in order to calculate the different impacts and obtain results that meet the defined goal. Consequently, the analysis of the results is presented in a flow chart of the technical system. Emissions, energy requirements and material flows are calculated for each process included in system boundaries. Data have to be adapted and dimensioned to the functional unit, which is defined in the goal and scope.

In the Life Cycle Impact Assessment (LCIA), the product or production system is examined from an environmental perspective using category indicators. The LCIA also provides information for the interpretation phase. Each impact category is represented by an indicator which quantifies the damage via a reference unit. Thus, a relationship between the flow and the reference unit is established, enabling the quantification of an inventoried substance in the assessed impact. For each emission, the environmental mechanism is modelled and its contribution to the environmental impact is calculated. Two main types of characterization models are known, according to whether they consider intermediate (midpoint) impacts or final (endpoint) impacts [509]. The midpoint approach brings forth a lower degree of uncertainty, whereas the endpoint approach depicts the result at the end of the environmental mechanism therefore at the level of the areas of protection. These two approaches complement each other, surpassing their individual weaknesses and that is why some methodologies constitute a mixture of midpoint and endpoint indicators [510].

As described by the Environmental Protection Agency [511], abiotic depletion (ADP) categories deal with the use of natural non-living resources such as metal ores and crude oil, acidification potential (AP) assesses the impact of acid substances and their relative compounds and eutrophication potential (EP) concerns substances that enable microbiological growth and consequent oxygen consumption; global warming potential (GWP) includes all greenhouse gases and their cumulative effects over a given time period (by general convention 100-year values were used); ecotoxicity relates to the emission of substances affecting the ecosystems: freshwater aquatic ecotoxicity potential (FAETP) and marine aquatic ecotoxicity potential (MAETP) for water life, terrestrial ecotoxicity potential (TETP) for land based impacts and human toxicity potential (HTP) for harmful substances for mankind; ozone depletion potential (ODP) measures the impact of the gases responsible for the destruction of the ozone layer and instead, photochemical ozone creation potential (POCP) concerns the potential to create tropospheric ozone. A more detailed description of the impact categories may be found in Annex 1.

The impact assessment helps to increase the knowledge and understanding about the environmental inputs and outputs, and at the same time allows improving the inventory analysis. Following the ISO 14044:2006 guidelines "the LCIA phase shall be carefully planned to achieve the goal and scope of an LCA study. The LCIA phase shall be coordinated with other phases of the LCA to take into account the following possible omissions and sources of uncertainty".

Interpretation has the aim to analyze results and its relation to the goal and scope defined. In this phase following ISO 14044:2006 [19], conclusions are reached, the limitations of the results are presented and recommendations are provided based on the findings of the preceding phases of the LCA. A readily understandable, complete and consistent presentation of the results should be attained relative to the goal and scope defined. Reviewing and revising the scope, the nature and quality of the data collected may lead to an iterative process until the results are consistent with the defined goal. The fact that a relative approach was utilized in the LCIA phase should be reflected in the interpretation, as the final results may serve as recommendations to decision-makers.

In practice, the system is divided into processes which are linked to each other by flows of intermediate products, product flows or elementary flows. Intermediate product flows correspond to basic materials and sub-parts such as feedstocks and resources coming from other processes. Product flows are constituted by recycled materials and reusable components. Elementary flows include air, water, land, etc. The integration of all the inputs, outputs and flows according to the functional unit leads to the calculation of the environmental impacts, through the chosen methodology and indicators.

There are already some publications on LCA of different waste streams, but regarding all the specificity required by the ISO, it is difficult to compare them and take overall conclusions due to different scopes, aims, functional units, system boundaries, methodologies, etc. Rajaeifar et al. [512] made a compilation of several LCA studies for

MSW management systems highlighting the need to report complete and specific information and address malpractices such as deficiencies in goal and scope definition or using unrepresentative waste compositions. Various authors have published interesting assessments on WtE. Mendes et al. [513], Liamsanguan and Gheewala [514] and Parkes et al. [21] compared incineration and landfill-based operations in different locations, namely: Brazil, Thailand and England. Taking in consideration the system boundaries and features for each work, the authors reached similar conclusions: incineration created lower environmental impacts than landfill with respect to GWP. Pikon and Gaska [515] compared incineration impacts to other non-thermal processes, such as sorting, composting, recycling and biological treatment and also report lower greenhouse gas emissions for incineration. Ouda et al. [516] compare incineration to other options such as bio-methanation for the treatment of MSW in the Kingdom of Saudi Arabia, incineration proving to be efficient and adequate in terms of power generation and cost. Rajaeifar et al. [512] reported that incineration yields greater environmental benefits than other techniques, namely anaerobic digestion, landfilling or composting. Regarding the economic perspective, Rigamonti et al. [517] developed a combined sustainability tool incorporating environmental and financial indicators. This tool aims to give a more complete view of the assessed procedures whenever the implementation of a designated technology is being evaluated. Despite agreement among several researchers, Bueno et al. [518] have expressed concern about making direct comparison across different environmental categories, suggesting instead the use of indicators based on the same environmental yields to calculate the impact. Chen and Christensen [519] assessed two different incinerators in China and corroborated the environmental savings and sustainability profiles attained by this technique. Zaman [520] performed a comparative LCA study for MSW incineration and gasification, this last technique showing lower results for GWP and ecotoxicity categories. Al-Salem et al. [521], who appraised alternative scenarios for the waste management in the Greater London area, report lower greenhouse gas emissions from a technology based on gasification. Arafat et al. [522] also contextualized gasification performance among several other techniques and found it superior to most of the competing techniques. Gunamantha and Sarto [523] made a parallel LCA assessment between landfilling, incineration and gasification for solid waste in Indonesia and concluded that gasification portrayed the best environmental profile.

As no integrated LCA studies for Portuguese MSW samples were found, this chapter assesses the environmental impacts of incineration and regular gasification of such feedstock, these techniques being considered as low temperature WtE. Also, a case-study for the gasification of cork residues was herein included, as an application of regular gasification to a biomass sample (Ecorkwaste project).

4.2. MSW incineration and regular gasification

4.2.1. Materials and methods

The incineration plant assessed in this study works in continuous operation treating around 1 100 tonnes of waste per day and producing about 170 000 MWh of electricity per year, from which an average of 90% is supplied to the national electric grid. Waste is discharged in a closed depressurized building, where claws and hoppers move residues to the combustion grids. Here, the waste is decomposed at temperatures between 1000 ºC and 1200 ºC in the presence of excess oxygen, generating flue gases which are released at 950 ºC and also bottom ash. These gases go through an energy recovery boiler, where heat is utilized to produce steam which is later transformed into electrical energy in a turbine. Before its release into the atmosphere, the gaseous fraction is cleaned passing through scrubbers and filters, hazardous substances being removed and some even converted into marketable products (not considered here). Bottom ash is collected and landfilled and heat is used in a boiler, where steam is produced and then sent to a turbine to generate electricity [524]. Figure 15 presents the functioning of the incineration plant [524], its main units depicting the reception tank and hopper, the incinerator, the separation of magnetic materials, the boiler, the gas treatment system and the landfilling of slag and inert ashes.

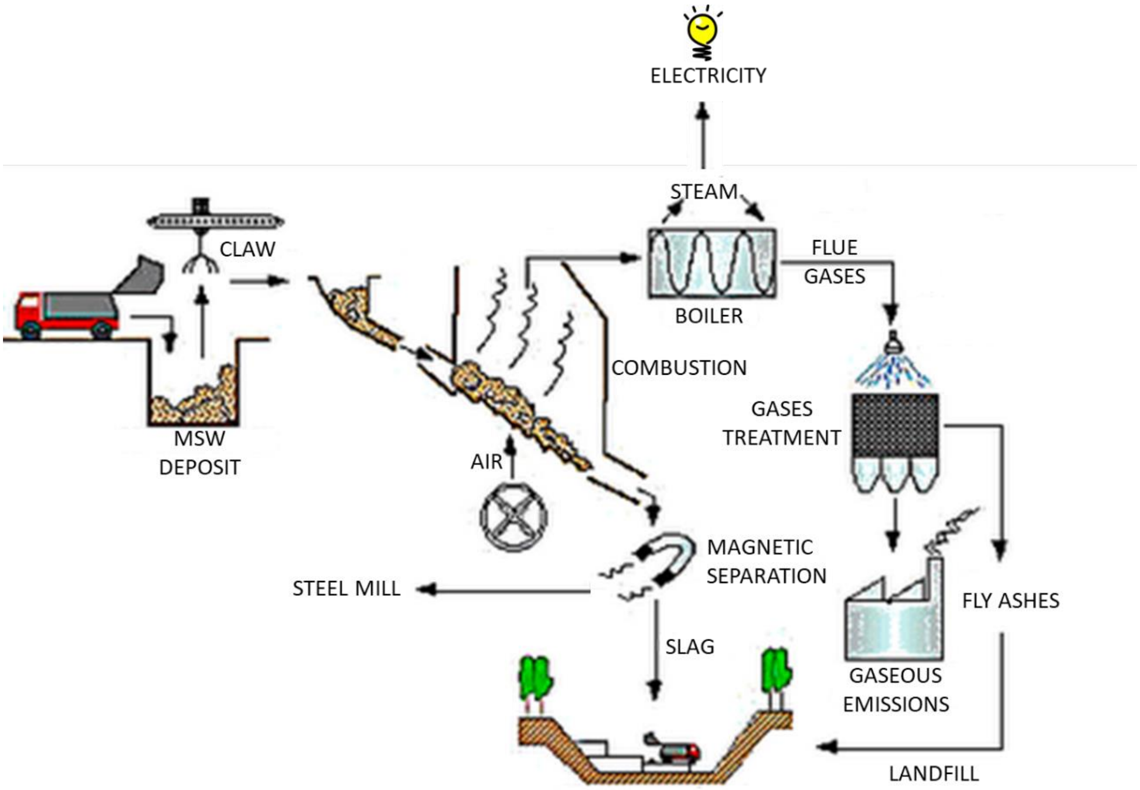

Figure 15 - Schematic of the incineration unit for municipal solid waste [524].

Regarding the gasification plant for MSW, it allows a maximum flow of 50 kg/h and works with a bubbling fluidized bed at an average temperature of 800 ºC. The plant is composed by the following units [525]:

- Feeding system with two storage tanks discharging the feedstock to the reactor through an Archimedes' screw and avoiding entrance of air into the feeding line;
- Fluidized bed reactor with a tubular shape and 4.15 m height, per 0.4 - 5 m diameter, internally coated with ceramic refractory material, enabling the feedstock entrance at 0.5 m from the bottom along with pre-heated air from the base at a maximum flow of 70 m^3/h. The gasification process is monitored by three temperature sensors inside the reactor and syngas leaves the chamber through the top, at nearly 700 ºC;
- Gas cooling system composed by two heat exchangers, the first one cools the syngas to roughly 300 ºC in an air co-current flow and the second one to 150 ºC by forced air flow from the outside;
- Bag filter made of cellulosic material, which removes carbon black and ash through the bottom, lastly conveying it to a proper tank;
- Condenser which handles the liquid formed in the cooling unit, cooling it down to room temperature on a third heat exchanger.

Figure 16 represents the gasification system.

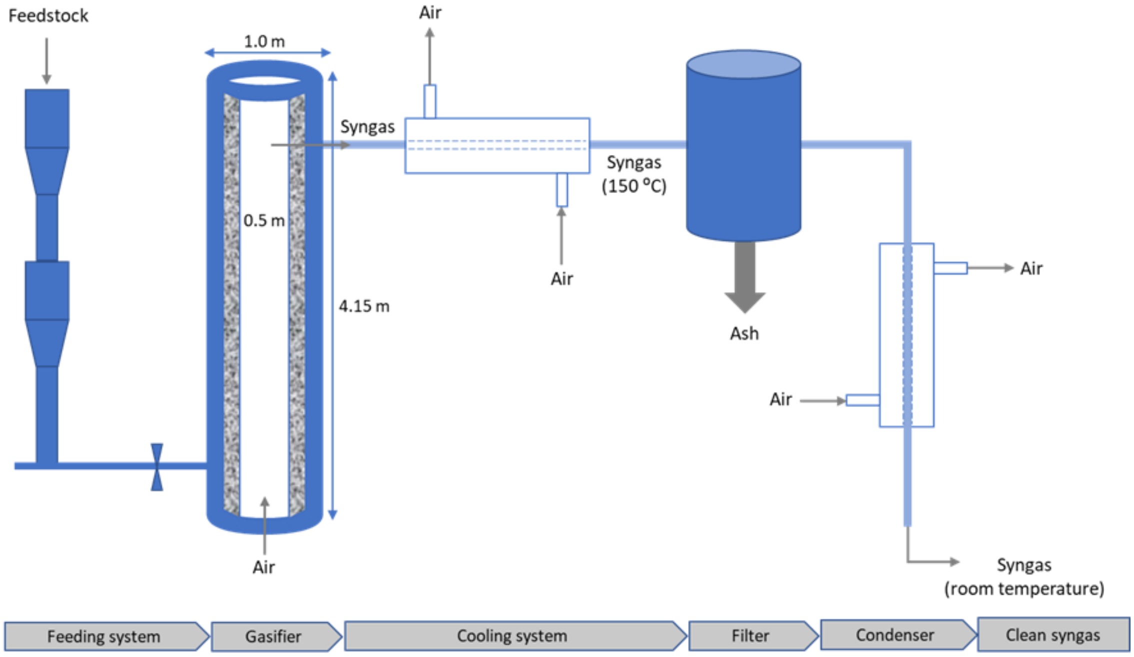

Figure 16 - Schematic of the bubbling fluidized bed gasifier.

4.2.1.1. Scope, system boundaries and functional unit

The scope of the present study for the conversion of MSW was the analysis of the environmental impacts caused by incineration and regular gasification of municipal solid residues. Data were modelled in GaBi® software, thus enabling the environmental assessment of eleven different impact categories, as recommended by CML 2001 methodology [509].

Figure 17 describes the limits of each system, dashed blue lines indicating the boundaries. Colored boxes represent the processes, which are connected by flows (arrows). MSW was considered an input as received at the plant, its origin, collection and transport to the thermal treatment facilities being excluded from the boundaries of the system. Also excluded were metallic scrap regeneration. The power generated from each WtE replaced the electricity from the grid, in an auto-consumption mode, indicated by the green route (electricity flow). The dotted green arrows stand for the seldom occasions where electricity from the grid is used to start the system, after maintenance or shut down periods. For the gasification scheme, decomposition was performed using a bubbling fluidized bed in the presence of oxidizing agents (oxygen and steam).

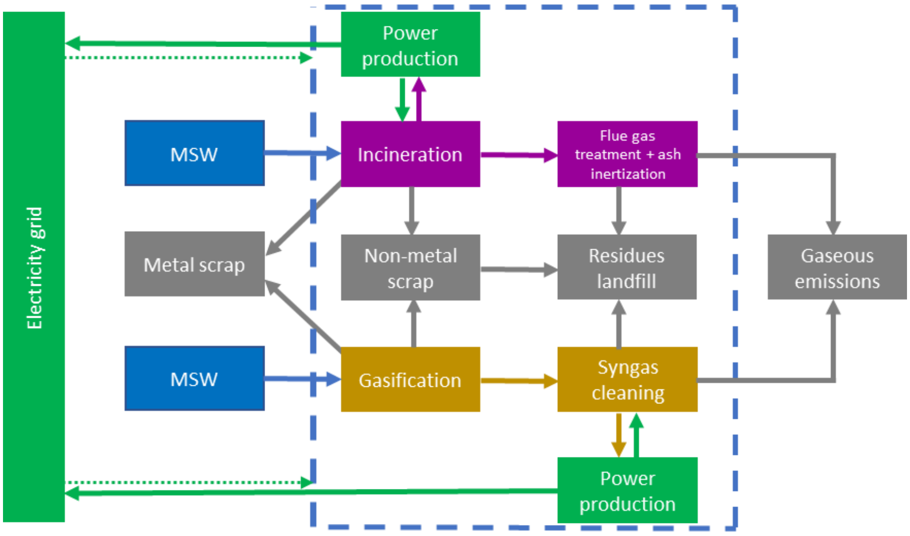

Figure 17 - System limits considered in this study for: incineration and regular gasification.

The blue route refers to the MSW path within the system, from its entrance to the combustion chamber, towards the gas cleaning processes (material flow). The grey route represents the sub-products of the techniques, some of them constituting possible hazards (gaseous emissions, landfill residues) and others secondary assets as metal scraps. The functional unit (fu) was defined as 1 tonne of MSW received at the plant, its characterization being shown in Table 8.

Table 8 - Characterization of the MSW used in this assessment.

Waste type	Weight %
Organic	37.57
Paper	10.47
Plastics	12.10
Metals	2.45
Glass	5.53
Textiles	16.46
Others	15.42

The selected MSW sample presented a lower heating value of 9 GJ/tonne and a moisture content of 40%. Thus, although drying was essential as pre-treatment, these residues showed promising energy content regarding energetic valorization [526].

4.2.1.2. Life cycle inventory and methodology

In order to assess the environmental impacts displayed by MSW treatment under the WtE techniques considered in the present section, a life cycle inventory for each of them was developed. The inventory data for the incineration study is mainly primary as it was directly provided by an industrial partner, whereas for regular gasification these data were adapted taking into consideration the standard flows included in the software database. Data modelling for MSW was achieved with product sustainability software GaBi® (database version 4.131 distributed by PE International) [527], the environmental performance being evaluated through the calculation of the suitable indicators by the use of CML 2001 methodology [509].

As seen from Figure 17, major processes may be considered for each of the WtE methodologies, namely the purple and orange boxes for incineration and regular gasification respectively, and also the landfill process (common to both). These are the focal stages where inputs and outputs need to be carefully accounted since variations in these may influence the environmental results significantly. Incineration concerns three main processes (Figure 18): MSW burn (incineration) producing heat and steam that are used to produce electricity; flue gas treatment and ash inertization; landfill of the remaining inerts. Gasification also includes three key processes (Figure 19): MSW degradation (gasification) producing syngas; clean-up steps from which syngas is further refined in order to be used for electricity generation; landfill of the inert solids produced.

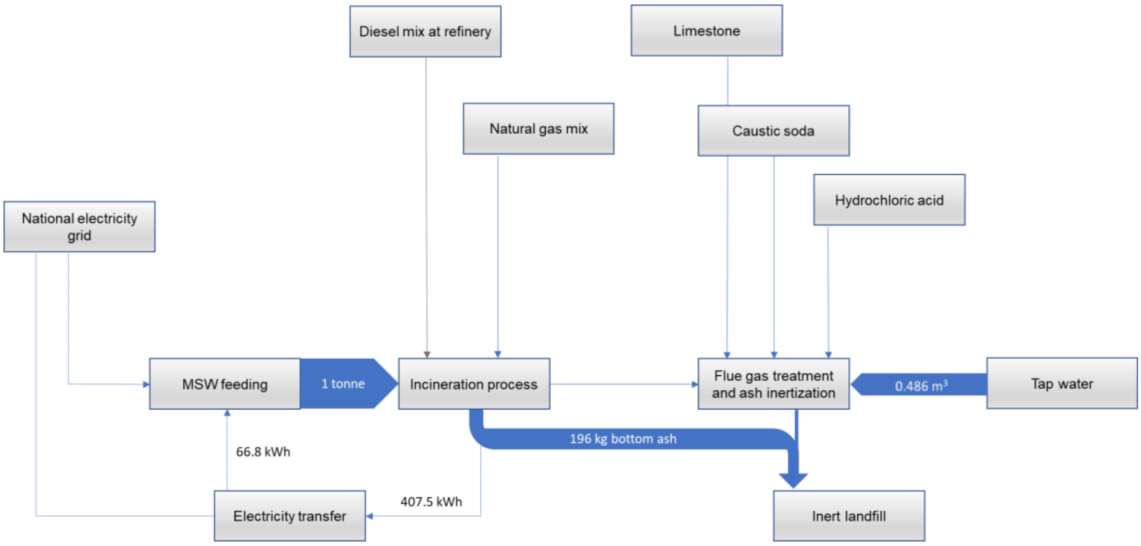

Figure 18 - Flowchart for the incineration of 1 tonne of MSW.

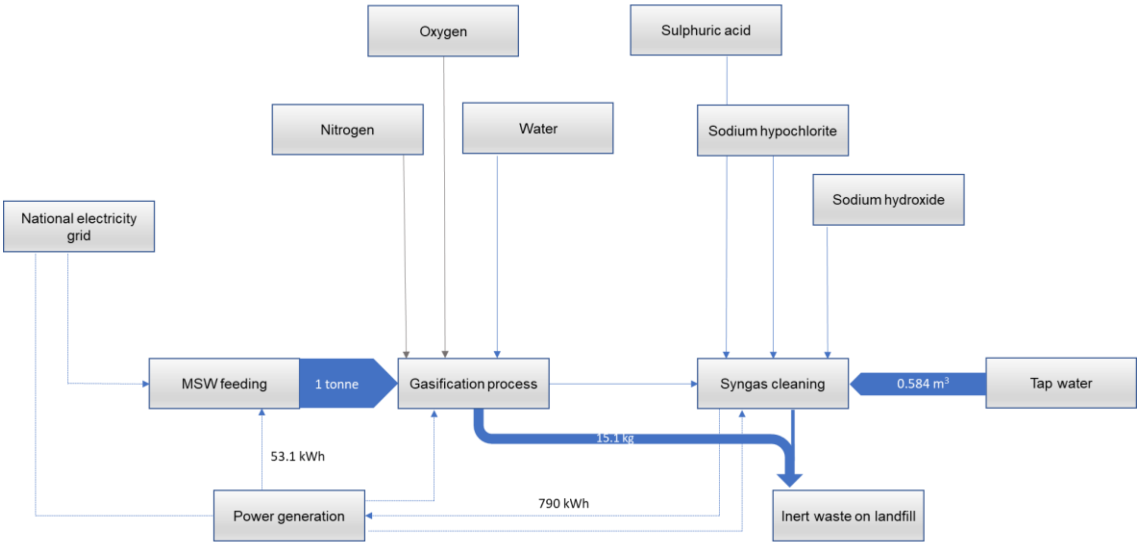

Figure 19 - Flowchart for the regular gasification of 1 tonne of MSW.

Besides the main marketable products generated from the techniques assessed (such as electricity, which has two purposes: supplying the facilities and contributing to the national grid), a common by-product is also produced during waste conversion: steam. However, this output was not considered for the calculations since it is utilized to resupply the system, in the units where steam is requested.

Table 9 shows the selected impact categories evaluated under CML 2001.

Table 9 - Impact categories assessed in the LCA of MSW.

Impact category	**Units**	**Abbreviation**
Abiotic Depletion Potential	kg Sb-eq.; MJ	ADP
Acidification Potential	kg SO_2-eq.	AP
Eutrophication Potential	kg PO_4-eq.	EP
Global Warming Potential	kg CO_2 eq.	GWP
Terrestrial Ecotoxicity Potential	kg DCB-eq.	TETP
Freshwater eutrophication	kg DCB-eq.	FAETP
Marine Ecotoxicity Potential	kg DCB-eq.	MAETP
Human Toxicity Potential	kg DCB-eq.	HTP
Ozone Depletion Potential	kg R11-eq.	ODP
Photochemical Ozone Creation Potential	kg C_2H_4-eq.	POCP

Analyzing the results achieved, in accordance to ISO 14044:2006 [19], their relation to the goal and scope previously defined leads to the conclusions. All the accounted methodologies make use of auxiliary materials and the complete LCI may be found in the Annex 2. To conduct the LCA study and present the results in a more reasonable fashion, different scenarios for incineration and gasification were settled as follows:

Scenario I: base case for incineration of MSW samples (purple route in Figure 17), excluding production, collection and transport to the WtE facilities; metal scraps were also not considered in the system; a restricted type of landfill was appraised (receiving only inert materials); the produced electricity was considered to replace the EU-28 electricity grid mix;

Based on the reference case presented above, four different scenarios were tested to verify the potential effects caused by distinct conditions.

- Scenario I-1: inclusion of plant construction and waste transportation to the treatment facilities in system boundaries. This plant was built with the expected duration of 50 years. In this hypothesis, the inputs and outputs related to the construction were taken into account. Regarding waste transport after collection, the average travel distance to reach the treatment facility is 25km.
- Scenario I-2: inclusion of plant construction and wastewater treatment facilities in system boundaries. Opposite to the base case, in this scenario the operating process consumes nearly 95% of the produced electricity, only 5% being directed to the national grid.

- Scenario I-3: using a typical European landfill. The only difference from this scenario to the reference case is the landfill process. In order to better understand the environmental profit of having a restricted type of landfill, a typical landfill was used in this scenario (average European situation) with surface and basic sealing, landfill gas treatment, leachate treatment, sludge treatment and deposition. Part of the gas is flared to produce electricity [527].

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

In the case of regular gasification, the settled scenarios were:

Scenario RG: regular gasification of MSW samples (golden route in Figure 17), excluding production, collection and transport to the WtE facilities; metal scraps were also not considered in the system; the produced electricity was considered to replace the EU-28 electricity grid mix.

For comparison purposes, three different WtE techniques were assessed as follows:

- Standard incineration: a GaBi® plan with well-documented European processes from the database, which simulates the incineration of 1 tonne of MSW with average characteristics by modelling typical inputs, outputs and flows [527];

- Standard landfill: a GaBi® plan with well-documented European processes from the data base, representing the landfilling of 1 tonne of MSW in a typical landfill with surface and basic sealing, landfill gas treatment, leachate treatment, sludge treatment and deposition. Part of the gas is flared to produce electricity [527];

- Fast pyrolysis: system combining a pyrolizer and a combustor where waste is firstly converted into syngas in a bubbling fluidized bed, then cooled and cleaned (dust and tars removal) and finally sent to the combustor where a CHP (combined heat and power) system produces electricity [528];

4.2.2. Assumptions and limitations

For the implementation of LCA, the following assumptions and hypothesis were considered:

(a) experimental data is representative of each type of WtE and waste stream, therefore constituting reproducible information;

(b) the electricity grid mix was considered as described in [529] for the EU-28;

(c) the electrical grid is capable of receiving and distributing the produced electricity to consumers.

As limitations, some important remarks must be referred:

- if higher moisture contents are observed, lower conversion efficiency will be achieved and higher energy amounts will need to be replaced in the system, once more energy will be spent in the drying step;
- if the EU-28 electricity grid is substituted by a different mix in a specific location, environmental results may differ from the ones presented here.

4.2.3. Results and discussion - incineration

4.2.3.1. Environmental performance

Figure 20 depicts the results for the impact categories for the incineration scenario I (base case). The impact categories are arranged according to the relative results and with adapted units, in order to facilitate the observation of the figures.

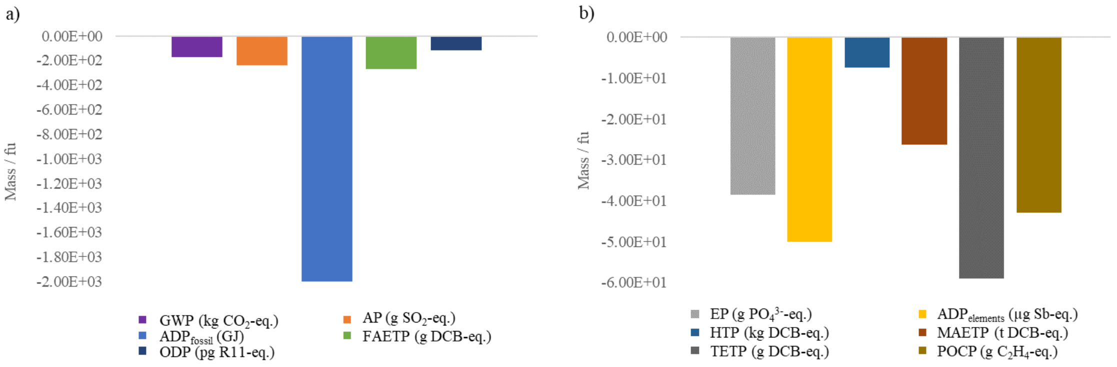

Figure 20 - Results for the impact categories for scenario I.

As may be seen from Figure 20, all the impact categories show negative values. This means that all depict a sustainable profile, accounting for environmental credits and therefore alleviating the use of natural resources.

In the case of Figure 20a, the avoided emissions of CO_2 (-158 $kg_{CO2\text{-}eq.}$/fu) and CH_4 (-12 $kg_{CO2\text{-}eq.}$/fu) from the landfill are the main contributors for the GWP net result presented, as reported in another work [530]. Other authors attribute this effect to the CO_2 released from the flue gas to the atmosphere, similar values for the total contribution of scenario I to GWP being also reported [521]. For the AP category, in a detailed observation of the modelled inventory, the prevailing harmful substances are sulphur dioxide and nitrogen oxides, mainly related to the flue gas treatment process, totalizing a net value of -0.242 $kg_{SO2\text{-}eq.}$ per tonne of residues treated. Mendes et al. [513] also confirm NO_2 as the most warning emission from incineration, assuring compliant gas treatment systems that effectively abate other emissions. ADP_{fossil} shows a great contribution for a sustainable system, saving *circa* 2000 MJ/fu and utilizing only 240 MJ/fu, while other works report lower relative achievements for half the daily waste amount treated [531]. The result accomplished for scenario I relates to the general avoided consumption of fossil sources such as hard coal, natural gas and lignite and reveals results similar to some authors [530] and improved when compared to other reports [514, 532]. Menikpura et al.

[533] reported a specific case were incineration promoted a reduction of 190% on net resource consumption. In the case of FAETP, scenario I has shown to be very compliant with major contributions of -0.105 kg $_{\text{DCB-eq.}}$/fu and -0.101 kg $_{\text{DCB-eq.}}$/fu from heavy metals to freshwater and air, respectively. These savings can be attributed to the landfill process and depict a better performance than reported by Toniolo et al. [534] who attained values between 3.09 and 7.27 kg $_{\text{DCB-eq.}}$/fu, thus meaning environmental burdens. ODP results are mainly subsidised by R114 (dichlorotetrafluoroethane), a contribution of $-1.73\text{x}10^{-10}$ kg$_{\text{R11-eq.}}$ being seen, in the net result of $-1.16\text{x}10^{-10}$ kg$_{\text{R11-eq}}$. Enhanced results for ODP were seen in literature, for a MSW sample similar the one utilized here but resourcing to a different LCA software and/or methodology [29, 531].

From Figure 20b, EP shows a contribution of approximately -0.039 kg$_{\text{PO4-eq.}}$ mainly attributed to NOx. Mendes et al. [513] also conclude that nitrogen compounds are the major contributors to this category, though the highest level of nitrogen compounds was seen to be released to the water. P_4 and NH_3 are the major emissions to the soil. The total contribution of this environmental category is somehow comparable to the values found in other reports, Gunamantha and Sarto [523] presenting an EP value double than the one seen here for scenario I ($-7.87\text{x}10^{-2}$ and $-3.86\text{x}10^{-2}$ kg$_{\text{PO4-eq.}}$/fu, respectively). Regarding ADP$_{\text{elements}}$, the profile attained by scenario I subscribes mostly to non-renewable elements copper, gold, lead and molybdenum (total amounts of $-4.98\text{x}10^{-5}$ kg$_{\text{Sb-eq.}}$/fu), due to the electricity production process. Mineral resources had been reported to be enhanced by the production of electric energy elsewhere [532]. HTP results account for savings of (-)7.45 kg$_{\text{DCB-eq.}}$/fu, which are a little under the values reported by Toniolo et al. [534] and Banar et al. [535]. Nevertheless, these are valuable results, consequence of the flue gas treatment and the landfill processes [519]. Comparable conclusions were drawn by others [530, 536]. For MAETP, a contribution of $-2.55\text{x}10^{4}$ kg$_{\text{DCB-eq.}}$/fu was seen, mainly due to processes such as the production of electricity and the flue gas treatment as corroborated by other studies [532]. Incineration scenario I depicted enhanced results when compared to published literature [534]. As far as TEPT is considered, the herein described incineration accounted for a high performance namely due to the avoided heavy metals in the agricultural soil (-0.0485 kg$_{\text{DCB-eq.}}$/fu), which enforced a net result of -0.059 kg$_{\text{DCB-eq}}$. Other authors confirm the release of heavy metals as the major impact for this category [29, 536]. When compared to published works, a good result for this impact category was achieved [534]. POCP results are mainly explained by the inorganic (CO,

NO_X, SO_2) and organic (CH_4) emissions to air which represent more than 60% of the total contributions. Poorer values for this category were found in literature, although calculated with a different LCA software and/or methodology, some of them even causing environmental damage [531, 535, 537]. Jeswani et al. [29] report improved results for this category.

4.2.3.2. Sensitivity analysis

As far as the sensitivity analysis is concerned, the results for the environmental impact categories calculated for each scenario are shown in Table 10.

Table 10 - Environmental impacts for scenarios of MSW incineration.

Impact categories	**Incineration scenarios**				
	I	**I-1**	**I-2**	**I-3**	**I-4**
GWP (kg CO_2-eq.)	-170.9	58	940	49	39.06
AP (kg SO_2-eq.)	-242×10^{-3}	-7.75×10^{-1}	-2.19	-2.04×10^{-1}	1.50×10^{-2}
EP (kg PO_4-eq.)	-38.6×10^{-3}	-4.60×10^{-2}	-4.25×10^{-2}	1.84×10^{-1}	1.20×10^{-2}
$ADP_{elem.}$ (kg Sb-eq.)	-50.1×10^{-6}	-4.00×10^{-5}	---	-4.87×10^{-5}	1.24×10^{-5}
ADP_{fossil} (MJ)	-2.00×10^{3}	-4.88×10^{3}	---	-1.84×10^{3}	464.6
FAETP (kg DCB-eq.)	-267×10^{-3}	-17	3.09	-1.34×10^{-1}	8.00×10^{-2}
HTP (kg DCB-eq.)	-7.45	46	-62.9	-7.161	2.93
MAETP (kg DCB-eq.)	-26.3×10^{3}	-2.16×10^{5}	7.94×10^{-1}	-2.57×10^{4}	2.19×10^{4}
TETP (kg DCB-eq.)	-59×10^{-3}	-3.00×10^{-1}	-7.64×10^{-3}	2.12×10^{-1}	1.42×10^{-1}
POCP (kg C_2H_4-eq.)	-4.29×10^{-2}	-84×10^{-3}	-9.56×10^{-1}	---	1.40×10^{-2}
ODP (kg R11-eq.)	-1.16×10^{-10}	-18×10^{-6}	-2.43×10^{-5}	---	1.02×10^{-10}

--- values below the methodology detection limit.

Concerning the main differences encountered between scenario I and I-1, GWP discrepancy is possibly due to the inclusion of plant construction, waste transport to the incinerator and also bottom ashes processing. I-1 presented higher CO_2 values (452 kg/t) and higher emissions (600 $g_{DCB\text{-}eq}$/t of NO_x and 75 $g_{DCB\text{-}eq}$/t of SO_2 to air) which contributed to GWP and HTP respectively, contrasting to the values achieved for I (158 kg/t; -217 $g_{DCB\text{-}eq}$/t of NO_x and -9.92 $g_{DCB\text{-}eq}$/t of SO_2 respectively). GWP result is in the same order of magnitude as reported by other authors [37, 530, 533], higher values being attained when plant construction and/or waste collection and transport are considered [535, 538], although CO_2 is still the major contributor. It must be stressed that the results on biotic CO_2 in all scenarios were not accounted once they are considered part of the carbon cycle, its effect on the GWP being inconsequential [539, 540]. This explains the relatively low contribution shown by the incineration process to GWP, Hong [541] obtaining a result similar to I in this category (-254 kg $_{CO2\text{-}eq.}$/fu). Observing Figure 22 it may be seen that these different boundaries do not interfere significantly in the correlation between scenarios, meaning that the global performance of the incineration plant is not affected by these modifications.

Scenario I-2 depicts positive impacts for GWP, FAETP and MAETP especially due to stack emissions of CO_2, NO_x and SO_2 whereas scenario I depicts negative results for these impact categories. This might probably be explained by the study boundaries that include the construction of the plant facilities (accounting for heavier effects on GWP) as well as the wastewater treatment plant [542] (influencing FAETP and MAETP), which are not within the system herein presented for the base case I. Observing Figure 22 these individual differences between impact categories in each case seem to influence the overall performance of the incineration plant, once the correlation coefficient achieved for scenarios I and I-2 is very low. As both I-1 and I-2 comprehend plant construction, comparing their results allows to see that the waste transport (I-1) is a more sustainable option impact than the inclusion of the wastewater treatment facility (I-2). This may be observed namely for GWP, FAETP, MAETP and TETP which depict lower harmful effects or even avoided burdens for I-1 rather than I-2. As a benefit, scenario I-2 presents a more sustained option in the case of AP and HTP. This is due to the wastewater treatment facility, which reduces the release of acidic and toxic effluents.

Scenario I-3 shows worse results than scenario I only for GWP, EP and TETP while AP, $ADP_{elements}$ and FAETP are improved and MAETP, HTP and ADP_{fossil} present similar values to the reference case. This seems to create a balance between all the impact categories, and that is why landfill type does not seem to affect the plant performance as may be confirmed by the high correlation coefficient to scenario I seen in Figure 22.

Regarding I-4, all the impact categories show inferior results to the reference case, owing the environmental burdens to the plant energy requirements, once electricity self-consumption will not occur. As far as AP is concerned, the production of electric power seems to reduce the positive impact of this category, as also reported in literature [521], Passarini et al. [532] showing that when the energy recovery doubles, AP will no longer be a hazard, becoming an environmental credit. Other authors had already reported on the importance of recovering energy through incineration concluding that lower carbon footprints and higher electricity savings are attained [37, 538].

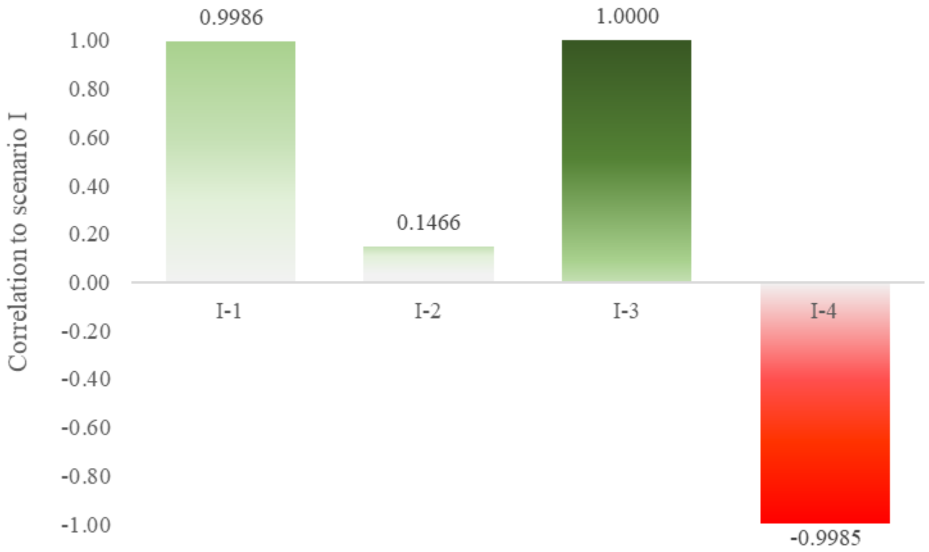

Figure 21 - Correlation of different scenarios to the reference case.

As Figure 21 shows, two of the suggested scenarios are highly correlated to the reference case, I-1 presenting a correlation coefficient of 0.999 and I-3 perfectly matching the global environmental results achieved by scenario I. This means that the alterations imposed by these scenarios do not change the final environmental performance of the incineration held under the conditions of this study. Therefore, it is possible to say that the life cycle assessment conducted is a robust and reliable evaluation as well as the incineration plant maintains its environmental sustainability even considering the inclusion of the plant construction plus the waste transport to the treatment facilities and the less restricted type of landfill. In a detailed observation (not shown here), it may be seen that both I-1 and I-3 result in severe avoided impacts for the environment, the most spared segments being material resources, fresh water and air.

Regarding the inclusion of the wastewater treatment facilities, this will have a visible effect on the plant performance, supported by the low correlation coefficient achieved for scenario I-2. The possible causes for this may rely on the fact that the wastewater treatment affords sludges, which require processes such as water removal, pathogen destruction and digestion before being disposed. This is in accordance to the fact that this scenario consumes much more energy than the reference one, 95% of the generated energy being reused to operate the plant itself. Relative to scenario I-4, the result was somehow expected not to correlate so well with the reference case once electricity production is one of the major advantages of the incineration plants, as aforementioned [37]. Therefore, when considering only waste treatment, incineration may be viewed as an unsustainable technique, jeopardizing the environment instead of contributing to its maintenance and equilibrium. This is better understood through a hot-spot analysis, explained in the next section.

4.2.3.3. Hot-spot analysis

The hot-spot analysis allows a more detailed discussion of the conditions that affect incineration the most. Figure 22 reports the results for this analysis.

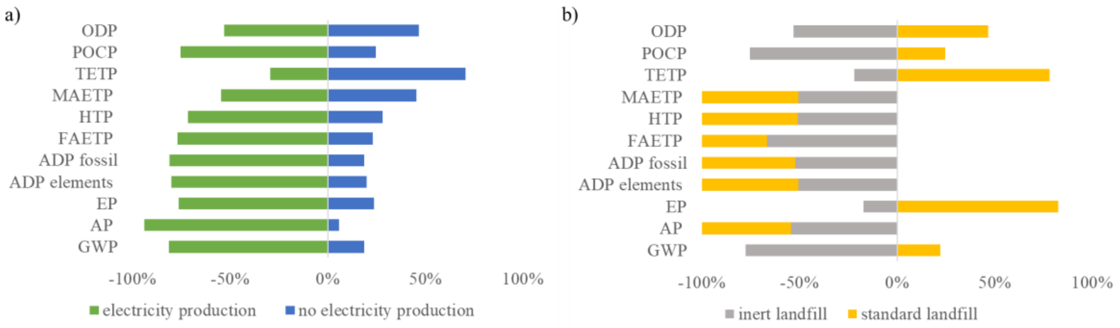

Figure 22 - Hot spot analysis for the incineration of MSW.

In the case of electricity generation within the incineration system (I), Figure 22a shows unquestionable gains for all the assessed categories, TETP and ODP suffering higher repercussions if energy production is neglected and all the electric inputs have to be supplied by the national grid (scenario I-4). This benefit has also been reported by Eriksson and Finnveden [543] in a recent paper about the key parameters in WtE systems. To enhance this feature, a possible mechanism to be used is the production of electricity from the landfill gas, which can be taken into account in a further stage of development of the facilities, as recommended by other authors [541, 544].

As can be seen from Figure 22b, although the correlation coefficient between scenarios I and I-3 is 1, inert landfill (I) favors a more environment-friendly approach than the typical one (I-3), all the categories showing negative values for the environmental impacts in the first case. This is even more significant in the case of TETP, EP, ODP, POCP and GWP which, when evaluated under a standard landfill scenario exhibit the opposite behavior, meaning high environmental damage. MAETP, HTP, ADP (both genres) and

AP share relative quotas between the two landfill types, which indicates that they are not influenced by this variable, depicting similar results in both cases, whereas FAETP renders a pronounced effect of approximately 80% towards the inert landfill.

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

4.2.3.4. Process by process performance

After comparing the created scenarios, the environmental evaluation of scenario I was done process by process so that weak points were noticed and possibly corrected in the future, if necessary. Figure 23 describes this assessment with an insight for better perception on the flue gas treatment and ash inertization profile, as well as for landfill profile.

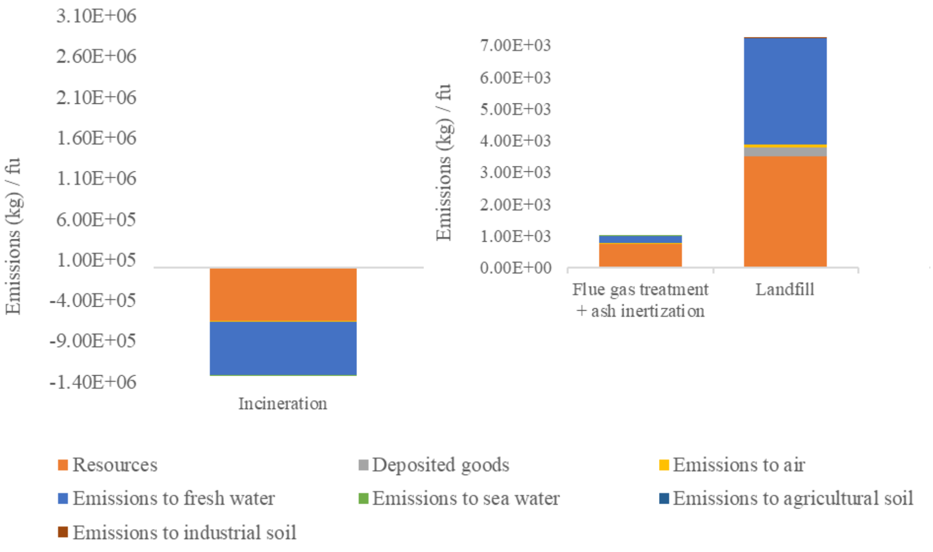

Figure 23 - Process performance for the incineration of MSW.

As already commented, the evaluated plant is very effective and environmentally sustained, as confirmed here. Furthermore, there are no reports on public health issues related to this facility neither environment emissions above the legal limits. Highlights must be given to the massive avoided burdens in the incineration process unit, mostly due to the electricity production and also to the utilization of waste as fuel, since this represents a noxious asset for nature and, this way, it is converted into a useful feedstock instead of deposited. In what concerns the electricity production, it must be stressed that this contribution is an approach, once this is not an established process in the plan, rather constituting an output of the incineration process. Hence, the balance was achieved subtracting the results for scenario I-4 from the ones for scenario I, since the electricity production is the only difference between these two scenarios [514], more than 700 $t_{emissions}$/fu being mitigated. The most protected sections are natural resources, fresh water and minorly air, meaning an overall avoidance of 1300 $t_{emissions}$/fu.

The electric power generation revealed very prone to the success of the incineration facilities (as in general in EU-28 region) and also in other reported studies [532, 545, 546], but this is not always true. Depending on the type of resources utilized to compose the grid mix electricity available for the consumer, the avoided impacts generated by the electricity provided from incineration will be different and sometimes not so significant [513].

The flue gas treatment and ash inertization process consumes resources and provokes emissions to fresh water (summing nearly 1 $t_{emissions}$/fu), landfill raising this impact to 7.2 $t_{emissions}$/fu, with the contribution of the deposited products and also non-negligible emissions to the air. These two processes have harmful impacts on environmental compartments, but landfill is the one presenting worse results as reported elsewhere too [513, 515].

4.2.4. Results and discussion - gasification

4.2.4.1. Environmental performance

Figure 24 presents the environmental impacts achieved for the regular gasification of MSW, affected by the adequate scaling factors and sorted by type of contribution.

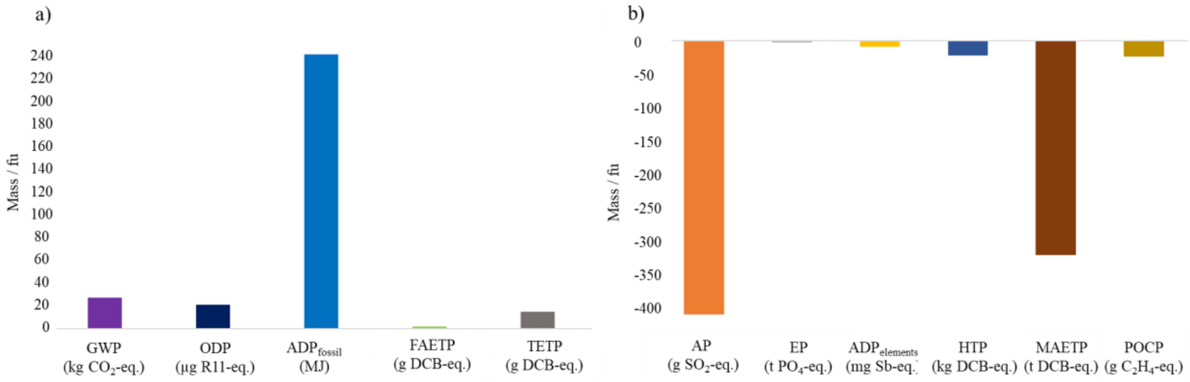

Figure 24 – Environmental results for regular gasification.

As seen in Figure 24a, positive impacts (environmental damage) were achieved for GWP, ODP, ADP_{fossil}, FAETP and TETP. On the other hand, Figure 24b shows that AP, EP, $ADP_{elements}$, HTP, MAETP and POCP depicted negative values (avoided burdens).

According to the calculated balances, the major substance contributing to GWP is carbon dioxide, namely due to the production of the oxygen used as oxidizing agent during gasification step. GWP denotes a hazard for environment, although its value is low when compared to other similar LCA studies [547]. The reason for this small impact is the substitution of the grid electricity by the produced electricity, which avoids the grieving of fossil fuels [520]. Gasification step appears to be also the cause for ODP positive value, due to halogenated organic emissions to air. This may be possibly explained by the plastic fraction present in MSW, which most of the times comprehends polymers with halogens like the common PVC, for instance [521]. Again, oxygen production is pointed as the explanation for the ADP_{fossil} value, once it grieves non-renewable energy resources such as hard coal, lignite and natural gas, as well as uranium. Taking into account the electricity production by the gasification step, ADP_{fossil} was predicted to show a negative value alleviating the environment instead of the 240 MJ presented herein. A conceivable explanation for this occurrence relies on the fact that metal scrap recovery is out of the boundaries limiting this study, which diminishes the beneficial contribution to this category of impact [547]. Regarding the ecotoxicity categories that show positive impacts, FAETP result is driven by the contribution of two processes accounting for gasification namely nitrogen and oxygen production which contaminate freshwater with chromium and zinc. TETP value is attributed to the release of mercury to the air due to oxygen production, and also to the syngas cleaning step which releases nitrogen oxides. These results had already been evidenced by other authors [520], a deep explanation for metal partitioning being found in [221].

For Figure 24b, all the presented categories suggest that syngas cleaning step is the most environment friendly process once it enables the removal of sulphur dioxide accounting for the AP result, while contributing to the EP value through the ablation of nitrogen, as confirmed elsewhere [520]. Concerning $ADP_{elements}$, syngas cleaning treatment affords sodium chloride, as well as redeems hydrogen fluoride, which contributes to HTP and MAETP results. POCP outcome is due to the production of nitrogen oxides and sulphur dioxide, also during syngas treatment step. The power production achieved by gasification is also a parameter that promotes better performances in the case of AP and POCP [520]. From the categories depicted, the syngas cleaning step seems to be the most favorable stage of the system enabling major contributions as seen for MAETP, EP and HTP. MAETP shows a significant contribution to the environmental credits achieved by the technique, more than 312 tonnes of DCB-eq. being saved per functional unit, mainly related to the hydrogen fluoride. The second most important contribution is presented by EP, which showcases a total of (-)2320 $kg_{PO4\text{-}eq.}$ mostly caused by nitrogen compounds, especially nitrogen oxides. HTP also depicts a very important contribution to the environmental credits, presenting a net result of roughly (-)22kg of DCB-eq., due to the avoided hydrogen fluoride emission.

4.2.4.2. Process by process performance

As seen in the above section, different steps of the global gasification plan account for distinctive impact categories, gasification process being the major player in the case of the positive impacts (resource depletion) and syngas cleaning playing a significant role in the case of negative impacts (resource savings). A quantitative evaluation of the global performance of each of the three chief processes in gasification is depicted in Figure 25.

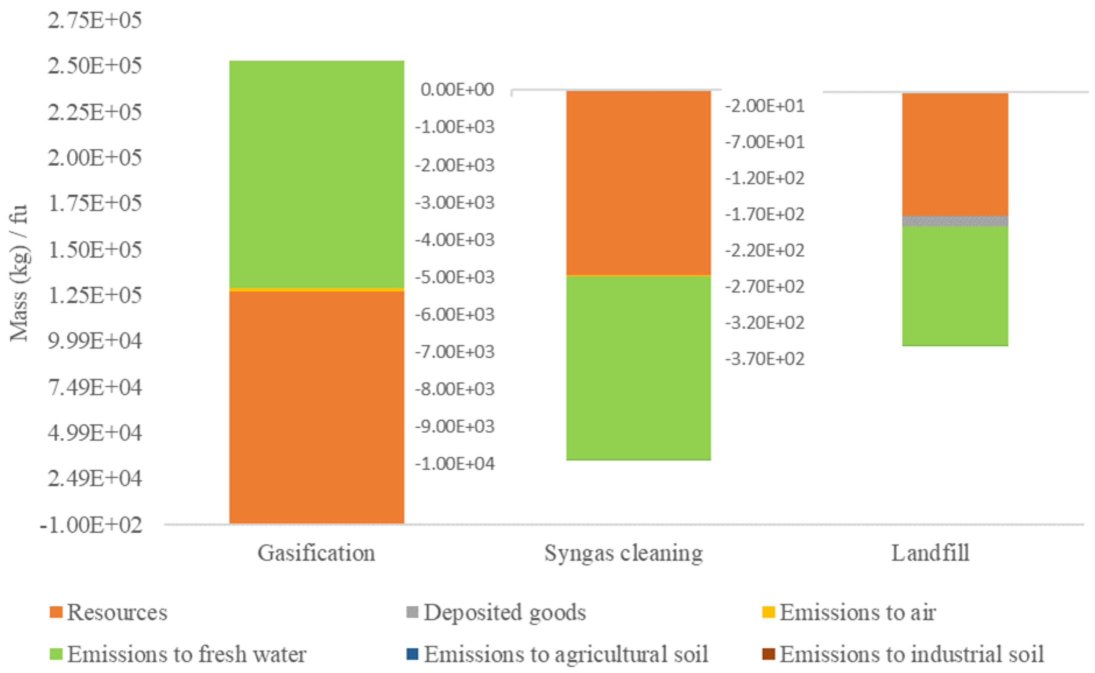

Figure 25 – Process performance for the regular gasification of MSW.

From Figure 25, “resources” and “emissions to freshwater” may be seen as the dominant flows in the three processes, each of them contributing to almost 50% of the total profile. Refining the balance, it is possible to state that in the case of gasification process, a total sum of more than 250 tonnes per functional unit is achieved, water constituting the dominant resource and water from the technosphere constituting the prevalent flow accounting to emissions to freshwater. Relative to the narrow section corresponding to emissions to air, organic compounds are the top emissions (nitrogen compounds, carbon monoxide and oxygen). It should be reminded that Directive 2000/76/EC [548] requires a minimum residence time of two seconds at 850 ºC for combustion gaseous products of non-hazardous waste and at 1100 ºC for gaseous outputs of hazardous streams.

During syngas cleaning treatment and landfill, “resources” and “emissions to freshwater” represent negative quantities that account for approximately 10 t and 341 kg of environmental credits per functional unit, respectively. In accordance to other authors [12, 549], gas treatment procedures must be suitable for each plant, enabling an efficient air pollution control step. This will effectively reduce or remove noxious gaseous emissions to keep up with the legal limits. Apart from the referred flows, landfill also depicts a parcel for “deposited goods”, which represents the avoided overburden of stockpile, namely particulate matter, inert slags and ashes.

4.2.4.3. Sensitivity analysis

After observing dominant sustainable results for low temperature gasification, it is interesting to perform a sensitivity analysis in order to attest the reliability of this thermal treatment for municipal solid residues, when compared to other techniques in which the feedstock undergoes distinct temperature ranges. Therefore, a comparison of the attained results to other WtE techniques is presented in Table 11. The results and detailed description for fast pyrolysis were taken from [528]. It is important to notice that variables such as functional unit and MSW composition were kept constant along the sensitivity test, while system boundaries were the most approximate to the ones applied in this research. This way, the robustness of the LCA approach was tested under different WtE methodologies for the same waste sample but at distinct temperature profiles throughout the waste conversion.

Table 11 - Sensitivity analysis for MSW regular gasification.

Impact categories	**Regular Gasification**	**Standard incineration**	**Landfill***	**Fast pyrolysis***
GWP (kg CO_2-eq.)	27	430	$2.09x10^{-12}$	$2.19x10^{-10}$
EP (kg PO_4-eq.)	$-2.32x10^{3}$	$-3.89x10^{2}$	$3.72x10^{-12}$	$-4.16x10^{-11}$
AP (kg SO_2-eq.)	$-3.99x10^{-1}$	-2.426	$-5.49x10^{-12}$	$-1.19x10^{-10}$
ODP	$2.08x10^{-08}$	$-3.96x10^{-5}$	$1.25x10^{-10}$	$5.71x10^{-9}$
$ADP_{elements}$ (kg Sb-eq.)	$-9.35x10^{-6}$	$-6.09x10^{-3}$	---	---
ADP_{fossil} (MJ)	$2.40x10^{2}$	$-9.26x10^{2}$	$1.37x10^{-12}$	$-2.56x10^{-12}$
FAETP (kg DCB-eq.)	$1.86x10^{-3}$	-0.382	$5.29x10^{-11}$	$9.61x10^{-12}$
MAETP (kgDCB-eq.)	$-3.12x10^{5}$	$-3.40x10^{5}$	$-1.37x10^{-11}$	$2.91x10^{-10}$
TETP (kg DCB-eq.)	$1.45x10^{-2}$	$-1.61x10^{-2}$	$1.40x10^{-10}$	$-3.85x10^{-11}$
HTP (kg DCB-eq.)	-21.8	-73.5	$2.09x10^{-10}$	$1.27x10^{-10}$
POCP (kg C_2H_4-eq.)	$-2.33x10^{-2}$	$-1.38x10^{-1}$	$2.13x10^{-15}$	$1.55x10^{-13}$

*data adapted from [528]

As seen from Table 11, regarding the environmental impacts standard incineration seems to be the most sustainable treatment with eight out of ten categories (excluding $ADP_{elements}$ due to lack of data for some experiments) achieving optimum results when compared to other treatment technologies. It is good to keep in mind that these are average European results which, due to the large number of assessed plants may have more balanced and representative outcomes when compared to real one-plant cases, like the other techniques herein presented. The lowest values for GWP are achieved by landfill (the main contribution due to the landfill gas release to the atmosphere in the form of methane and carbon dioxide), whereas low temperature gasification performs better for EP. For HTP, both gasification and incineration present values in the same order of magnitude corresponding to environmental credits.

Moreover, besides EP, regular gasification proves to afford enhanced results for some further categories, namely MAETP, HTP and POCP when compared to all the other techniques, excluding incineration. This supports regular gasification as a suitable and trustworthy WtE technique, superior to a myriad of preceding technologies, regarding its environmental outcomes especially for EP, AP, MAETP, HTP and POCP. On the other hand, when comparing our study to plasma gasification, this last advanced thermal treatment presents upgraded results for categories such as GWP, ODP, ADP_{fossil}, FAETP and TETP. In this case, GWP derives from the flue gases released from the stack which are mostly composed of carbon dioxide.

As a more direct means to interpret so many comparisons within the proposed scenarios, the environmental categories may be utilized not only to quantify the associated impacts but also to rank the alternatives from the point of view of the avoided burdens. This helps to identify critical situations and to plan future actions to abate related problems.

4.3. WtE comparison for municipal solid waste

4.3.1. Environmental impacts

Table 12 presents the environmental impact comparison between the incineration and the regular gasification of MSW.

Table 12 - Environmental impacts for incineration and regular gasification of MSW.

Impact categories	**Environmental quantities**	
	Incineration	**Gasification**
GWP (kg CO_2-eq.)	-170.9	27
EP (kg PO_4-eq.)	$-38.6x10^{-3}$	$-2.32x10^{3}$
AP (kg SO_2-eq.)	$-24.2x10^{-2}$	$-39.9x10^{-2}$
ODP (kg R11-eq.)	$-1.16x10^{-10}$	$2.08x10^{-8}$
$ADP_{elements}$ (kg Sb-eq.)	$-50.1x10^{-6}$	$-9.35x10^{-6}$
ADP_{fossil} (MJ)	$-2.00x10^{3}$	240
FAETP (kg DCB-eq.)	$-26.7x10^{-2}$	$1.86x10^{-3}$

MAETP (kg DCB-eq.)	$-26.3x10^3$	$-3.12x10^5$
TETP (kg DCB-eq.)	$-59x10^{-3}$	$1.45x10^{-2}$
HTP (kg DCB-eq.)	-7.45	-21.8
POCP (kg C_2H_4-eq.)	$-4.29x10^{-2}$	$-2.33x10^{-2}$

As may be seen from Table 12, incineration presents negative values for all the environmental categories, while gasification affords environmental hazards for some, namely GWP, ODP, ADP_{fossil}, FAETP and TETP. A similar trend for GWP and ecotoxicology categories has also been seen in other reported studies [520]. Despite these positive values, gasification shows top performance for EP, AP, MAETP and HTP, portraying major environmental credits for these impact categories, when compared to incineration. Taking in consideration the balances performed by the software, GWP is majorly attributed to CO_2 during the production of the gasifying agent. Although positive, this GWP value is lower than for other published literature [547], mainly due to the saved fossil fuels accomplished with the electricity reposition in the grid [520]. ODP outcome is related to the emission of halogenated compounds during gasification step, which may be justified by the high level of plastics (for instance PVC) [521] in the MSW sample assessed. The major cause for the achieved ADP_{fossil} result is the use of non-renewable resources such as hard coal, lignite, natural gas and uranium reserves for the production of oxygen during gasification step. A critical factor underlying this result might be the exclusion of metal scrap recovery from the system boundaries, which together with the electricity replacement should be enough to alleviate the related burdens [547]. As far as the ecotoxicity is concerned, nitrogen and oxygen production are the key contributions to FAETP outcome, since they promote fresh water contamination with chromium and zinc, while TETP is explained by the release of mercury as gaseous emission to the air as well as by the release of NO_x during syngas cleaning step. Regarding the impact categories which afforded major environmental credits for gasification, the modelled balances suggest that syngas cleaning is the more obvious contribution, once this step lowers SO_2 and nitrogen (enhancing AP and EP, respectively) and redeems HF (contributing to MAETP and HTP results). Regarding $ADP_{elements}$ and POCP, the impacts attained for these categories are nearly in the same order of magnitude than the ones seen for incineration.

As far as incineration is concerned, interesting results are seen, alleviating the environmental burdens associated with the resources required by thermal conversions.

This technique shows a more sustainable profile for categories such as GWP, ADP, FAETP, TETP and POCP. A comprehensive comparison to other results will be endeavored in the next section, making use of the balances afforded by the software.

The relative impacts portrayed by each WtE technique may be seen in Figure 26, gasification being once more highlighted due to less sustainable results for some of the assessed environmental categories.

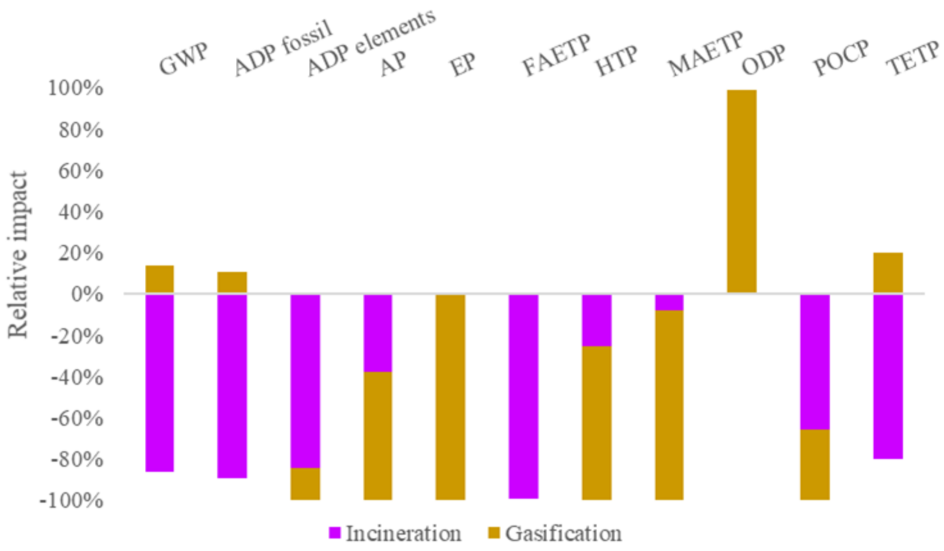

Figure 26 – Incineration and regular gasification comparative performance.

According to Figure 26, incineration shows remarkably sustainable results for GWP, ADP, FAETP, POCP and TETP, while gasification portrays high level performance for AP, EP, HTP and MAETP.

Regarding GWP, incineration depicts avoided emissions of CO_2 and CH_4 due to landfill (more than 80% of the total impact), the reintroduction of the produced electricity in the systems aiding to lower the consumption of fossil fuels, correspondingly reducing CO_2 emissions. Some literature report higher GWP impacts for similar assessments [528], the differences being attributed to biogenic CO_2 [550]. Concerning ADP_{fossil}, a similar trend is observed mainly because major savings in non-renewable sources such as hard coal, natural gas and lignite are attained. Both the landfill process and the electricity production account for the recovery of 2000 MJ per tonne of treated residues in incineration. This trend has also been shown by other authors although with lower efficiencies [514, 531]. $ADP_{elements}$ gathers approximately 80% contribution from incineration and only 20% from gasification. Incineration depicts savings in resources such as copper, gold, lead and molybdenum due to the electricity production as also reported in [532], while gasification subscribes to the saving of mineral salts such as sodium chloride. FAETP category result presents nearly 100% contribution from incineration, the explanation relying in the avoided release of heavy metals to fresh water and air due to landfill process. Enhanced results are seen for incineration when compared to published literature [534]. Referring to TETP outcomes, a contribution of approximately 80% from incineration may be seen, due to the avoided heavy metals in agricultural soil. Some published literature report inferior results to the herein presented [534]. ODP category shows gasification as the responsible for environmental burdens, while incineration does not play a significant role. R114 is the chief emission accounting for almost 100% of the total share of the environmental hazards of this technique.

Incineration reduces the emission of NO_x, P_4 and NH_3 to the soil contributing to AP values similar to other works [521, 523] due to the electricity production process, as also seen in [551]. HTP results for gasification rely on the abatement of emissions such as organic and inorganic compounds and heavy metals to air as well as organic substances to fresh water due to the flue gas treatment and the landfill processes [519]. Similar results were achieved in other works [528]. Inorganic (CO, NO_X, SO_2) and organic (CH_4) emissions to air are allocated as the main contributors for POCP during incineration.

4.3.2. Resources and emissions

Figure 27 portrays the comparative assessment between the evaluated WtE in terms of resources and emissions.

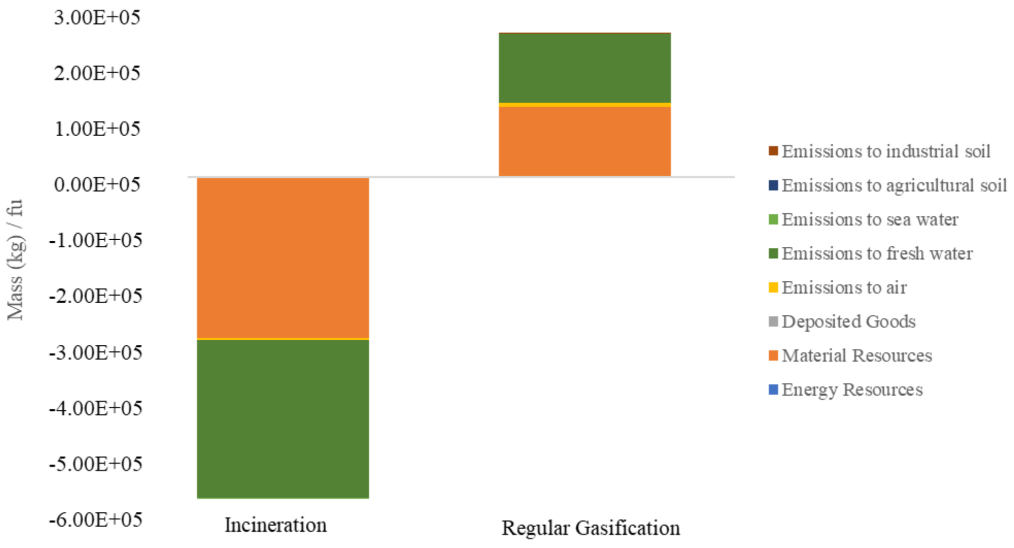

Figure 27 - Overall emissions for incineration and regular gasification of MSW.

As overall observation, it may be said that material resources and emissions to fresh water are the major outcomes from the assessed WtE techniques. As mentioned previously, regular gasification depicts a more hazardous environmental profile (saving more than 240 tonnes of emissions per tonne of treated waste), only minor credits being shown related to the emissions to industrial soil (saving nearly 1 kg of emissions per functional unit). Incineration constitutes a more sustainable option, saving almost 600 tonnes of resources and emissions per functional unit (295 tonnes of material resources and 291 tonnes of emissions to fresh water).

As stated by Zaman [520], the environmental burdens associated to the thermal conversion techniques are mainly due to their emissions (both gaseous and solid), which may be below the established legal limits but at the same time contribute to environmental hazards. Figure 28 portrays a detailed description of the major emissions related to the assessed WtE, so that some of the environmental aspects previously mentioned may be contextualized.

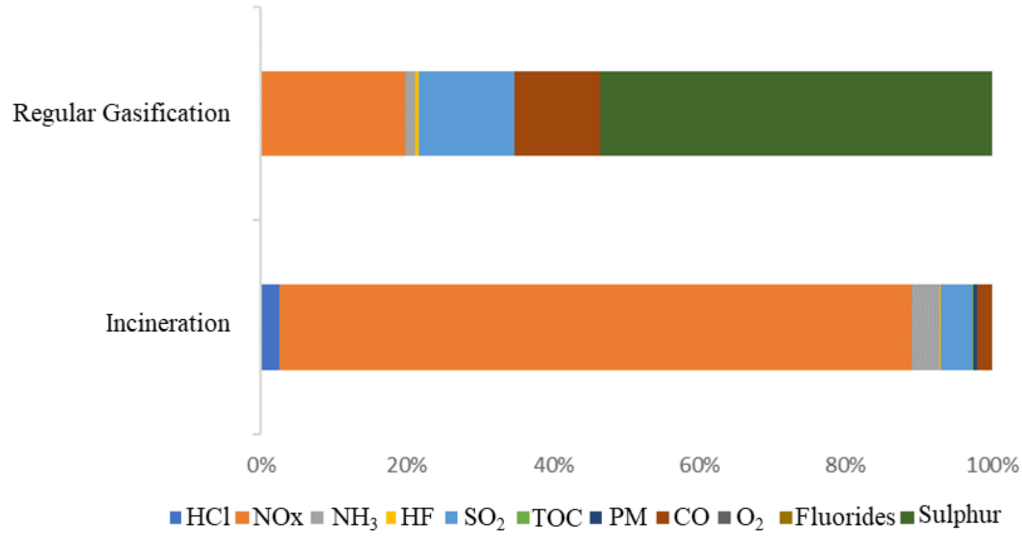

Figure 28 - Main emissions for incineration and regular gasification of MSW.

As seen from Figure 28, the emissions from incineration are dominated by NO_x from the flue gas cleaning process, accounting for a share of nearly 85% of the total emissions for this technique (4.05×10^{-10} kg/fu). Minor emissions are SO_2, NH_3, CO and HCl. This has also been reported in [12]. Regarding gasification, the most pronounced emission is related to sulphuric compounds, which represent more than 50% of the total share (0.615 kg/fu), followed by NO_x (0.226 kg/fu), SO_2 (0.15 kg/fu) and CO (0.133 kg/fu), all of them due to the syngas cleaning facility. Similar trends were achieved in [489].

4.4. Ecorkwaste project as a biomass gasification case-study

The southern Mediterranean countries are the World's major producers of cork. More than 65% of the area and more than 85% of production are concentrated in Portugal, Spain, Italy and France. Besides, important transformation cork industries are located in other European countries such as Germany or England [552]. Over 42% of cork extracted from trees is ranked first quality and further sent to cork plates manufacturing, while the second-quality cork (58%) is triturated and sent to agglomerate industry, mostly for the manufacture of insulating materials.

Regarding waste generation in cork industry, three chief residue streams are found [553]: the large quantities of forestry waste generated during the extraction process and in the maintenance of trees; defective cork plates in the manufacturing process (2-4%)

which are sent to landfill; at the end-use level, where over 30% of cork plates are used for stoppers and packing rings while the rest (70%) is triturated. Around 30% of this triturated material becomes powder and is mainly sent to landfill (sometimes burnt without energy production) and the rest is transported to agglomerate industry to be recycled [553]. In case the agglomerate factory is quite far from the cork factory, it is a common practice to send the triturated material to landfill too, due to excessive transport costs. Triturated cork waste is occasionally composted and used in the agriculture, but this treatment is mostly uneconomical. Finally, over 0.5-1% of the stoppers are defective and thereby sent to landfill also. In relation to cork stoppers, it should be noticed that there are few specific “collect and recycle” programs. That is why most of them end at final treatment plants (landfill, incineration) or at best, recycled as organic matter. Nevertheless, cork has two interesting physical characteristics: it has a high lower calorific power, between 18 000 and 20 000 kJ/kg, and also has absorbing properties for some organic compounds [554]. Then, valorizing the cork waste for energy production is a very interesting alternative to comply with the European Commission directives under the waste management framework.

In this study, gasification is used as a thermal strategy to convert cork wastes into energy, in order to demonstrate the valorization of cork residues. This contributes to the implementation of the Waste Framework Directive (2008/98/CE) following the objectives and goals of the Roadmap for a Resource-Efficient Europe. Technological, R&D and industrial partners were gathered under the framework of the LIFE+ Ecorkwaste Project and thus, a gasification plant with capacity to treat 15 kg of cork residues per day was designed. The ultimate goal was to develop and optimize the experimental procedure so that the gasification plant could be implemented at an industrial scale. To achieve that, cork waste with certain particle size was used as substrate for energetic valorization in a gasification process. Therefore, main environmental targets of the study were: to decrease the waste disposal in landfills, to achieve higher rates of cork waste reuse and valorization, also to increase energy savings in the industry as well as minimizing the effects of landfilling on human health and the environment. Other collateral benefits of the main environmental targets proposed above are the development of new uses for cork waste that provides the opportunity to increase the benefits of cork forestry management and cork industry. In order to assess the environmental, techno-economic and social impacts of this technology, LCA and LCC were performed, as well as a socio-economic matrix integrating various aspects of the technique was developed. This project was developed in Eurecat facilities (Manresa, Barcelona).

4.4.1. Materials and methods

The function of the system is to treat thermally cork residues coming from winemaking industries, recovering energy in the form of electricity and heat as main products.

A fluidized bed gasifier with 1.5 m high and 0.6 m diameter was installed inside a stainless-steel container and used for cork gasification, along with all the necessary components as seen in Figure 29. Grey components represent the process steps, while green elements stand for the system marketable products. A biomass flow of 12 kg/h was projected to produce 10kW of electrical (kW_e) energy and 20kW of thermal (kW_{th}) energy.

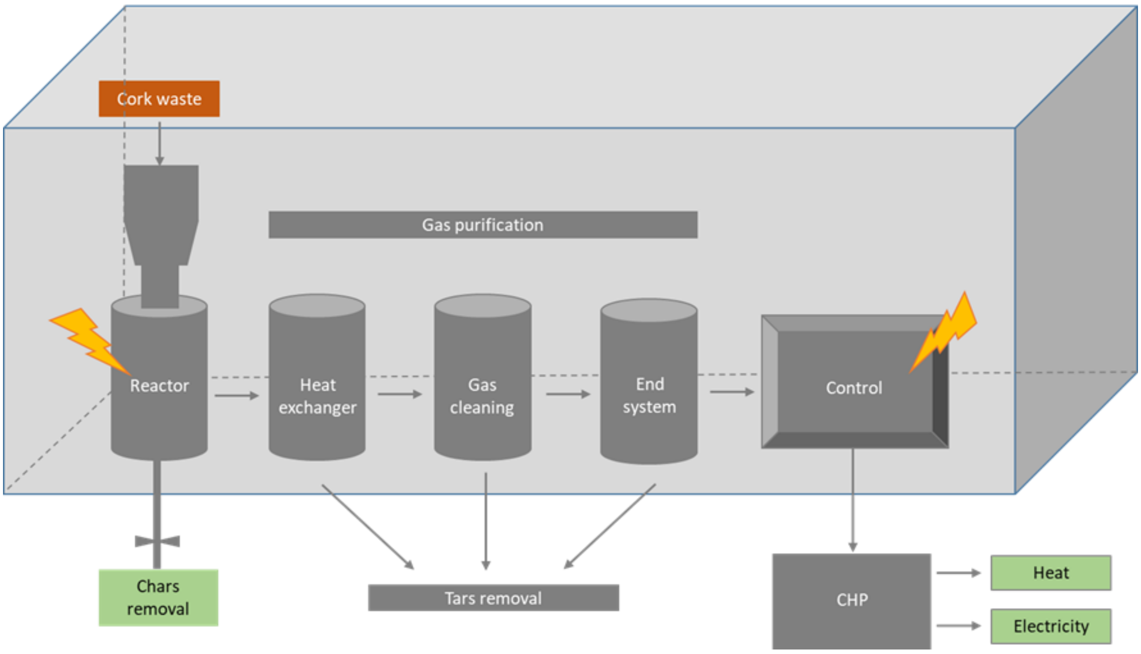

Figure 29 - Schematic representation of the gasifier utilized for cork residues.

Biomass was introduced in the system through a feeding stage and then decomposed in the gasifier at 800 ºC. The remaining solids were removed from the reactor in the form of chars. The produced gas was sent to the heat exchanger for cooling and then further directed to the cleaning system, tars being removed throughout the process and subsequently incinerated. The average molar composition of the produced syngas was as follows: carbon monoxide (9.61%), hydrogen (5.32%), carbon dioxide (8.50%), methane

(3.42%) and nitrogen (67.81%). A CHP equipment was used in the final stage of the system in order to generate the two main gasification products: electricity and heat. The heat produced was utilized in the system for cooling or heating purposes during syngas production and the electricity was also applied within the system, the excess being sold to the national grid.

The gasification system is similar to the one presented in section 4.2.1 (Figure 16), and further details on the functioning of each component may be found in Annex 3.

4.4.1.1. Scope, system boundaries and functional unit

The aim of the LCA study was to determine the environmental performance of Ecorkwaste gasification technology for cork valorization. This process was carried out in a gasification plant operated in Eurecat facilities, in Manresa (Barcelona). The wastes utilized were cork residues/by-products with grain size lower than 4 mm. The functional unit was determined as “the production of 1 MWh of energy from cork by-products by gasification”.

Within the system boundaries, all the processes made during cork treatment had been considered, as well as the electricity consumed, resources and materials used. The plant has a treatment capacity of 96 kg/day, projected to produce approximately 600 m^3 of syngas, and to supply a potential of 10 kW of electricity and 20 kW of thermal energy. The infrastructure of the plant was included in the study, as well as the products obtained during the functioning regime (energy and chars) and the avoided burdens (avoided landfill of cork residues). Excluded from the system boundaries are the cork residues generation, collection and transportation to the treatment facilities.

The system boundaries and main processes are similar to the ones depicted in Figure 17 for the golden route, but replacing MSW by the cork waste samples. Cork residues were provided by an industrial partner, its characterization being shown in Table 13.

Table 13 - Characterization of the cork residues used in this assessment.

Ultimate analysis	
C (%)	52.80
H (%)	6.28
N (%)	0.545
S (%)	0.015
Proximate analysis	
Volatiles (%)	1.95
Fixed Carbon (%)	18.88
Moisture (%) *	7.965
Ash (%)	4.325
HHV (MJ/kg)	21.2
LHV (MJ/kg)	20.4
LHV (MJ/kg) *	18.71

*wet basis

4.4.1.2. Life cycle inventory and methodology

In the LCI stage, data was collected and interpreted in order to calculate the different impacts. Emissions, energy requirements and material flows were calculated for each process included in system boundaries. Data was adapted and dimensioned to the functional unit, which had been previously defined.

In this case, Ecoinvent v2016® and SimaPro software Developer 8.5.2.0, using ReCiPe v1.13 midpoint and cumulative energy demand v1.09 impact assessment methods were used. Table 14 shows the selected impact categories according to the main goals proposed in the project.

Table 14 - Impact categories assessed in the LCA of cork residues.

Impact category	Units	Abbreviation
Global warming	kg CO_2-eq.	GW
Terrestrial acidification	Kg SO_2-eq.	TA
Freshwater eutrophication	Kg P-eq.	FE
Marine eutrophication	Kg N-eq.	ME
Fossil resources scarcity	kg oil-eq-	FRS
Cumulative energy demand	MJ	CED

The inventory data for the LCA study is mainly primary as it was taken from tests running the actual gasification plant. Other operation aspects have been accounted, bibliographic sources being used for data collection, as for instance: the emissions from syngas combustion in the CHP engine [555], the avoided burdens due to the prevented cork landfilling [556] or the tar management outcomes [557]. The complete LCI information for this study may be found in Annex 4.

LCA was conducted considering three gasification scenarios in order to understand the environmental outcomes of the alternatives when compared to the conventional system. Scenario E-1 constitutes the gasification base case without any valorization strategy for the chars produced, whilst scenarios E-2 and E-3 promote char valorization in two distinct options considering them as a by-product instead of waste, and scenario 4 refers to the conventional system of energy production, as described below.

Scenario E-1: Base case - no valorization of chars was considered, meaning that the plant was operated in a standard regime and the chars were considered as waste and disposed in an inert landfill.

Scenario E-2: Raw material production from chars - based in scenario E-1 but using char for the production of black carbon (the production of black carbon through the standard procedure was replaced, related burdens being avoided).

Scenario E-3: Chars used as absorbent for heavy metals - based in scenario E-1 but using chars as absorbent agent for materials contaminated with heavy metals. The contaminated chars should be out of the system limits, however as a worst-case scenario, their landfilling as hazardous waste was considered in a conservative approach.

Scenario E-4: Conventional system of energy production - this scheme reports a combination of energy production between electricity and heat, in the same proportion as Ecorkwaste plant produces them (53% of the energy is in heat form, while 47% is produced as electricity). Thus, 530 kWh would be allocated to heat production in an industrial site, while 470 kWh are produced by means of the Spanish electricity mix.

4.4.2. Assumptions and limitations

For the implementation of LCA, the following assumptions and hypothesis were considered:

(a) experimental data is representative of each type of WtE and waste stream, therefore constituting reproducible information;

(b) the electricity grid mix was considered as described in [529] for the EU-28;

(c) in scenario E-3, a conservative situation was considered including the landfilling of the contaminated chars in the system boundaries, although this constitutes the disposal of residues from the valorization of a by-product of the original system. Therefore, this scenario is presented as a worst-case approach;

(d) the cork residues and MSW production rate is maintained along the duration of the project and the gasification plant lifetime;

(e) the electrical grid is capable of receiving and distributing the produced electricity to consumers.

As limitations, some important remarks must be referred:

- if higher moisture contents are observed, lower conversion efficiency will be achieved and higher energy amounts will need to be replaced in the system, once more energy will be spent in the drying step;
- the engine required to produce electricity from the syngas generated in the Ecorkwaste gasification plant had to be theoretically considered within the system boundaries. Its working regime is detailed in [555];
- if the EU-28 electricity grid is substituted by a different mix in a specific location, environmental results may differ from the ones presented here.

4.4.3. Results and discussion

4.4.3.1. Ecorkwaste plant environmental performance

After the study of MSW regular gasification, a case-study comprising the assessment of the environmental impacts of cork residues through the same technique was held. The results for the scenarios appraised are resented in Table 15.

Table 15 - Environmental impacts for the Ecorkwaste scenarios assessed.

Impact category	**Ecorkwaste scenarios**			
	E-1	E-2	E-3	E-4
GW (kg CO_2-eq.)	121.8	40.9	133.8	186.0
TA (kg SO_2-eq.)	0.67	0.30	0.70	1.53
FE (kg P-eq.)	0.05	0.05	0.06	0.08
ME (kg N-eq.)	3.97×10^{-3}	3.58×10^{-3}	4.21×10^{-3}	0.01
FRS (kg oil-eq.)	37.0	-39.3	39.30	42.3
CED (MJ)	2216.7	-1306.6	2363.0	4604.7

From Table 15, it is worth to mention that within each impact category, all the scenarios present results in the same order of magnitude, allowing options to be more straightforwardly compared. In addition, it is observed that scenario E-2 (black carbon production from gasification chars) portrays negative values for FRS and CED. This means that there are environmental credits associated with this scenario, alleviating Nature from the environmental charges seen in the other options. These results derive from the lower consumption of fossil resources and energy promoted by the valorization of chars, in contrast to the conventional production of black carbon which requires high temperatures and high contents of carbon [558, 559]. Also, in scenario E-2 the manufacture of the commercial product is replaced by a strategy in which the raw material is not directly extracted from Nature, being alternatively considered a waste stream of other process, carrying none of the upstream burdens. This lowers the environmental costs associated to the technique [557].

In a closer look, it is observed that scenario E-4 (production of energy from the conventional system) depicts the most jeopardizing profile, all the impact categories resulting in higher values than the other scenarios. CED and GW are the environmental categories with higher impacts, which is consistent with the fact that the electrical grid mix in Spain in composed of around 70% of fossil sources and only 30% of renewable sources [560]. This trend was also seen for the gasification of other biomass streams [561]. The main environmental impacts derive from the materials used for the current lines and the construction materials on the medium and high voltage level, namely steel, copper and aluminum [562] followed by the emission of N_2O, O_3 and SF_6 during electricity transmission and distribution [563]. In fact, Cherubini et al. [564] conducted a thorough review of the LCA studies for several bioenergy systems and conclude that most authors found a significant net reduction in greenhouse gas emissions and fossil energy consumption when bioenergy replaces fossil energy.

Figure 30 depicts the comparison of the environmental performance of all the scenarios.

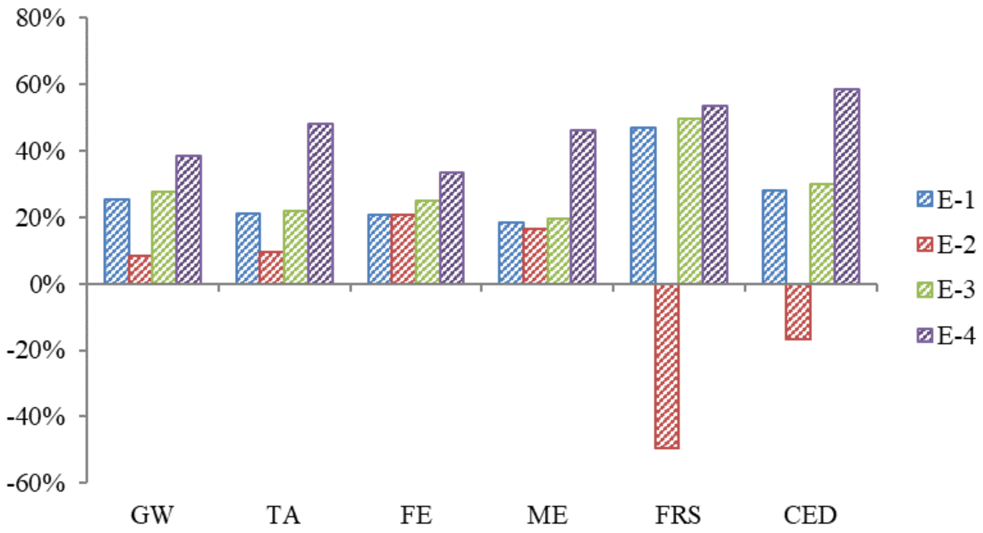

Figure 30 - Environmental assessment for Ecorkwaste impact categories.

In a general view, scenario E-4 affords overall contributions that range from 33% to 58% within the impact categories assessed, followed by scenario E-3 with an average contribution of 25%, nevertheless reaching a 50% contribution for FRS category. Similar or lower contributions were seen for scenarios E-1 and E-2. This is mostly due to the fact that scenarios 1-3 are considered waste-to-energy technologies meaning that they incorporate energy production and waste management in the same technique [547], while scenario E-4 covers energy production which is not totally achieved from renewable sources, therefore being less sustainable. Actually, even considering scenario E-3 as the worst-case scenario (due to the inclusion of the hazardous landfilling of the contaminated char), lower impacts are seen when compared to scenario E-4. In a recent review, Tziogas et al. [565] draw attention to one of the main findings among the reviewed works: renewable energy techniques provide higher contribution to sustainable development than the conventional schemes, confirming the results of the present study.

From these results it is possible to preliminarily point scenario E-2 as the most advantageous in terms of environmental impacts, followed by scenario E-1, then scenario E-3. Scenario E-4 is not based in a gasification system, rather is partly based on fossil resources as it depicts the electricity mix and heat production, therefore presenting significant environmental hazard. Nevertheless, in order to better understand the role of the phases in the overall system to each impact category, a detailed discussion for scenarios 1-3 is provided in the following sections.

4.4.3.2. Environmental performance of scenario E-1

Figure 31 shows the environmental profile attained for scenario E-1, for each environmental category and process step.

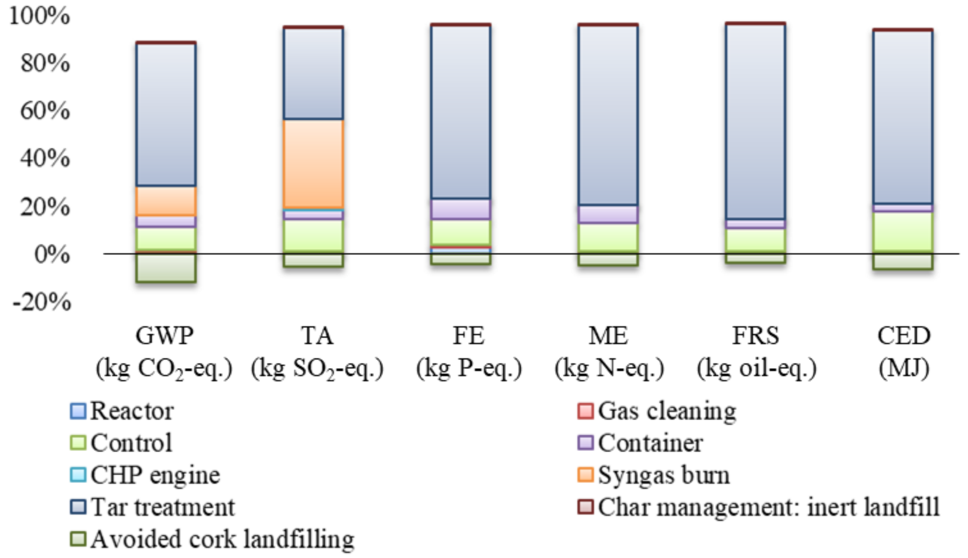

Figure 31 - Environmental assessment for Ecorkwaste scenario E-1.

Results shown in Figure 31 point to some clear trends: by one hand, the contribution of tar management process is the highest in all the studied impact categories, achieving contributions higher than 80% in some of the categories. Tar is a hazardous waste [566] and therefore its treatment magnifies the overall environmental impact of the process. By the other hand, syngas burning emissions is the second higher contributor, but just in a few categories, such as TA (almost 40% of contribution) and GW (10% of contribution). This is justified by the release of noxious emissions [555].

On its behalf, the operation of the plant causes *circa* 15% of the impact through all the studied categories. This impact is mainly caused by the electricity consumption of the control stage (computer, sensors, gas analyzer and monitoring devices), whereas the contribution of the plant operation to the environmental profile is actually very low. Therefore, the impacts from the rest of the plant are mainly induced by the production of capital goods. Similar trends on the contribution of the plant facilities for the overall impacts were reported in [561] for a different biomass stream. In the same study, the CHP emissions present the most significant role for most of the impact categories assessed, namely TA, FE and terrestrial ecotoxicity, in contrast to what is seen in the present study.

It is also worth to mention the effect of the avoided cork landfilling, which allows to decrease the overall impact of the system in all the categories. This is the advantage of not managing cork wastes in landfill [567]. In fact, the contribution of the cork avoided landfilling herein presented is more significant than the value seen in other studies [568]. GW and CED are the most benefited impact categories, important amounts of CO_2-eq. and energy being spared. Besides that, GW does not seem to be affected by the CHP engine, in agreement with [30]. This was also seen for all the other categories in the case of syngas burning emissions, except for TA. For this category, the less affecting aspect of the system is the inert landfilling of the produced chars which prevents any leaks and leaching [511], therefore contributing to lower acidification levels in Nature. Furthermore, another key aspect is the negligible contribution of char landfilling to the environmental profile of the system; its contribution is close to 1% of the analyzed impacts. Although for a different biomass stream and type of landfill, higher contributions from this stage were seen in [561].

Although high temperature steam gasification generally reduces the yield of tar [569], in the present study tar management is the step that presents the higher impacts in all the environmental categories. Furthermore, GW and CED are the most affected categories due to the incineration process itself, which demands significant energy levels in order to maintain the required high combustion temperatures. This is in accordance with [557].

4.4.3.3. Environmental performance of scenario E-2

Figure 32 presents the results for the impact categories achieved for the system, when char is valorized as precursor for black carbon production, scenario E-2.

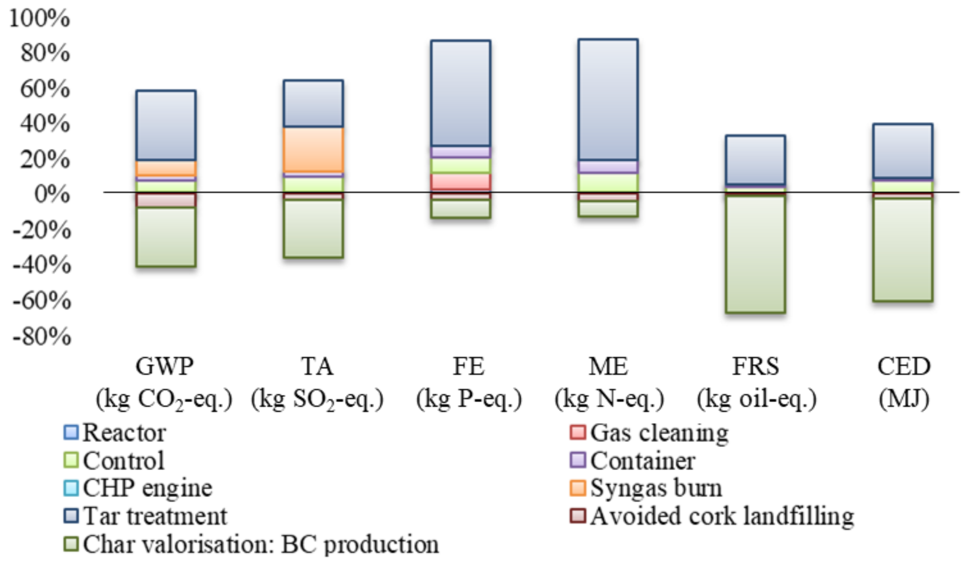

Figure 32 - Environmental assessment for Ecorkwaste scenario E-2.

According to Figure 32, the individual contribution of the avoided BC production in FRS and CED is sufficient to counterbalance the sum of all the other aspects for these categories. This was also reported in other studies where tar from gasification was recycled and used as aggregate for construction [557]. The avoided production of BC from the conventional raw material sets even higher environmental benefits than the previous scenario, more than 3500 MJ of energy, roughly 80 kg CO_2-eq. and 76 kg oil-eq. being saved per functional unit (among other lower savings). The explanation for these results relies in the fact that the conventional production of black carbon involves high contents of energy and carbon [558]. These results support a more sustainable environmental profile for this scenario, once FRS and CED show a total outcome below zero. In the case of GW and TA, this effect was not observed but the contribution from the avoided BC production is rather high (40% and 35%, respectively). Avoiding cork residues landfilling has a lower effect in the impact categories, nevertheless granting 10% contribution for GW. Lower avoided burdens for cork residues landfill were seen in [567].

Regarding the environmental burdens, tar management process is still the most contributing process (with shares between 25% and 70%), followed by syngas burning emissions, these last ones only for GW and TA. Gas cleaning is the second most contributing step to FE with *circa* 10% share, while for ME the same portion relates to the control system.

Similar to scenario E-1, the avoided landfill of the cork residues promotes environmental credits although in this case the contribution is lower than the reported for the avoided production of BC. Direct comparisons are very difficult to attain due to different functional units, methodologies or system boundaries [564]. However, reported literature suggests that enhanced avoided burdens for some of the impact categories would be achieved if incineration or recycling were considered instead of landfilling the cork residues used in the gasification experiments [567]. Relative to the other categories, their values remain the same as in scenario E-1, as the only dissimilarity between these scenarios is the replacement of the inert landfilling with the avoided burdens of black carbon production.

4.4.3.4. Environmental performance of scenario E-3

Figure 33 presents the results for the impact categories achieved using char as heavy metals absorbent, scenario E-3.

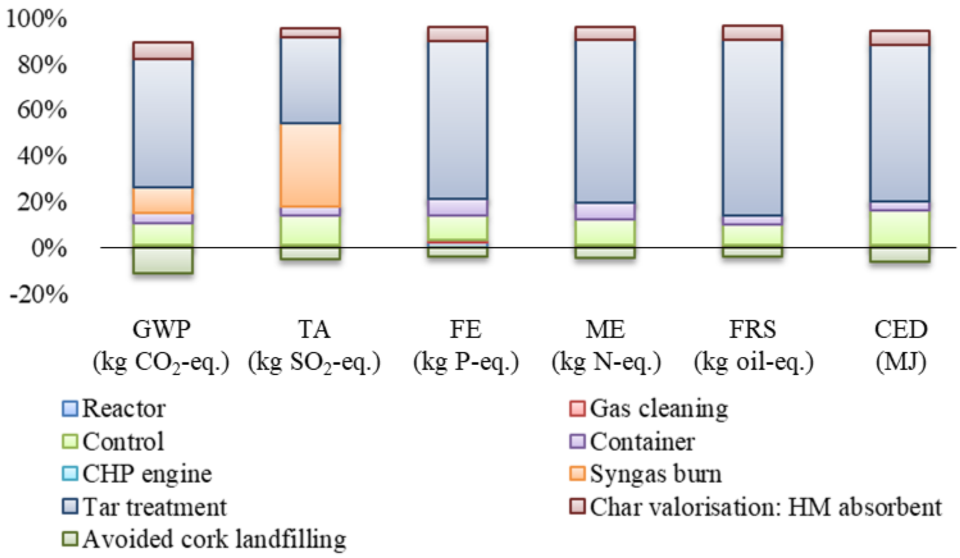

Figure 33 - Environmental assessment for Ecorkwaste scenario E-3.

In this scenario, only the avoided cork landfilling shows negative values, all the other aspects of the overall system contribute to the environmental burdens. When compared to the inert landfilling of chars achieved in scenario E-1, the hazardous landfill herein presented shows an increase of one order of magnitude for all the impact categories, except for ME where the harmful effects are increased by a multiplying factor of 100. It is clearly seen that the addition of a hazardous landfill process increases the overall impact, representing an increase of approximately 10% in relation to the base case scenario for all the studied categories. This effect is driven by two causes: on one hand, the impacts generated by the landfill itself, which affect all the studied impact categories [570]; on the other hand, the absence of avoided impacts except cork landfilling. As observed in Table 15, from the gasification alternatives this scenario is the one showing higher impacts, only exceeded by the conventional system of producing energy (scenario E-4).

The impact categories more influenced by the presence of the hazardous wastes are CED and GW, a rough increase of 150 MJ and 12 kg CO_2-eq. per functional unit being accomplished. However, gaseous emissions also draw concern especially relating health risks [571]. Regarding char valorization, scenario E-3 follows a similar approach to E-1. The difference relies in the hazard wastes as char from scenario E-3, which contain heavy metals.

4.5. Partial conclusions

A life cycle analysis of one tonne of municipal solid wastes was conducted for two WtE techniques: incineration and gasification. Eleven impact categories were assessed, in order to evaluate the environmental performance of the procedures. The results were then compared so that the main features of each conversion scheme could be highlighted.

Incineration has unveiled its enhanced performance when compared to low temperature gasification, namely depicting greater results for nine out of eleven impact categories. Gasification presented environmental burdens for some of the impact categories (GWP, ADP_{fossil}, ODP and TETP). Nevertheless, EP, AP, MAETP and HTP depicted excellent results, this treatment performing better than incineration in these cases. Under this gasification scheme, one tonne of treated MSW obviates the emission of more than 2.3 tonnes PO_4-eq. (EP) and almost 0.40 kg SO_2-eq. (AP), while the marine aquatic compartments are saved from 312 tonnes DCB-eq. (MAETP) and humans are spared from nearly 22 kg DCB-eq. (HTP). Incineration presents negative values for all the impact categories, meaning environmental benefits such as saving natural resources and/or lowering pollutant emissions. Indeed, incineration displays superior results for

GWP (approximately -171 kg CO_2-eq.), ADP (-2 MJ of fossil resources and -50.1x10^{-6} kg Sb-eq.), FAETP (-0.267 kg DCB-eq.), POCP (-4.28x10^{-2} kg C_2H_4-eq.) and TETP (-5.90x10^{-2} kg C_2H_4-eq.). The achieved results were similar or even improved when compared to literature, the main explanation relying in the electricity production in the case of incineration and in the high efficiency attained in the cleaning step for gasification. Material resources and emissions to fresh water were seen to be the main savings for incineration, although incineration depicted more than 500 tonnes of environmental credits per functional unit. NO_x and SO_2 were the main emissions seen for incineration, while sulphur compounds constitute the major emission for gasification. The most hazardous process seen for incineration is the landfill step, whereas in the case of gasification the thermal treatment itself shows the highest environmental burdens, while syngas cleaning and landfill present environmental credits.

When correlating distinct incineration scenarios, it is possible to conclude that the replacement of the inert landfill utilized in the base case by a standard procedure shows no major differences in the overall performance of the technique, even though three impact categories show poorer results (GWP, EP and TETP). As far as the electricity production is concerned, it is a chief aspect of the incineration process, since in its absence this WtE is not environmentally sustainable.

Performing a sensitivity analysis for different waste management technologies, within similar system boundaries, standard incineration performed better for almost all the impact categories, except for GWP and EP where landfill and gasification at low temperatures, respectively, depicted higher performances. Furthermore, when compared to the other techniques excluding incineration, low temperature gasification evidenced improved results for most of the categories, namely EP, AP, MAETP, HTP and POCP. Directly comparing regular gasification results to incineration results, some benefits were shown by this last technique. This happened once the excess amount of air present in the reaction chamber during regular incineration promoted the total oxidation of all the compounds derived from waste combustion, contrary to what was achieved in the gasification experiment herein investigated. Together with the usual oxygen-deficient atmosphere, low temperatures triggered a poor environmental performance, advantages from regular gasification being overcome by incineration. However, the excessive levels attained by incineration in the GWP category claim for a more sustainable methodology which is able to reduce this impact and comply with the current demand for climate change regression.

It is important to stress that these conclusions are valid within the assumptions and limitations referred, namely for a MSW sample as described in Table 8 and for the EU-28 electrical grid, among other conditions. If these are not met, the final outcomes will definitely be different and thus the contribution of each technique will also change.

Regarding the gasification of cork residues, under the Ecorkwaste project, the LCA study was conducted for four different scenarios in a cradle-to-grave approach. The main conclusions are that Ecorkwaste gasification technology constitutes a successful circular economy (CE) case study, once the feasibility of energy production from wastes of cork industry has been proven. This technology allows producing energy in a more sustainable way when compared to the conventional scheme, notable differences between the systems being observed. A critical phase is the management of the produced waste: tars, as a hazardous residue, should be reduced at the minimum but chars are suitable for valorization which allowed to settle two valorization scenarios. Even for the worst scenario in char valorization (using char as heavy metals absorbent), the gasification scheme affords better environmental impacts than the conventional configuration for producing energy. Nonetheless, this scenario reflects a conservative situation, because the waste management of a second use of a waste should not be allocated to the gasification system. The scenario where char is utilized to produce black carbon presents improved performance, environmental credits being attributed to the system (namely for the FRS and the CED), which dramatically decreases the overall impacts of the system. A common environmental credit to all the considered scenarios is the avoided cork landfilling.

Chapter 5 – Environmental Assessment of Two-stage Plasma Gasification

Part of the content of this chapter may be cited as:

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5.1. Plasma gasification and related benefits

As seen in the previous chapter, low temperature WtE show some distressing effects for the environment, presenting jeopardizing values for some impact categories. Therefore, it is advisable to find more bearable alternatives in order to enhance these outcomes. According to [528], plasma gasification presents improved impacts for the environmental categories where regular gasification seems to perform worse: GWP, ODP, ADP_{fossil} still present positive results but with lower absolute values (meaning less environmental damage), whereas FAETP and TETP go down from positive to negative results (which stands for environmental credits), therefore granting an eco-friendlier behaviour. Thereby, if correctly adapted to the system boundaries, feedstock and experimental conditions, plasma gasification might pose a possible alternative to improve the exhibited environmental impacts for regular gasification. This has already been reported by other authors, when assessing waste management facilities [528, 572], some of them attaining waste volume reductions as high as 95-99% [573, 574].

Several types of plasma systems and torches exist but, generically speaking this is a severely high temperature treatment which in a deprived oxygen atmosphere, depending on the selected waste fraction and under suitable operational conditions, affords reduced hazardous air emissions as well as low leachate toxicity and also enhanced energy production [575, 576]. Plasma technology may be viewed as a waste treatment technique by itself or as a step through which raw producer gas from gasification is cleaned, both enabling high energy and carbon conversion efficiencies in the production of a cleaner syngas [577]. This efficacy is enlightened when plasma is coupled with gasification once the oxygen-starved ambient produces less volume of gas than incineration, which lowers the operating costs and maximizes the cleaning process, ensuring compliance with actual legislation [577]. Plasma gasification of the inorganic ashes generates a new dense and vitrified by-product (vitrified slag) which is suitable for specific uses such as aggregate production for construction purposes [550, 577], raising even more the environmental credits associated to this technology.

Besides the environmental benefits achieved, although few data are available and technology continues in development, plasma gasification is pointed as a very promising combination with higher energetic performances when compared to traditional WtE processes due to the use of compact and highly effective devices [62, 577].

Depending on the waste composition, differing standards and definitions are applied by distinct world regions/countries/socio-economic organizations [578]. In other words, the same MSW component may be understood as waste in one country and as recyclable material elsewhere and this hampers tentative comparisons between MSW compositions in diverse regions. In the end, the discrepancy in definitions is a result of different policies and responsibilities prevailing with respect to the waste cycle, depending on the country or legislative body as well as the political, social and economic framework [579]. Usually, in developed metropolitan areas there is a variety of sectors which introduce commercial, industrial, touristic and educational activities, whereas in districts far from such cities the main activities are likely to be agriculture and forestry. These generate highly specific waste streams with their own characteristic MSW compositions [580]. This is deeply related to the populational growth and the socioeconomic development. As population increases and the world continues to urbanize, the concept of sustainable development is an issue of major concern. “Urban metabolism” is a concept that first appeared in 1965 [581], and has received increasing attention up to the present [582-584]. The environmental aspects of urban metabolism are assessed by means of different tools, one of them being LCA [582, 585, 586]. It contributes directly to the “urban quality” as defined by Garau and Pavan [587], the latter embodying health, well-being, environment and governance. Tagliaferri et al. [588] analysed different scenarios in the UK including plasma gasification for the treatment of MSW. The new approach concerning plasma-based gasification depicted higher efficiency in the production of renewable methane, which might replace natural gas in the future. Evangelisti et al. [550] also assessed this same technology, for the treatment of several waste streams obtaining environmental credits for most of the impact categories. The authors also compared plasma gasification with techniques such as pyrolysis, combustion and classic gasification. The advanced plasma technique produced an improved overall profile compared to the conventional WtE options, mostly due to its higher electrical efficiency. Other studies have reported high conversion efficiencies attained with this plasma-based technology [577, 589] as well as volume reductions of up to 99%, this being substantially higher than conventional incineration [574, 590].

The neighboring populations often show concern about possible impacts in public health due to waste treatments in nearby locations, which may have adverse effects on the quality of life [512, 530]. Nevertheless, our current understanding of the possible waste management scenarios available at urban, regional or even national scales has increased the social awareness of the importance of this type of renewable energy technologies [591].

As far as the electrical utilization is concerned in residential spaces, heating is the most demanding area, followed by lighting and electrical appliances. Countries such as the Netherlands, Portugal, Germany and Ireland show consumption drops of over 35% since 2000, once they have adopted the heating requirements and incorporated building features that are consistent with the desired comfort levels and high efficiency [592]. In the present chapter, besides the LCA for the plasma gasification of MSW, a relation between the amount of energy used and the yield of waste produced per capita is proposed. Also, considering the reports on the high efficiency related to the plasma gasification technique (in comparison to incineration and regular gasification), an estimate of the potential electricity production capacity from the thermal conversion of MSW is herein performed, as a worthwhile approach to “translate” the concept of WtE techniques to a broader audience.

5.2. Materials and methods

5.2.1. MSW two-stage plasma gasification

The two-stage plasma gasifier plant is similar to the regular gasification plant described in section 4.2.1 (Figure 16), with an extra step after the gasification unit: the plasma torch. Four major processes are comprised in the system herein studied: MSW gasification (first stage), plasma (second stage), syngas treatment and landfill of the inert products.

After the waste fraction is conveyed to the gasifier, its decomposition occurs in a bubbling fluidized bed through the controlled action of oxidant agents (oxygen and steam), producing syngas at high temperatures. Subsequently, this raw syngas with ash produced during gasification, unconverted char and vestigial tars are sent to the plasma unit. Here tars are cracked and all the particles entrained in the gas as well as the ash are captured and vitrified due to the severely high temperatures. After cooling the hot syngas, it flows through the cleaning units where it is conveniently treated by means of dry filters and scrubbers, so as to eliminate the remaining air pollutants. Harmful compounds are neutralized and drained from the system, the resulting inert residues being removed from the facility and landfilled. A gas engine is then utilized for the production of electricity.

5.2.2. Scope, system boundaries and functional unit

The scope of this study was the analysis of the environmental impacts caused by the two-stage plasma gasification of the MSW sample characterized in Table 8. Similar to the low temperature techniques, data was modelled by the product sustainability software (GaBi® - database version 4.131 distributed by PE International [527]), which enabled the environmental assessment of the two-stage plasma gasification process. This was performed evaluating eleven different impact categories through CML 2001 methodology [509], as presented in Table 9.

Figure 34 describes the limits of the system, dashed lines indicating the boundaries. Colored boxes represent the processes, which are connected by flows (arrows). MSW was taken as an input as received at the plant, its origin, collection and transport to the thermal treatment facilities being excluded from the boundaries of the system. The power generated upon the two-stage plasma gasification of MSW replaced the electricity from the grid, in an auto-consumption mode, herein shown by the upper route (green, electricity flow).

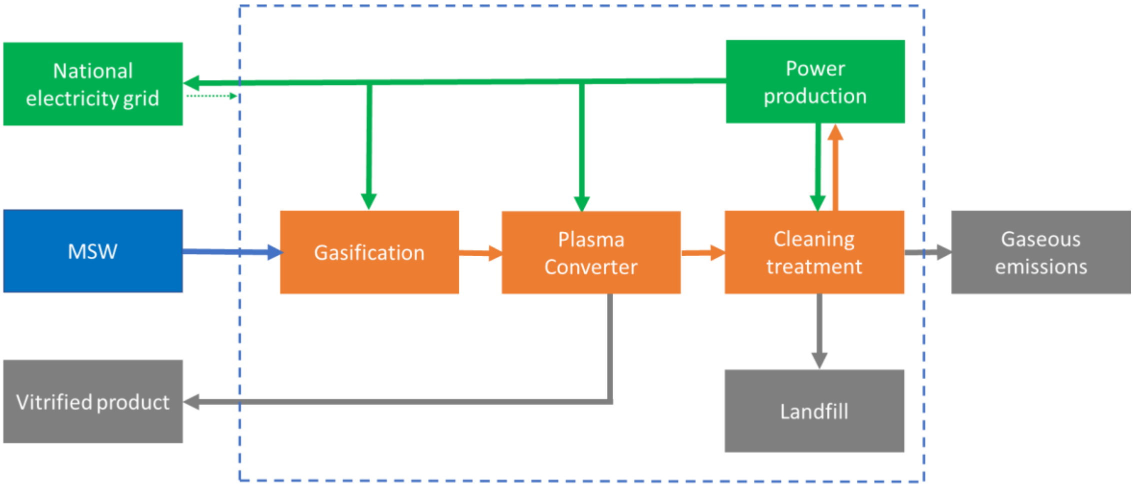

Figure 34 - System limits for the two-stage plasma gasification of MSW.

As in the case of the low temperature techniques, the central route (blue) refers to the MSW path within the system, from its entrance to the gasification chamber, moving towards the plasma torch and further gas cleaning (material flow). The lower route (grey) represents the potentially hurtful outputs of MSW two-stage plasma gasification as well as the by-product formed in the plasma converter (vitrified slag) which can be sold to construction or ceramic companies. The functional unit (fu) was defined as the two-stage plasma gasification of 1 tonne of MSW as received at the plant by, its characterization being shown in Table 8.

5.2.3. Life cycle inventory and methodology

An overall plan is composed by processes, which are interconnected by flows so that the modelling software performs the environmental impact calculations based on the actual scenario proposed for the experiment. This way, specific balances between the inputs and the outputs refer exactly to each process, based on the main operational data which are listed in the life cycle inventory, reported in Annex 1. Figure 35 depicts the two-stage plasma gasification plan settled in GaBi®.

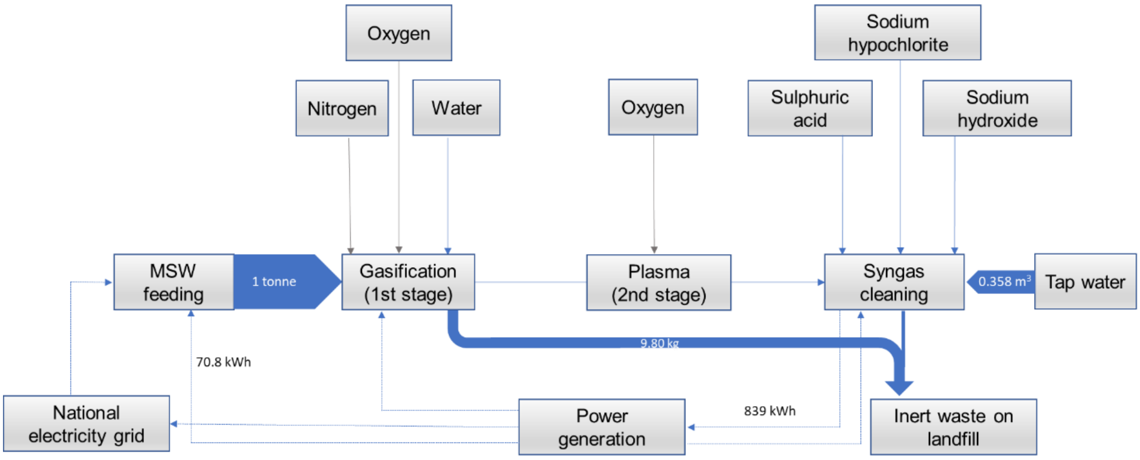

Figure 35 - Flowchart for the plasma gasification of 1 tonne of MSW.

As in this WtE there is an extra product which may account for environmental effects (vitrified slag), two different scenarios were posed to conduct the LCA study as follows:

- Scenario PG-1 (reference case): only the production of electricity was considered (in order to mimic the boundaries of the LCA performed for the low temperature techniques);
- Scenario PG-2: the production of electricity and the vitrified slag were both accounted.

Along with the vitrified product shown in Figure 32, another by-product is produced during the plasma gasification of MSW: steam. However, this output was not considered for the life cycle assessment once it is used to refuel the system, in the units where steam is supplied.

5.3. Assumptions and limitations

For the implementation of LCA, the following assumptions and hypothesis were considered:

(a) experimental data is representative of each type of WtE and waste stream, therefore constituting reproducible information;

(b) the electricity grid mix was considered as described in [529] for the EU-28;

(c) the electrical grid is capable of receiving and distributing the produced electricity to consumers.

As limitations, some important remarks must be referred:

- if higher moisture contents are observed, lower conversion efficiency will be achieved and higher energy amounts will need to be replaced in the system, as more energy will be spent in the drying step;
- if the EU-28 electricity grid is substituted by a different mix in a specific location, environmental results may differ from the ones presented here;
- as there are few LCIs available for MSW samples and for the assessed techniques, an extrapolation of the electricity produced from the MSW amount generated *per capita* in several parts of the world was conducted using the MSW characterization presented in Table 8. This is a feasible approach given that the MSW sample resembles the average global composition presented in [570].

5.4. Results and discussion

5.4.1. Two-stage plasma gasification environmental impacts

Table 16 presents the environmental impacts achieved for the two-stage plasma gasification, for the considered scenarios.

Table 16 - Two-stage plasma environmental results for MSW treatment.

Impact categories	**Two-stage plasma gasification scenarios**	
	PG-1	**PG-2**
GWP (kg CO_2-eq.)	-31.0	-3.36x10^{3}
AP (kg SO_2-eq.)	-39.7x10^{-2}	-1.03x10^{-2}
EP (kg PO_4-eq.)	-1.55x10^{3}	-6.54x10^{-5}
ADP$_{elements}$ (kg Sb-eq.)	-1.62x10^{-5}	-1.82x10^{-1}
ADP$_{fossil}$ (MJ)	-382	-8.41x10^{2}
FAETP (kg DCB-eq.)	-6.41x10^{-2}	-1.22x10^{-4}
HTP (kg DCB-eq.)	-14.7	-19.4
MAETP (kg DCB-eq.)	-2.14x10^{5}	-1.07x10^{4}
TETP (kg DCB-eq.)	-2.95x10^{-2}	-6.61x10^{-2}
POCP (kg C_2H_4-eq.)	-2.23x10^{-2}	-8.62x10^{-3}
ODP (kg R11-eq.)	-2.13x10^{-8}	-9.86x10^{-7}

As may be seen from Table 16, the assessed plan for plasma gasification held in this research gave rise to negative values for all the environmental categories in both scenarios. These are very promising results, once they contribute to the alleviation of the environmental burdens associated with the resources required by the thermal technique. Regarding the main differences among the scenarios, PG-2 performed better for some impact categories such as GWP, ADP$_{elements}$, ADP$_{fossil}$ and ODP, whereas HTP and TETP values were in the same order of magnitude as scenario PG-1. POCP, MAETP, FAETP EP and AP depict enhanced results in the case of scenario PG-1.

The explanation for most of these differences relies in the fact that the recovery of the vitrified slag and its inclusion in the construction industry avoid the extraction of natural rock-type resources, lowering the abiotic depletion of elements and fossil fuels as well as the emission of greenhouse gases [62, 593]. This enforces lower impacts in ADP and GWP, as well the formation of less NOx compounds, also contributing to the reduction of ODP effects. As far as HTP is concerned, slightly better results are achieved for scenario PG-2 mostly due to the tar cracking promoted by the plasma converter and to the entrainment of ash and particulates in the vitrified slag, reducing the latent exposure to these compounds [577]. This was also reported by Danthurebandara et al. [593], who evaluated several recovery options for the vitrified slag, ranging from aggregate, inorganic polymer cement and block, blended cement and blended cement block. TETP also depicts small differences when compared to scenario PG-1, nevertheless enhanced results are accomplished due to lower landfilling of APC residues [62]. The results for the categories in which PG-2 performed worse are majorly related to the oxygen usage in the plasma torch [593].

As the two-stage plasma gasification is a recent application of plasma technology, there are not enough thorough studies on MSW treatment to enable a complete comparison of each environmental category. Therefore, a detailed portrayal of the respective emissions is further attempted. In an extended description, Figure 36 depicts the relation between each impact category and the respective environmental emissions for the reference case (PG-1).

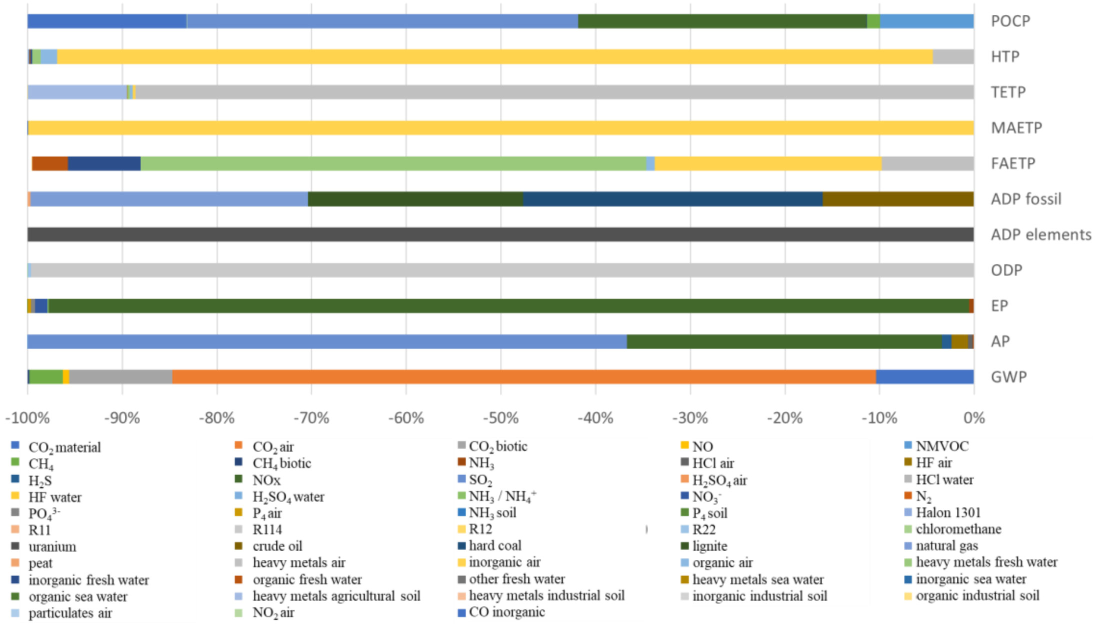

Figure 36 – Relative contribution of the emissions for two-stage plasma gasification of MSW.

Carbon dioxide is the major avoided emission contributing to GWP, namely during gasification and plasma conversion steps, with a small contribution of methane (less than 5% of the total share). The reduction in the consumption of fossil fuels due to the electricity generation in plasma gasification, contributes to a reduced release of CO_2, as it is further introduced in the system preventing the use of national grid mix which is roughly composed by more than 40% of fossil fuels [594]. Published literature reports higher GWP impacts for similar waste streams and assessments [528], Evangelisti et al. [550] accounting the differences for biogenic CO_2 inclusion and exclusion.

Eutrophication and acidification potential values are explained by the high efficiency of the plasma converter, which reduces significantly the release of substances with surfactant and acid behavior respectively, and these are mainly excreted during the syngas treatment in less advanced techniques, thus being severely reduced in the case of plasma gasification. Regarding the results for these two categories, $-1.55\text{x}10^{3}$ kg PO_4-eq. and $-39.7\text{x}10^{-2}$ kg SO_2-eq. respectively, inferior results for EP (approximately -0.04 kg PO_4-eq.) and slightly better for AP (approximately -1 kg SO_2-eq.) have been reported elsewhere [550], recalling that factors such as small differences in MSW composition can promote these differences. This might be the basis for the emissions herein seen, EP being dominated by NOx emissions (> 95% of the total share) while AP is mostly due to SO_2 emissions (roughly 65% of the total share), besides NOx contribution. Applying the necessary proportion factor, worse values for EP ($1.4\text{x}10^{-4}$ kg PO_4-eq./kg of MSW) and similar values for AP ($-9.71\text{x}10^{-4}$ kg SO_2-eq./kg of MSW) were also reported [528].

Regarding ODP not only the plasma converter justifies the negative values of this indicator (preventing the release of harmful gases) but also the electricity production achieved in the process, which by replacement of the grid electricity prevents the generation of substances prone to ozone layer degradation. In this specific study, R114 is the chief emission for ODP accounting for almost 100% of the total share, as shown in Figure 36. Notwithstanding the result for $ADP_{elements}$ is small ($-1.62\text{x}10^{-5}$ kg Sb-eq.), its negative value may be associated to the enforcement of the renewable energies share in the national electricity mix, in this case avoiding the ablation of uranium. As far as ADP_{fossil} is concerned, it is possible to observe that each tonne of MSW treated saves more than 380 MJ of energy. This is mainly due to the avoided expenditure of non-renewable resources, acquired by the electricity production through the use of the producer gas as stated by other authors [528]. In this case, these are mainly hard coal, natural gas, lignite and crude oil in descending order of shares. Evangelisti et al. [528] also confirm that net electrical efficiency is the cause for sustainable results in this category.

Relative to the ecotoxicity categories, results are once more explained by the proficiency attained with plasma conversion once both aquatic (freshwater and marine water) and terrestrial reservoirs are kept from the hazardous emissions, as well as the primary resources used in the production of the auxiliary materials commonly utilised for syngas cleaning in other thermal treatments are saved. In the case of FAETP, the most prevented hazard is the emission of heavy metals to freshwater while for MAETP this refers to the emission of various inorganic substances to air. In the case of TETP the release of heavy metals to air and to agricultural soil constitutes the major environmental savings. FAETP and TETP results are somehow better than the ones achieved by Evangelisti et al. [550]. Also, as the raw syngas achieved before the final steps is already cleaner than the obtained from other WtE techniques, lower amounts of chemicals are disposed [528].

Relative to human toxicity, the plasma converter significantly reduces flue gas contaminants, namely inorganic substances that would be released to the air, empowering syngas cleaning as the major step alleviating the air emission of noxious compounds. Landfilling of reduced amounts of inert matter also highlights the good result for this indicator. With the necessary adjustment of the functional unit it relates to, the HTP value reported by other authors seems to be a bit better (roughly -40 kg DCB-eq.) than the one achieved in this assessment for a similar strategy (-14.7 kg DCB-eq.) [528].

POCP result also shows a major contribution from the syngas cleaning step, once most of the prevented emissions (nitrogen oxides and sulphur dioxide) refer to substances that generate precursor gases, potentially ending up in more ozone. Albeit POCP value attained in this study is environmentally beneficial ($-2.23\text{x}10^{-2}$ kg C_2H_4-eq.), somewhat better results have been published elsewhere ($-8.6\text{x}10^{-2}$ kg C_2H_4-eq.) [528, 550]. This is explained by the inclusion of a by-product within the boundaries of the referred studies, a secondary aggregate (resembling the herein called vitrified slag) which will replace the need to produce primary aggregate from natural rock, constituting an avoided burden.

5.4.2. Process-by-process performance

As seen, different processes influence distinct impact categories throughout the two-stage plasma gasification. As said before, the four chief processes that govern the overall waste treatment are MSW gasification (first stage), plasma converter (second stage), syngas treatment and landfill of the inert products. Figure 37 portrays a quantitative evaluation of their individual performance for scenario PG-1, a clarification on the case of landfill being shown for visual purposes.

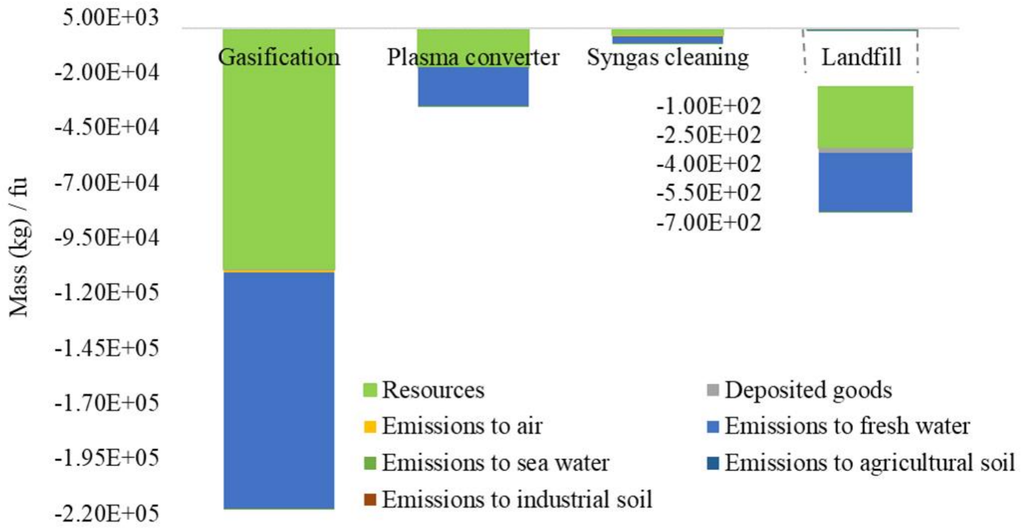

Figure 37 – Process performance for the two-stage plasma gasification of MSW.

As shown in the previous section, all the impact categories depicted negative values for the plasma gasification of one tonne of municipal solid wastes. Thus, by plotting the overall performance of each of the processes a coherent observation may be done, all of them showing results below zero. This means that all the processes are concomitant to an environmentally sound technique, even more enhanced by the evidenced "self-consumption" of the electricity generated within the system. Resources and emissions to freshwater are the dominant flows, a contribution of almost 50% of each being observed in the four processes. In total, each tonne of MSW permits the saving of more than 260 tons of combined flows, water constituting the leading resource saved. Regarding the narrow section corresponding to emissions to air, organic substances such as nitrogen compounds, carbon monoxide and oxygen are the top emissions. Again, it should be notice that the minimum residence time of two seconds for combustion of gaseous products of non-hazardous wastes at 850 ºC and for the gaseous outputs of hazardous streams at 1100 ºC is required by Directive 2000/76/EC so as to reduce these compounds to values below legal limits [548].

Observing the general magnitude of each process to the overall environmental profile of the two-stage plasma gasification, it may be seen that gasification depicts the higher avoided burdens, followed by the plasma converter, the treatment step and lastly, landfill. This behavior is probably due to the high electricity demand during the gasification step, which by self-supply of the system itself, enables upgraded environmental credits at this stage. As the cycle evolves towards the production of a cleaner syngas, each step requires less resources and releases even less pollutants once the cleaning systems receive lower flows to treat, eventually ending in a markedly reduced amount of inert material sent to landfill due to the virtually non-existent yield of fine ash and air pollution control residues [595]. This is also shown by the small grey portion on landfill results, which corresponds to deposited goods such as particulate matter, inert slags and ashes. Ray et al. [577] demonstrate the efficiency of the plasma to crack and reform tars as well as other condensable species (namely hexane, toluene and phenol) normally found in the raw syngas leaving the gasifier. The high levels of these substances in the raw syngas are effectively reduced by the plasma torch, reaching concentrations three orders of magnitude lower. This may be explained not only by the temperature effect on these substances, benzene concentration becoming negligible at 1030 ºC, but also by the plasma geometry and energy density. Plasma configuration and high energy density accomplish an optimal fluidization of the molten slag arriving at the torch, capturing any solid particle. For a deeper understanding of the plasma action and possible parameter variations that will influence syngas composition, interesting conclusions were drawn by Materazzi et al. [596], who developed a model to predict syngas yield and composition for the two-stage plasma gasification of different mixtures of waste streams. Simulation results were compared to experimental data from an actual WtE plant, deviations of 3%-6% being explained based on the assumptions made throughout the model conception. The authors also compare a single stage process to the two-stage option and report a complete carbon conversion in the second case, the arc power assuring the char decomposition. A clear downgrade in the process efficiency is as well seen when the plasma converter is switched off.

5.5. Comparison with low temperature techniques

In order to assess the environmental profile of the WtE techniques assessed so far, Table 17 shows the comparison of the results for the low temperature techniques and the plasma gasification, relative to their most similar scenarios (reference cases).

Table 17 – Comparison of the environmental impacts for the thermal conversion of MSW.

Impact categories	**Waste-to-Energy techniques**		
	Incineration	**Regular Gasification**	**Plasma Gasification**
GWP (kg CO_2-eq.)	-170.9	27	-31
EP (kg PO_4-eq.)	$-38.6x10^{-3}$	$-2.32x10^{3}$	$-1.55x10^{3}$
AP (kg SO_2-eq.)	$-24.2x10^{-2}$	$-39.9x10^{-2}$	$-39.7x10^{-2}$
ODP (kg R11-eq.)	$-1.16x10^{-10}$	$2.08x10^{-8}$	$-2.13x10^{-8}$
$ADP_{elements}$ (kg Sb-eq.)	$-50.1x10^{-6}$	$-9.35x10^{-6}$	$-1.62x10^{-5}$
ADP_{fossil} (MJ)	$-2.00x10^{3}$	240	-382
FAETP (kg DCB-eq.)	$-26.7x10^{-2}$	$1.86x10^{-3}$	$-6.41x10^{-2}$
MAETP (kg DCB-eq.)	$-26.3x10^{3}$	$-3.12x10^{5}$	$-2.14x10^{5}$
TETP (kg DCB-eq.)	$-59x10^{-3}$	$1.45x10^{-2}$	$-2.95x10^{-2}$
HTP (kg DCB-eq.)	-7.45	-21.8	-14.7
POCP (kg C_2H_4-eq.)	$-4.29x10^{-2}$	$-2.33x10^{-2}$	$-2.23x10^{-2}$

As may be seen from Table 17, both incineration and plasma gasification present negative values for all the environmental categories, while regular gasification generates environmental hazards for some categories, namely GWP, ODP, ADP_{fossil}, FAETP and TETP. A similar trend for GWP and ecotoxicology categories has also been reported in other studies [520]. Despite these positive values, regular gasification provides high performance for EP, AP, MAETP and HTP, indicating major environmental credits for these impact categories, when compared to the other WtE options. Taking in consideration the balances performed by the software, GWP is primarily attributed to CO_2 during the production of the gasifying agent. Although positive, this GWP value is lower than reported in other published studies [547] mainly due to the fossil fuels saved by the electricity being fed back into the grid [520]. The ODP outcome is related to the emission of halogenated compounds during the gasification step, which may be justified by the high level of plastics (for instance PVC) [521] in the MSW sample assessed. The major cause for the achieved ADP_{fossil} result is the use of non-renewable resources such as hard coal, lignite, natural gas and uranium reserves for the production of oxygen during the gasification step. A critical factor underlying this result might be the exclusion of metal scrap recovery from the system boundaries [547]. As far as the ecotoxicity is concerned, nitrogen and oxygen production are the key contributions to FAETP outcome, since they promote fresh water contamination with chromium and zinc, while TETP is explained by the release of mercury as well as from the release of NO_x during the syngas cleaning step.

This was also reported in [597]. Regarding the impact categories which afforded major environmental credits when regular gasification is applied, the modelled balances suggest that syngas cleaning is the more obvious contribution, once this step lowers SO_2 and nitrogen (enhancing AP and EP, respectively) and redeems HF (this contributing to MAETP and HTP results). Regarding $ADP_{elements}$ and POCP, the impacts attained for these categories are nearly in the same order of magnitude as those for the other techniques.

With regard to incineration and two-stage plasma gasification, both techniques present very interesting results, alleviating the environmental burdens associated with the resources required by thermal conversions. Nevertheless, while two-stage plasma gasification depicts high level results for ODP and TETP, incineration shows a more sustainable profile for categories such as GWP, ADP, FAETP, TETP and POCP.

5.5.1. Relative impacts

The relative impacts associated with each WtE technique are shown in Figure 38, regular gasification being once more highlighted as the only conversion methodology presenting environmental burdens for some of the assessed environmental categories.

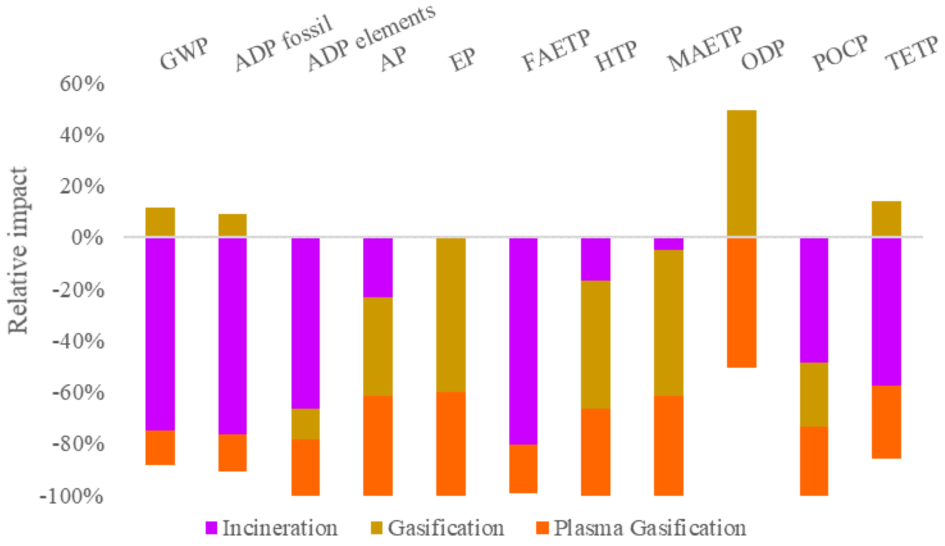

Figure 38 - Relative results for the environmental comparison of the WtE techniques.

Incineration shows significant avoided burdens for GWP, ADP, FAETP and TETP, while two-stage plasma gasification performs better for ODP, and superior to incineration for AP, EP, HTP and MAETP.

Regarding GWP, incineration provides higher avoided emissions of CO_2 and CH_4 due to landfill (approximately 75% of the total impact), when compared to the total avoidances from gasification and plasma steps in two-stage plasma gasification (approximately 12% of the total impact). In both cases, the re-introduction of the generated electricity in the system also aids in lowering the consumption of fossil fuels, correspondingly reducing CO_2 emissions. Some published studies report higher GWP impacts for similar assessments [528], the differences being attributed to biogenic CO_2 [550]. Concerning ADP_{fossil}, the ratios are similar to GWP mainly because major savings in non-renewable sources such as hard coal, natural gas and lignite are achieved. Both the landfill process and the electricity production account for the recovery of 2000 MJ per tonne of treated residues in incineration. This trend has also been reported by other authors although with lower efficiencies [514]. In two-stage plasma gasification, the electricity production is the major contributor to the overall results as seen in [528], 382 MJ being produced per functional unit. $ADP_{elements}$ generates a 65% contribution from incineration and only 20% from plasma gasification. Incineration produces savings in resources such as copper, gold, lead and molybdenum due to the electricity production as also reported in [532], while plasma gasification results in the saving of mineral salts such as sodium chloride. In the FAETP category there is an 80% contribution from incineration and roughly 20% share from plasma gasification. This is attributed to the avoided emission of heavy metals into fresh water and air as a result of the landfill process in incineration and to the plasma stage in plasma gasification. Both incineration and two-stage plasma gasification depict enhanced results when compared to published literature [534, 550]. Referring to TETP outcomes, a contribution of approximately 60% from incineration and nearly 30% from plasma gasification may be seen. With respect to incineration, the avoided heavy metals in agricultural soil is the most featured impact, although it should be noted that some published literature have reported inferior results to the herein presented [534]. Besides agricultural soil, major environmental savings concerning the emission of heavy metals are also achieved by the two-stage plasma process. In the case of MAETP, the most prevented hazard is the emission of inorganic substances such as hydrofluoric acid, both in incineration and plasma gasification, due to the electricity production and the flue gas treatment, as also corroborated by other authors [532]. The incineration results herein presented for MAETP are superior to those reported elsewhere [534].

ODP category credits are due to two-stage plasma gasification (50% contribution for the total impacts), regular gasification being responsible for environmental burdens, while incineration does not play a significant role. R114 is the chief emission accounting for almost 100% of the total share of environmental credits, the plasma converter proficiency and the electricity production justifying the performance of this technique.

Regarding two-stage plasma gasification, EP and AP values are based on the high efficiency of the plasma converter, which severely decreases the emission of substances with surfactant and acid behavior, respectively. The results for these are improved when compared to the published literature, the variances in MSW composition accounting for these differences [528, 550]. Incineration reduces the emission of NO_x, P_4 and NH_3 into the soil thus contributing to AP and EP values similar to those reported in other works [521, 523], this being attributed to the electricity generated from the system, as also seen in [551]. HTP results for incineration rely on the abatement of emissions such as organic and inorganic compounds and heavy metals into the atmosphere as well as organic substances into fresh water. This is due to the flue gas treatment and the landfill processes [519], whilst for plasma gasification the plasma converter is the major step alleviating the air emission of noxious compounds. Similar results were achieved in other works [528].

Inorganic (CO, NO_X, SO_2) and organic (CH_4) emissions to the atmosphere are the main contributors to POCP during incineration, while two-stage plasma gasification prevents NO_x and SO_2 due to the syngas cleaning step. Slightly improved results for this technique have been published elsewhere [528, 550], given the inclusion of a by-product within the boundaries of these other studies, and involving the replacement of natural rock, thereby constituting an extra avoided burden.

5.5.2. Environmental performance

Figure 39 provides a comparison between the assessed WtE with respect to resources and emissions. As an overall observation, it may be said that material resources, energy resources and emissions to fresh water are the major outcomes from the assessed WtE techniques, especially from incineration and two-stage plasma gasification.

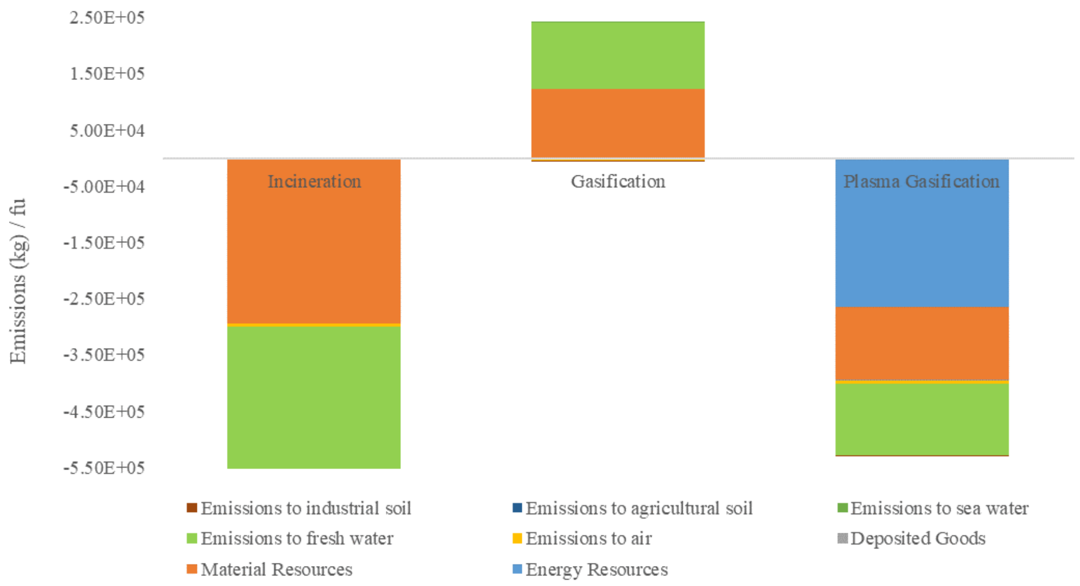

Figure 39 - Environmental overall performance comparison for the WtE assessed.

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

Evangelisti et al. [528] also report an overall excellent performance of a two-stage plasma gasification treatment for MSW, considered an improved environmental solution when compared to other available technologies. The authors argued that the electricity produced in a two-stage plasma gasification facility is generated from the combustion of a high-quality syngas which affords a high temperature gas which then supplies a gas engine, whereas the flue gas resulting from the combustion process in incineration generates steam, which is afterwards employed in a steam turbine to produce electricity, with lower levels of efficiency [598]. Another possible reason accounting for the upgraded environmental performance of two-stage plasma gasification may be the lower air pollution residues removed from the system, when compared to other WtE techniques [574]. Moreover, plasma gasification occurs in a sub-stoichiometric oxygen atmosphere resulting in lower CO_2 emissions than for incineration [520]. This oxygen-starved situation promotes lower gas yields than incineration, which maximizes the cleaning process [595]. Furthermore, less off-gas emissions and even less landfill requirements result from lower levels of gas produced.

As stated elsewhere [520], the environmental burdens associated to the thermal conversion techniques are mainly due to their emissions (both gaseous and solid), which may be below the established legal limits but at the same time contribute to environmental or public health hazards. As the progression from incineration to regular gasification and then two-stage plasma gasification affords a cleaner gas, it was expected that this last technique would produce lower emissions than the other two. In fact, the emissions from plasma gasification are all below zero which indicates that this WtE methodology prevents the release of noxious compounds into the environmental compartments. This depicts the environmental gains entailed in what regards air, water and soil contamination.

Detailing the releases seen in the software for the analyzed techniques, the emissions from incineration are dominated by NO_x from the flue gas cleaning process, accounting for nearly 85% of the total emissions for this technique ($4.05\text{x}10^{-10}$ kg/fu). Minor emissions are SO_2, NH_3 and CO, as also reported in [12]. Accordingly, incineration-based techniques were seen to depict noxious effects for the human health and ecosystem quality indicators mainly due to the respiratory inorganics emitting sulphate and nitrate compounds [512]. Notwithstanding, climate change related categories are also negatively affected by incineration technologies due to the emission of greenhouse gases as CO_2 and CH_4 [530]. Regarding regular gasification, the most pronounced emission is related to sulphuric compounds, which represent more than 50% of the total share (0.615 kg/fu), followed by NO_x (0.226 kg/fu), SO_2 (0.15 kg/fu) and CO (0.133 kg/fu), all of them due to the syngas cleaning facility. These substances are responsible for raising the acidification potential, contributing not only to the acid rain problems as well as to the contamination of the aquifers and water reservoirs. Similar trends were achieved in [489].

Concerning the avoided emissions related to two-stage plasma gasification, SO_2 is the major contributor with almost 60% of the share (0.217 kg/fu), followed by NO_x with 35%

(0.180 kg/fu). Published literature for this conversion scheme reports comparable values [528]. The efficiency of plasma gasification to crack and reform tars and other condensable species has been shown in [577], where high yields of these substances in raw syngas are successfully decreased by the plasma torch, achieving concentrations three orders of magnitude lower than the original values. Apart from the high temperatures generated in the plasma torch, its configuration and energy density seem to play an important role in the destruction of these species, since they provide an optimal fluidization state ensuring that virtually all the particles are trapped [596]. All these strategies promote less impact in the public health, reducing the noxious emissions and alleviating aerial contamination. The ecotoxicity categories are less influenced as well, which also enhances human welfare.

5.5.3. Comparative efficiency

Following the discussion of the environmental aspects of the thermal treatments, it is important to evaluate their efficiency. This was performed by assessing three distinct variables: waste reduction (in mass %), energy production (in GJ) and solid residues generation (in kg). Figure 40 describes the comparative assessment.

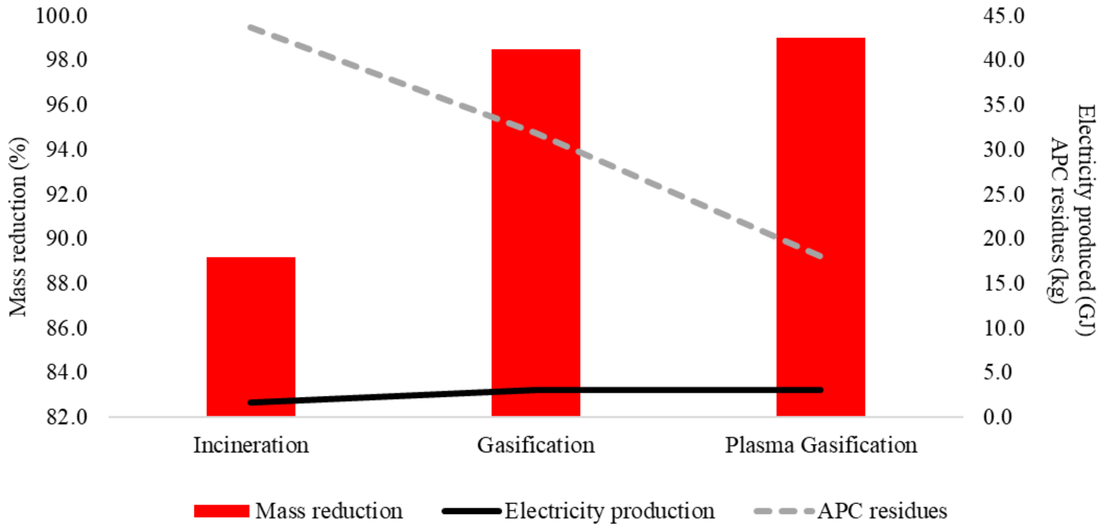

Figure 40 - Efficiency profile for the WtE techniques.

As can be seen from Figure 40, incineration achieves a lower waste reduction (approximately 89%) than regular gasification (98.5%), with two-stage plasma gasification achieving the highest mass reduction (99%). Likewise, regarding the formation of APC residues, a reduction from 42 kg/tonne for incineration, to 28.9

kg/tonne for regular gasification and 15.1 kg/tonne for plasma gasification is seen. Thus, under the conditions applied in this study, plasma gasification is suggested as the more efficient technique for waste disposal, when compared to incineration and regular gasification. This is probably because plasma gasification demands less resources and releases even fewer contaminants due to its advanced cleaning systems. A noticeably reduced quantity of inert material is sent to landfill, and also the yield of fine ash, particulate matter, inert slags and ashes are practically non-existent [595].

Taking into consideration the electricity production achieved by each technique, two-stage plasma gasification shows a more efficient profile, one tonne of treated residues affording almost double the amount of electricity when compared to incineration (3 GJ vs 1.7 GJ, respectively). Similar conclusions have been noted in the published literature, particularly under conditions in which an internal combustion engine/steam combined cycle is utilised [486]. Similar results were achieved elsewhere which may be improved if a cogeneration system is applied [572]. However, comparing the net power results of the present study to a compilation of plasma technologies performed by Ruj and Ghosh [11] the two-stage plasma gasification outcomes herein presented rank even higher than the ones reported for industrial processes, these ranging from 1.62 GJ to 2.22 GJ per tonne of MSW treated.

All the evaluated efficiency parameters point towards the same conclusion: plasma gasification shows the best performance in terms of mass reduction, residues production and electricity generation. This is a significant finding when considering the choice of a WtE technique, since the final aim of these waste disposal methods is to convert waste into energy, and this is better accomplished by the plasma gasification as demonstrated in this study. Besides that, the waste management efficiency and the integration of energy recovery processes are considered the most environmentally friendly options regarding urban sustainability [599].

As far as the efficiency is concerned, considering the average yield of waste *per capita* and the average electric consumption *per capita*, it is possible to estimate the share of energy which could potentially be produced from the waste generated by each person globally, using the herein presented WtE options. Table 18 depicts the results achieved applying the techniques herein assessed (and their electrical efficiencies) with respect to different geographical regions.

Table 18 - Electricity generation by each WtE, from the MSW produced *per capita*.

Region	**Average waste generation (kg/capita/day)***	**Average electric power consumption (kWh/capita/day)****	**% of electricity consumption covered by the production from MSW**		
			Incineration	Regular Gasification	Plasma Gasification
AFR	0.65	1.323	23.28	40.93	41.23
EAP	0.95	10.07	4.47	7.86	7.92
ECA	1.1	14.72	3.54	6.23	6.27
LCR	1.1	5.833	8.94	15.72	15.83
MENA	1.1	7.877	6.62	11.64	11.72
OECD	2.2	21.88	4.77	8.38	8.44
SAR	0.45	1.937	11.01	19.36	19.50
World	1.2	8.567	6.64	11.67	11.76

*data from [570].
**calculated based on data from [600].
AFR – Africa region; EAP – east Asia and pacific region; ECA – Europe and central Asia; LCR – Latin America & the Caribbean; MENA – middle east and north Africa; OECD – organization for economic co-operation and development; SAR – south Asia region.

Table 18 suggests that, based upon the average values taken from the relevant literature and assuming no losses in conversion efficiency and no significant changes in MSW composition, if the MSW generated by each person was thermally converted into energy and afterwards used as electricity, a high proportion of the daily electrical consumption *per capita* would be achieved. In fact, depending on the world region and its “urban metabolism”, the thermal treatment of the daily waste produced by a citizen could afford values between 4% and 41% of the electricity consumed daily by that same citizen.

The highest contribution to the electricity replacement is seen for the Africa region, where despite the fact that both the electricity consumption and the waste production are reduced compared to all of the evaluated geographic regions (1.32 kWh of electrical demand; 0.65 kg of waste), the ratio between these two parameters is the lowest. Conversely, in Europe and Central Asia both the electricity consumption and the average waste production are very high but the ratio between them is not so favorable: 1.1 kg of waste is produced *per capita* and almost 15 kWh are required to fulfil the electrical demand. This promotes the lowest contribution (of the energy produced from MSW) to the electrical demand *per capita* (in the order of 3% to 6%).

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

Figure 41 presents the relation between the electricity use and the waste production for several geographical regions.

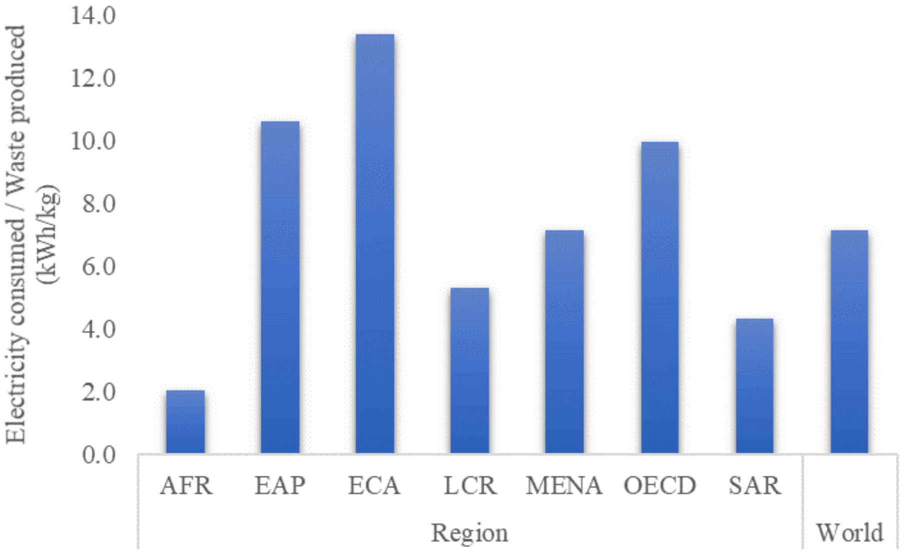

Figure 41 - Electricity use relative to the waste generated worldwide.

From the exposed, socio-economic correlations may be potentially inferred for the diverse world areas, regarding population habits and regional trends. Therefore, the relation between the electricity consumed and the waste produced may be suggested as a potential approach for evaluating the level of development of a country, community or society. In this assessment, higher income countries are seen to produce more waste and to require more energy on a daily basis, which is consistent with a society with superior economies and standards of living, while for the lower income countries the electrical requirements are more easily achieved and the level of waste produced is significantly lower [570]. As most of the nowadays' commodities depend on electric power, the social welfare is herein implied and an indicator such as the ratio of electricity consumed *per* waste generated might serve as a basis for the strategic development of waste management options or even electrical grid planning. As stated by the World Bank [570], waste generation rates will more than double over the next two decades and the solid waste management costs are expected to be raised by 175%. Thus, a strategy such as the one presented in this section might be of potential interest.

5.6. Partial conclusions

Two-stage plasma gasification may be seen as an alternative to enhance low temperature gasification results, since it may be used as a cleaning technique for raw syngas. The highly energetic arc technology purges the incoming producer gas, reducing the original harmful emissions and therefore lowers its environmental impacts. A more effective conversion is attained and a high-quality syngas is produced. Thus, environmental reservoirs and supplies are relieved from contamination and exaggerated consumption.

As there are few reports on experimental values for the assessed categories concerning the same type of plasma gasification, extensive contextualization of the obtained results was hampered. Still, it was possible to conclude that GWP and EP values were improved when compared to literature, while AP and POCP values were similar or at least in the same order of magnitude. Evaluating the performance of the system when the vitrified slag is considered enables even lower environmental impacts especially for GWP, ADP, ODP, HTP and TETP. This confirms the sustainable character of this technique, even when this by-product is not taken into account.

Within all the environmental savings achieved, CO_2, NOx, SO_2, heavy metals and inorganic substances are the key avoidances. Whereas the gasification step is the greatest contributor to the overall performance of the WtE technique, landfill has a minimal effect once there is a gradually decreasing flow throughout the system, promoted by the cleaner treatments applied, which lead to smaller yields of residues. The general performance of this WtE technique is mainly explained by the high efficiency attained with plasma conversion and by the utilization of the produced electricity to feed the system itself, replacing part of the electrical grid mix share.

A comparison of the attained results to incineration and regular gasification shows that two-stage plasma gasification is a much more sustainable option, affording an overall better performance, environmental credits mainly due to savings of energy and material resources, as well as emissions to freshwater. Regular gasification depicts some harmful impacts, ODP being the least counterbalanced category, GWP, ADP_{fossil} and TETP also showing environmental burdens. However, this technique yields excellent results for EP, AP, MAETP and HTP, performing even better than the other WtE options for these categories. Meanwhile, incineration portrays environmental drawbacks especially regarding emissions to air and material resources. In what concerns waste reduction, two-stage plasma gasification proved to be a more effective disposal technique affording a mass reduction almost three times higher than incineration, and producing also lower amounts of air pollution control residues. Relative to the energy produced, plasma gasification almost doubles the result achieved for incineration.

It is important to stress that these conclusions are valid within the assumptions and limitations referred, namely for a MSW sample as described in Table 8 and for the EU-28 electrical grid, among other conditions. If these are not met, the final outcomes will definitely be different and thus the contribution of each technique will also change.

In order to understand the application of these technologies in daily life, an estimate of the % of electricity that could be produced from the waste amount generated *per capita* in the world was conducted. High contributions were seen for Africa and South Asia due to the lower electrical demand, whereas the OECD countries were seen to surpass both the world average waste production and the electrical requirement *per capita*. In fact, depending on the world region and its “urban metabolism”, the thermal treatment of the daily waste produced by a citizen could afford values between 4% and 41% of the electricity consumed daily by that same citizen.

The renewable energy potentially achieved from the thermal conversion of MSW through the WtE herein studied would enable the reduction of greenhouse gases as well as the reduction in energy consumption, this in turn enhancing the quality of life of the population. This is supported by the low GWP and ecotoxicity results encountered, especially in the case of incineration and plasma gasification.

Chapter 6 – Socio-economic Viability of Waste-to-Energy Techniques

Part of the content of this chapter may be cited as:

Ramos, A., J. Berzosa, F. Clarens, M. Marin and Abel Rouboa (2019). "Environmental and socio-economic assessment of cork waste gasification: life cycle and cost analysis." Accepted for publication in Journal of Cleaner Production. DOI: 10.1016/j.jclepro.2019.119316

6.1. Incentives to implement WtE

As seen in the previous chapters, from the WtE assessed, regular gasification and two-stage plasma gasification presented opposite profiles to some extent: regular gasification depicted environmental burdens for some impact categories while two-stage plasma gasification has shown to contribute only with environmental credits, assuring a sustainable and environment-friendly outline. Aiming to complement the LCA results, other domains for the techniques should be assessed in order to provide an integrated panorama and aid policy-makers, regulatory authorities and motivate a broader range of stakeholders. As far as incineration is concerned, it is a well-established procedure, several plants already operating worldwide which corroborates the environmental results herein achieved. Regarding the implementation of new projects, the standard procedure involves several steps depending on aspects such as financing sources, geographical area and accessibility (among others) [601]. These aspects take different importance depending on the stakeholder perspective. Figure 42 illustrates the main participants in a WtE project, the yellow sections constituting the stakeholders directly related to the plant, while the green ones relate to actuators passible of being sub-contracted or presenting subordinate roles.

Figure 42 - Stakeholders for the waste-to-energy projects.

In the perspective of the major investors of the WtE projects, the cost difference to the conventional options must be counterbalanced. Therefore, to encourage the investment in the production and use of renewable energy, favorable policies play an important role, especially when the technologies involved are at an early stage of settlement. Thus, some sector-specific regulatory framework that could be considered consists in [601]:

- Reduction or abolishment of subsidized fossil fuel-based energy;
- Introduction of carbon dioxide pricing, through carbon taxes or trading schemes;
- Defining renewable energy targets within the total energy supply, rather than specific technologies;
- Impose renewable energy obligations requiring the installation of certain production capacity, the purchase of specific energy shares or the blending of different biofuels;
- Granting feed-in policies, assuring that the renewable energy producers receive a specified price per kilowatt-hour of electricity or heat fed into the grid, or even priority rights in the sale process to the grid;
- Emitting renewable energy certificates, which could be traded and sold to consumers who did not achieve their renewable energy obligations or simply want to buy it voluntarily;
- Conducting renewable energy tenders over the production energy capacity;
- Establishing tax incentives or credits for renewable energy stakeholders (developers, investors, owners…), improving the attractiveness and viability of new projects;
- Providing investment grants to support the costs associated to the renewable energy projects, especially when investment risks are foreseen;
- Enabling energy metering so that periods of excess consumption might be offset by periods of surplus generation;
- Empowering grid flexibility, as a means of balancing the rising share of variable renewable electricity forms within the grid;
- Adapting the feedstock supply chain (collection, transport and delivery logistics) to the WtE needs.

In this chapter, an economic study is performed to assess the feasibility of two of the proposed thermal conversion schemes namely, the gasification of cork residues through the Ecorkwaste strategy and the two-stage plasma gasification of MSW. The social component of the implementation of these strategies was also assessed by means of an importance matrix combining environmental, technical, economic and social indicators to support a more integrated study. In the case of plasma gasification, this work was conceived as a pre-feasibility study in the early stage of the overall development of the implementation of the technique.

6.1.1. Life cycle cost analysis

Life cycle cost compares the cost-effectiveness of alternative investments or decisions from the perspective of an economic stakeholder. Its purpose is to determine which option fits better the economic sustainability of the project, company or service. To accomplish the LCC analysis, the activities causing direct costs or profits, during the economic life of the investment should be considered. It is important to keep a defined time-horizon employing flexible depreciation, tax accounting and discounting to update the real value of the money involved. This enables a dynamic life cycle methodology to be applied as well as defining the investment costs and their timing. Some cost risks may also be entailed, their alteration or avoidance constituting a function of the investment options [602].

The life cycle costing methodology follows four phases [603], as seen for the LCA methodology: definition of scope, boundaries and functional unit; recompiling the life cycle cost inventory; determining the cost allocation by category; interpreting the results. In the first phase the functional unit and the system boundaries should be specified according to the LCA study, also the cost categories and the discount rate and taxes should be fixed. In the inventory phase, data should be collected taking into account the features decided in the previous phase, resourcing to the LCI phase of the LCA study whenever possible. Phase three consists in the aggregation of costs per category, employing the discount and tax rates in the calculation method (whether it is done with a dedicated software or an Excel® spreadsheet). In the last phase the results should be presented by cost category enabling their interpretation and determining if they match the defined goal and scope. Also, a sensitivity analysis should be carried out based in the discount rate or in the operation and maintenance costs, for instance.

Under a financial LCC perspective, all the costs for fulfilling the functional unit of the system should be included (for instance investment costs, operative costs, decommissioning costs, revenues), while an environmental LCC may be viewed as a monetarization of the environmental effects of the system [603]. This reduces the number of decision variables and may serve as a complement to the financial LCC, so the boundaries of the system should be carefully revised and double counting of the costs must be avoided. In the case of the waste management techniques, the financial LCC should include all the costs for the extended system meaning that all the commodities produced may be considered a functional unit. The functional unit should not be double counted in the form of revenues. The combination of both the financial and the environmental LCC promotes a welfare economic analysis, their aggregated or individual utilization providing different decision levels [604].

When no LCC analysis is done relative to a parallel LCA study, three major consequences may arise: the relevance of the LCA in the decision-making process is limited, the search for the most cost-effective solution to environmental improvements is inhibited and important environment-related alternative decisions may be lost, negatively influencing the company or the project owner. A practical example of this is the price of a good or service: it should carry the entire economic life cycle, including also the negative environmental effects taxation.

6.1.2. Socio-economic assessment

Petit-Boix et al. [599] highlight the lack of integrated studies to fill the gap between the environmental and the socio-economic sustainability in the urban context. The authors cite that “a sustainable community is one that is economically, environmentally, and socially healthy and resilient. It meets challenges through integrated solutions rather than through fragmented approaches that meet one of those goals at the expense of the others”. This is especially true in the case of new technologies, as less information is available and there is the need to prove its efficacy and convince several stakeholders with different backgrounds and expectations.

Sometimes, rather than conducting an integrated study, one specific feature of a new technology is emphasized while other aspects of the low carbon technologies are assessed separately. This results in a reduced social acceptance of a novel project’s implementation, especially when waste management is the topic, since people tend to relate it to social discomfort. Hence, Mavrotas et al. [26] propose a multi-objective optimization to assess several WtE techniques for MSW management. The goal was to get a set of solutions which could minimize both the cost and greenhouse gas emissions simultaneously, in order to establish a compromise between (at least) two parameters enhancing the support of the interested parties relative to the WtE scenarios. The authors launched a multi-criteria simulation and, by changing each variable discretely, accomplished several alternative scenarios optimizing all the features, instead of only one. This provides fruitful information for the decision-maker, enabling the selection of the most adequate option depending on the real context of the project and its primary goals. Bong et al. [605] also contributed to the engagement of stakeholders, investigating the key strategies required to reach different audiences in the production of biogas as an alternative to fossil fuels. The authors' suggestion is to attract foreign investors, to develop the human capital, and to collaborate with other sectors of activity, as well as the establishment of incentives from the governments to aid in the application of these renewable energy forms. Also, if the proposed technology affords sub-products with commercial value, both from an economic and environmental perspective (among other factors), the intrinsic worth of the project is strengthened and this in turn constitutes a social benefit [606]. This may be regarded as an extra argument in favor of the WtE for the communities and the decision-makers. A compilation of surveys relating to the social acceptance of low carbon energy and associated infrastructures was reported by Batel et al. [25], the authors commenting on the advantages of utilizing the public involvement in the decision-making process.

Furthermore, as reported by Fischer et al. [607], the success of the social engagement within a project for energy production also depends on the identification of possible causes for the project failure, developing new plans to improve the project's viability. This aids in the scale-up process of the infrastructures as well, which may promote advantages at a wider range than the local level. These examples illustrate an important social aspect related to the implementation of new technologies at the population-level: if the benefits of a proposed technology (well-being, environmental or economic revenues, for instance) are well understood, the communities are more likely to accept and support its employment. An aligned strategy concerning the environmental, technical, economic and social spheres of the WtE technologies may serve as a hot-spot tool to identify their strongest and the weakest features, enabling an easier benchmarking. Ultimately (and as a common sense example for all the audiences), environmental impacts such as GWP and ecotoxicity categories may be related with the need to spend more energy in order to climatize spaces (due to the atypical temperatures along the year), and with the reduced natural reservoirs of clean water or fresh air due to the effluent emissions, respectively. This will have a direct effect on the living conditions for communities, potentially challenging them to change their living habits and accept an altered quality of life.

6.2. Materials and methods

Although two different feedstocks (biomass and MSW) and WtE techniques (regular gasification and two-stage plasma gasification) were utilized in this chapter, the economic and social assessments were performed under the same approach for each study. However, a careful evaluation of each of the situations was held, taking into account their specific differences especially in the consideration of the dedicated markets and in the development of the socio-economic matrix.

As far as the cost allocation is concerned, the same methodology was applied in both cases, costs being distributed into capital costs (CAPEX) and operational costs (OPEX). CAPEX costs are comprised of three main categories: “Technology development” represents all the preliminary work necessary before the gasification plant was implemented; “Plant” encompasses the costs of the gasification facilities; “Other expenses” depict costs that cannot be clearly allocated to the other categories: fees, consultancy and legal affairs. OPEX costs accounts all expenditures associated to the operation phase of the treatment system. These include cost of consumables utilized such as overheads, staff, energy consumption, and general plant maintenance. A summary of the items in each category is presented in Table 19.

Table 19 - Summary of the main cost categories considered in the LCC assessment.

	Category	**Description**
CAPEX costs	**Technology development**	Expenses from preliminary research
	Plant	Expenses from plant construction
	Other expenses	Other general costs
OPEX costs	**Overheads**	General functioning costs
	Staff	Plant operators and all manpower
	Waste management	Treatment of the generated residues
	Energy	Cost of electricity and other energy sources
	Maintenance	Maintenance of the plant

Each flow of the LCA study was monetarily quantified, accounted and classified using the CAPEX-OPEX distinction in order to ensure the similarities to this analysis. Thus, a summary of all the accounted costs was obtained and described based in the input-output inventory according to the stated categories.

6.2.1. Ecorkwaste project

6.2.1.1. LCC impact assessment

The techno-economic impact evaluation was developed by means of LCC. This study followed the recommendations of SETAC [603] and ISO 15663-1, 15663-2 and 15663-3[1]. These approaches were merged to the ISO 14040 and ISO 14044 rules of life cycle assessment in order to obtain an LCA-LCC aligned methodology. In that sense, a parallel scheme to life cycle assessment was deployed, using the same system boundaries, the same functional unit and applying cost units to the life cycle inventory, as advocated in [604]. LCC was performed to assess the economic feasibility of the system, comparing the results to the conventional scenario of producing electricity via the Spanish grid mix. The economic performance of the system was related to the total amount of cork wastes produced yearly in Catalonia in order to show the relevance of the development of such a treatment plant. This enables a more reliable source of information once the technology is commercialized.

The cork gasification plant has a lifespan of 20 years, and two scenarios for the LCC were projected: a batch working regime (8h/day) and a continuous work regime (365 days/year) in order to reflect a more realistic experimental scale-up [608]. The results of these scenarios were compared to the conventional production of 1 kW of energy (kW_e + kW_{th}) in the location of the gasification plant (Spanish regional electrical grid) to predict the cost differences when substituting energy from the electrical grid by the renewable source.

6.2.1.2. LCC methodology

Similar to the LCA perspective, the LCC was built with primary data gathered from the gasification plant. As far as the monetarization of the inventory was concerned, partners of the project provided cost information on the prototype and plant construction,

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[1] ISO 15663-1, 15663-2 and 15663-3, Guidance on application of methodology and calculation methods. This standard was last reviewed and confirmed in 2012.

technology development activities and general functioning costs, while values such as staff and plant maintenance were appraised *in situ*. Otherwise, some information has been taken from bibliographic sources: waste management[2], energy [609], product revenues [610, 611] and avoided fees [612]. The following situations were compared:

- Scenario E-2 (best LCA performance from options E1-E3, in Chapter 4), in two distinct working regimes:

a) Batch experiment (real operation regime)

b) Continuous operation regime

- Scenario E-4: energy production from the Spanish electrical grid mix.

In accordance to the fact that the gasification plant was projected to be installed in an on-going company, the Staff category would be easily fulfilled by current workers, but for the purposes of LCC the working time was evaluated according to the national average wage for workers in this sector[3]. Also, there are incomes from the products of cork waste gasification. These relate mainly to the production of char [610] and to the avoided landfill fees [612]. The sum of these profits will balance the OPEX costs, assisting in the project economic sustainability.

6.2.2. Two-stage plasma gasification of MSW

6.2.2.1. LCC impact assessment

Similar to the LCA perspective, the LCC was built with primary data gathered from the plasma gasification plant. As far as the monetarization of the inventory was concerned, R&D activities and general functioning costs were appraised *in situ*. Otherwise, information on the plant construction cost was consulted in [590] and conveniently updated.

A 20-year lifespan was considered for the plasma gasification plant. The results were compared to the conventional landfilling of 1 tonne of MSW, using the EU-28 data as much as possible to account the flows and predict the cost differences among the techniques. When no EU-28 data was available, the economic flows were directly taken

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[2] www.generadordeprecios.info/obra_nueva/Gestion_de_residuos/Gestion_de_residuos_peligrosos/Transporte_de_residuos_peligrosos/GEB020_Transporte_de_elementos_de_fibrocem.html

[3] https://www.indeed.es/salaries/Operario/a-de-producci%C3%B3n-Salaries,-Catalunya?period=hourly

from dedicated sources. As far as revenues are concerned, two major products may be achieved from the plasma gasification of MSW: electricity and vitrified slag.

6.2.2.2. LCC methodology

Regarding the production of the vitrified slag, three scenarios were posed (PG-1 and PG-2 as in the LCA assessment described in section 5.2.3, and PG-3 as a new option):

- Scenario PG-1: considering only revenues coming from electricity (to mimic the boundaries of the environmental assessment);
- Scenario PG-2: considering revenues both from the electricity and the vitrified slag sales;
- Scenario PG-3: considering the vitrified slag as a waste to manage.

Electricity was considered to replace the correspondent electricity grid mix amount, while vitrified slag has further utilizations as ceramic component or as aggregate in the construction industry [577]. Electricity sales price was the same as considered in other studies [590], while the vitrified slag was quoted based in the sales price for construction agglomerate[4]. Regarding the vitrified slag management as a waste from the system, the disposal was quoted based in the delivery of inert residues of ceramic nature[5]. All the other costs associated to the OPEX category were based on EU-28 values.

In order to appraise the robustness of the economic assessment, a sensitivity analysis was performed assessing the critical variables which may affect the viability of the project namely: electricity sales price, landfill fees, discount rate, vitrified slag sales price and initial investment. Therefore, the variation of these parameters and their influence over the project's NPV (net present value) were evaluated in a sensitivity test, to monitor the system behavior to stressful scenarios. To do this, the electricity sales price was varied among the values practiced in the EU-28 [609], whereas the landfill fees were changed in accordance to [612]. The discount rates tested were ranged from 0% to 14% (resembling [613]), while for the vitrified slag sales a variation of 50%-150% in the standard price applied in the LCC study was performed. Regarding the capital expenses, 50% to 100% of the total CAPEX were considered.

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[4] www.drpinfratech.com/crushed-stone-aggregate.html (access date: March 2019)

[5] http://www.geradordeprecos.info/obra_nova/Gestao_de_residuos/Gestao_de_residuos_inertes/Transporte_de_residuos_inertes/GRA020_Transporte_de_residuos_inertes_com_.html (accessed: July 2019)

6.2.3. Assumptions and limitations

Regarding the two-stage plasma gasification plant, it was considered that no borrowed capitals were used, therefore establishing the presented system as a conservative scenario, the initial investment constituting a big economical effort. These conditions test the feasibility of the system to some extreme consequences, the outcome being considered as an indicator and not a regular base case. This assumption may be considered for the economic analysis of the plant under a state, national and communitarian perspective [601].

As a limitation for both systems (Ecorkwaste and two-stage plasma gasification), heat was not considered for commercialization once this would require the plant to be located in an industrial park or with major heat-demanding companies nearby, also demanding a specialized distribution system. This would add an extra limitation to the viability of the project. Also, the market prices for the products (and by-products) and the general economic buoyancy constitute some limitations for the appraisal of the Ecorkwaste and the two-stage plasma gasification strategies, as they might alter the final outcomes [601].

6.2.4. Economic indicators

The main economic indicators were calculated according to Equations 3-5 [602, 614]:

- Net Present Value is the present worth of an investment. It represents the difference between the present worth of the expenses and the present worth of the revenues, recognizing the money update.

$$NPV = \sum_{t=0}^{N}[F_t/(1+d_t)^t] \tag{3}$$

where F_t is the net cashflow in the year t and d_t is the discount rate during period t. F_0 is considered the worth investment (t = 0) and is a negative value. The discount rate is calculated based on the cost of equity and the cost of required debt to implement the plant. In the herein considered case, there was no borrowed capital so a standard 4% d_t was used [615]. Positive NPV indicates that the investment is economically viable, negative NPV designates an unviable investment and neutral NPV shows a potentially viable investment with a return equal to the internal rate of return (IRR).

- Internal Rate of Return depicts the interest rate that equals the present value of future incomes to the initial cost, i.e., IRR defines the interest rate that causes the NPV to be zero. It represents a profitability measure determining the maximum rate of return for viability.

$$NPV = 0 <=> \sum_{t=0}^{N}[F_t/(1+IRR)^t] \qquad (4)$$

IRR is an excellent indicator between projects of different dimensions, once it enables a comparison among them, unlike NPV.

- Payback Period (PBP) is the time needed to recover the initial investment meaning that the shorter it is the higher the feasibility of the project. It should not be used as a comparative indicator for profitability; nevertheless, it serves the evaluation of the risk level of the project.

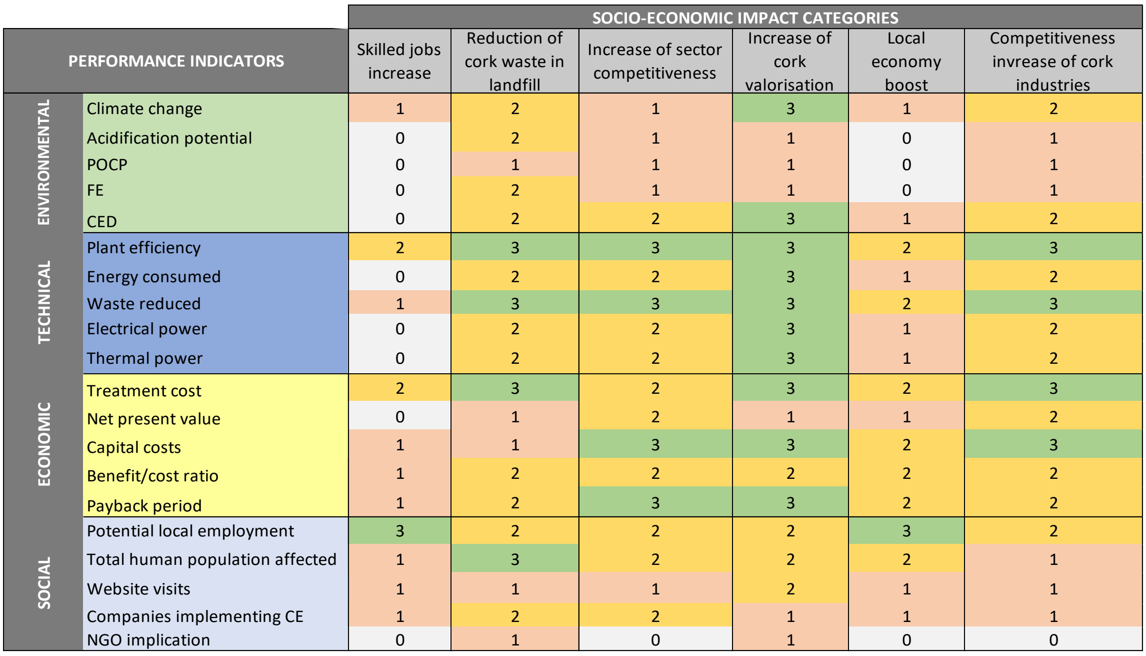
$$PBP = \frac{-\ln[1+\left(\frac{F_0}{F}\, x\, d\right)]}{\ln(1+d)} \qquad (5)$$

If the net cashflow in year t (F_t) is considered constant, then $F_t = F$. In other words, PBP is the first year when the cumulative difference among the considered system and the conventional system [612] is higher than the investment cost.

To calculate these parameters, the annual cashflows, the cashflow differences among the techniques, and also the revenues and savings were determined considering a discount rate of 4% and an inflation rate of 2% [616-618], in order to reflect the equilibrium between supply and demand.

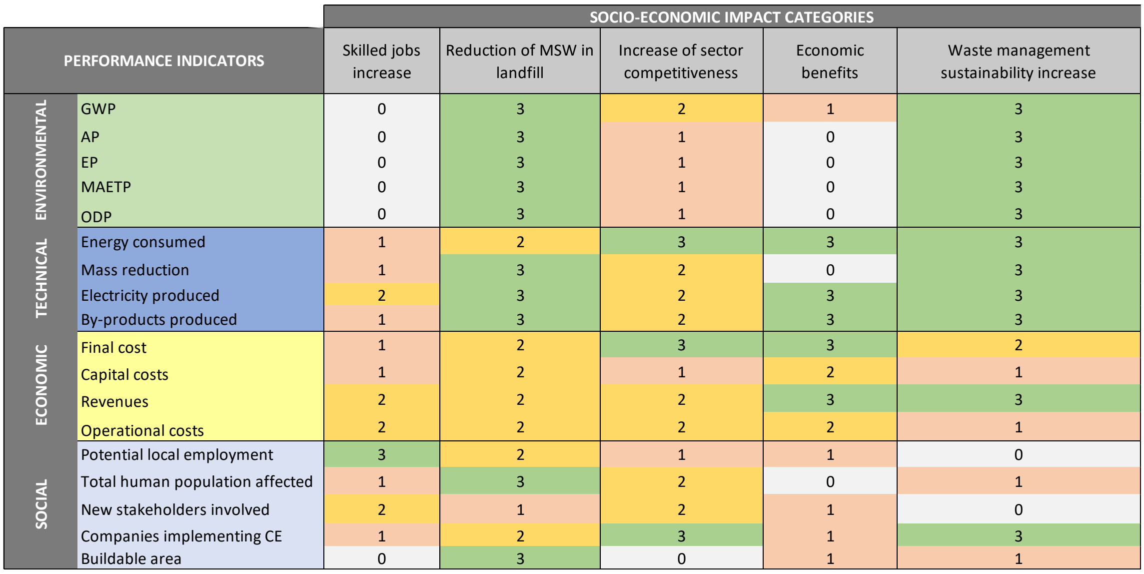
6.2.5. Socio-economic matrix

Aiming to determine the socio-economic impact of the techniques, a performance-importance matrix was developed and applied according to [619]. Firstly, the matrix was developed combining the main environmental, technical, economic and social indicators (rows) with the impacts of the technology (columns). Then the effect of each indicator over the impact of the technology and vice-versa was considered, and the matrix was filled by experts in the field. To do this, importance factors from 0 to 3 were implemented as a measure of the impact, in an upward mode of influence (0 meaning no relation at all and 3 meaning a very high impact). Figures 43 and 44 show the matrix with the experts' evaluation for Ecorkwaste project and two-stage plasma gasification, respectively.



PERFORMANCE INDICATORS		SOCIO-ECONOMIC IMPACT CATEGORIES					
		Skilled jobs increase	Reduction of cork waste in landfill	Increase of sector competitiveness	Increase of cork valorisation	Local economy boost	Competitiveness invrease of cork industries
ENVIRONMENTAL	Climate change	1	2	1	3	1	2
	Acidification potential	0	2	1	1	0	1
	POCP	0	1	1	1	0	1
	FE	0	2	1	1	0	1
	CED	0	2	2	3	1	2
TECHNICAL	Plant efficiency	2	3	3	3	2	3
	Energy consumed	0	2	2	3	1	2
	Waste reduced	1	3	3	3	2	3
	Electrical power	0	2	2	3	1	2
	Thermal power	0	2	2	3	1	2
ECONOMIC	Treatment cost	2	3	2	3	2	3
	Net present value	0	1	2	1	1	2
	Capital costs	1	1	3	3	2	3
	Benefit/cost ratio	1	2	2	2	2	2
	Payback period	1	2	3	3	2	2
SOCIAL	Potential local employment	3	2	2	2	3	2
	Total human population affected	1	3	2	2	2	1
	Website visits	1	1	1	2	1	1
	Companies implementing CE	1	2	2	1	1	1
	NGO implication	0	1	0	1	0	0

Figure 43 - Socio-economic importance matrix for the Ecorkwaste project.



PERFORMANCE INDICATORS		SOCIO-ECONOMIC IMPACT CATEGORIES				
		Skilled jobs increase	Reduction of MSW in landfill	Increase of sector competitiveness	Economic benefits	Waste management sustainability increase
ENVIRONMENTAL	GWP	0	3	2	1	3
	AP	0	3	1	0	3
	EP	0	3	1	0	3
	MAETP	0	3	1	0	3
	ODP	0	3	1	0	3
TECHNICAL	Energy consumed	1	2	3	3	3
	Mass reduction	1	3	2	0	3
	Electricity produced	2	3	2	3	3
	By-products produced	1	3	2	3	3
ECONOMIC	Final cost	1	2	3	3	2
	Capital costs	1	2	1	2	1
	Revenues	2	2	2	3	3
	Operational costs	2	2	2	2	1
SOCIAL	Potential local employment	3	2	1	1	0
	Total human population affected	1	3	2	0	1
	New stakeholders involved	2	1	2	1	0
	Companies implementing CE	1	2	3	1	3
	Buildable area	0	3	0	1	1

Figure 44 - Socio-economic importance matrix for two-stage plasma gasification.

After adequate filling, the scores were adjusted using a multiplying factor to balance out the accomplishment of each of the performance indicators, when compared to a "goal" scenario. This "goal" was established based on the expected values for each of the indicators, according to the characteristics of the system or (when necessary) to the conventional alternative, i.e., the Spanish national electrical grid mix in the case of Ecorkwaste project and the landfill option [620] for two-stage plasma gasification. The fulfilment adjustment factors were applied in relation to the criteria presented in Table 20. Furthermore, the expected trend concept was applied, indicators where higher values were expected had a positive sign (+), for instance the plant efficiency, as opposed to a negative sign (-) applied to those indicators where lower values are desired, like treatment cost.

Table 20 - Adjustment factors according to the accomplishment of the goal.

Level	Accomplishment (%)	Factor
Superior	> 150	2
Excellent	125 – 150	1.5
Average	75 – 125	1
Poor	50 – 75	0.5
Severe	< 50	0

6.3. Results and discussion

6.3.1. Ecorkwaste economic impact

As the most promising alternative relative to the environmental outcomes was scenario E-2, the LCC study was conducted comparing this case and the conventional energy production system (scenario E-4). The LCC study was performed with a cradle to gate approach in order to provide a global picture of the study related to the economic impacts. In order to embody a representative situation, the Technology Development category costs were normalized to accomplish the treatment of the total amount of cork wastes produced annually in Catalonia (1275 tonne/year), once after the technology is developed it is worth to implement it in other companies with this type of residues. As a result, the initial investment in all the resources put into the research activities preliminarily to the plant start-up were more efficiently managed, lowering the cost of the strategy per functional unit. Table 21 depicts LCC results.

Table 21 - LCC summary for the Ecorkwaste project.

		ECORKWASTE (€)				**CONVENTIONAL (€)**
Cost categories		**Batch operation**		**Continuous operation**		**Electric grid mix**
		Cost/MWh	**%**	**Cost/MWh**	**%**	**Cost/MWh**
CAPEX	Technology development	3.88	2.87	7.56	4.71	---
	Plant	50.29	37.20	50.29	31.28	---
	Others	0.55	0.41	0.55	0.34	---
	Sub-total	**54.73**	**40.48**	**58.41**	**36.32**	---
OPEX	Overheads	28.37	20.98	28.37	17.64	---
	Staff	21.92	16.22	43.84	27.26	---
	Waste management	0.01	0.00	0.01	0.00	---
	Energy	0.00	0.00	0.00	0.00	---
	Maintenance	30.17	22.32	30.17	18.77	---
	Sub-total	**80.42**	**59.52**	**102.39**	**63.68**	---
Revenues		(-)95.47	---	(-)136.05	---	---
TOTAL		**39.73**	**100**	**24.74**	**100**	**76.40**

As may be seen in Table 21, both Ecorkwaste gasification cases depict lower cost per MWh of energy than the conventional production system. In fact, more than 48% of the costs per MWh are saved in the batch regime, while in the continuous operation mode this scales up to nearly 68%.

Also, it is possible to observe that around 60% of the total expenses are allocated to the OPEX costs for both situations. The main differences between the batch operation and the continuous operation cases are due to the operating regime. Thus, whether in the real case a production period of 8 h/day only requires 1h of manpower, in the continuous operation case the system would be much more automated working for 24 h/day and requiring the presence of the operator for 2 h/day. As a result, the expenses related to staff are the ones that contribute more to OPEX category. In this case, they are higher in the continuous operation regime, representing 27.26% of the total costs per MWh, while in the batch regime only 16.22% is accounted. Nevertheless, in the continuous operation regime higher revenues are achieved both in terms of marketable products as well as avoided landfill fees, which enables a lower final cost per MWh (24.74 €/MWh). Indeed, an income of 136.05 € is seen for each MWh of produced energy in the continuous operation mode, while for the batch case only 95.47 €/MWh is attained. This value contributes to the OPEX costs, reducing the total value of this category and allowing the Ecorkwaste gasification strategy to have lower costs per functional unit than the conventional alternative, as previously mentioned. In the continuous operation mode, plant maintenance is the second higher OPEX cost, followed by the overheads of the facilities, while waste treatment and the consumed electricity may be considered negligible. In fact, maintenance costs have been reported as one of the chief costs in the thermal treatment of residues [621].

Regarding the CAPEX costs, the highest share in this category is attributed to the plant construction with shares between 30% and 40%, but this is only true regarding the normalization factor applied to the technology development costs, as previously mentioned. Otherwise, technology development costs would represent almost double the share of their actual contribution. Due to the economy of scale [622] improved economic performance is expected for wider samples, in this case leading to lower technology development costs/MWh. In this regard, the batch regime presents 2.87% cost share while the continuous operation mode shows 4.71% share.

In the end, it is critical for a country to have cheap electricity, as most of the nowadays commodities are energy-based and, if this is not assured, there is a major threat of competitiveness lost and ultimately impoverishment [623]. Therefore, Ecorkwaste gasification is empowered as a feasible and recommended alternative with potential to replace the use of fossil fuels for producing energy from cork residues.

Table 22 depicts the economic indicators calculated for the assessment of the gasification scheme proposed.

Table 22 - Economic indicators for Ecorkwaste project.

Economic indicators	Batch regime	Continuous regime
Payback period (years)	12	10
Internal Return Rate (%)	7.58	9.12
Net Present Value (€)	80 315.05	113 129.19
Life Cycle Cost (€)	44 418.78	69 903.98

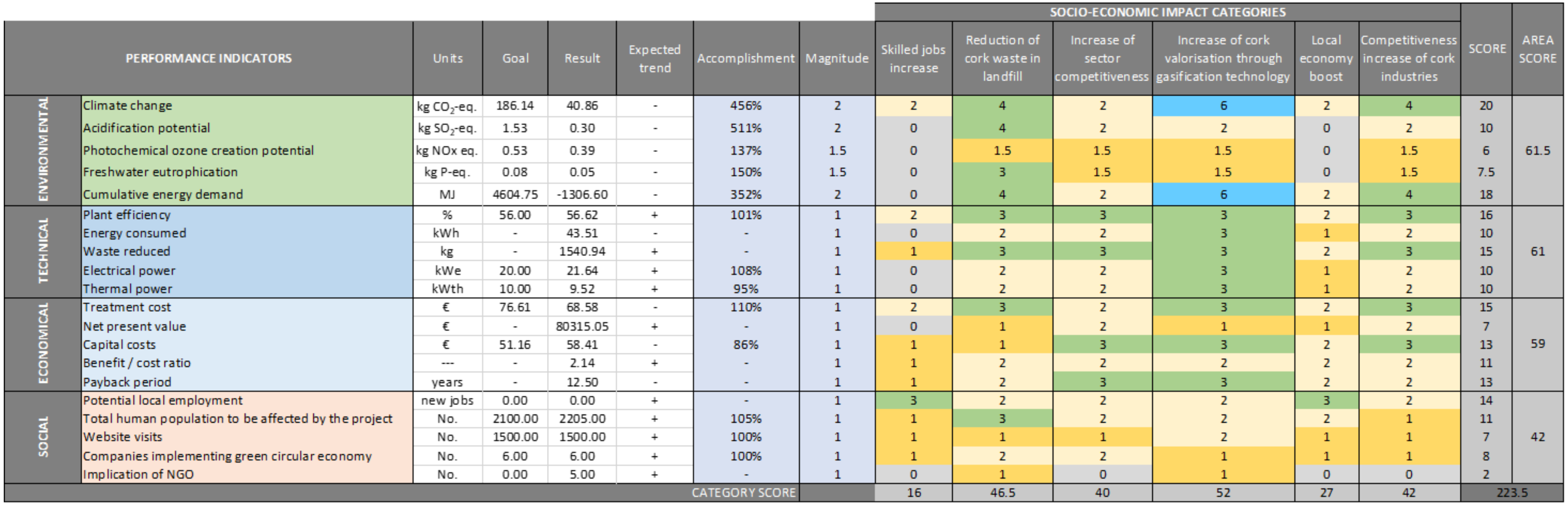
As may be seen in Table 22, NPV is positive for both regimens, which confirms that the project is economically viable either way. Nevertheless, the continuous operation regime is a more profitable option with a lower payback period (10 years) and higher IRR and NPV. LCC is higher for the continuous operation mode since the working period of the plant is higher in this regime (8400 h/year) than in the batch situation (1920 h/year), which raises the costs related to the consumables. Still, calculating the accumulated difference between the production of energy through Ecorkwaste gasification strategy and the conventional production along the project lifespan (not shown here), the batch regime depicts savings higher than 248 000 € while the continuous operation case portrays almost 299 000 € difference.

LCC assessments for the waste management techniques are still sparse and, considering also that distinct scopes, functional units and system boundaries affect the outcomes, only approximate comparisons of the results achieved in this study to literature data are accomplished. Nevertheless, comparing the economic indicators achieved for this study with an assessment for the gasification of Portuguese biomass published recently [624], although similar IRR was attained, lower payback periods were seen in the present study. This is related to the total capacity of the plant and to the initial investment (among other factors), which dictate the global performance indicators. This is also supported by the distinct NPV attained (significantly lower in the present study).

LCC is viewed as one of the key factors for investors and decision-makers. In this case, LCC acts as a driving force towards the cork treatment by gasification, since besides the economic profits showing the technique’s feasibility, it also promotes a suitable waste management in the cork industry, ultimately generating wealth and improving the sectors’ visibility. These strategies are necessary as a strengthening factor for sustainability and the eco-efficiency of the cork industries [625].

6.3.2. Ecorkwaste socio-economic assessment

In order to understand the relative importance of each indicator upon each impact category, as well as their effects and main outcomes, an integrated assessment of all the featured areas of the project is presented in the form of a hybrid-fulfilment importance matrix. Figure 45 shows the attained socio-economic matrix, comparing the results for each category with the “goal” scenario, according to the adjustment factors shown in Table 20.



								SOCIO-ECONOMIC IMPACT CATEGORIES							
PERFORMANCE INDICATORS		Units	Goal	Result	Expected trend	Accomplishment	Magnitude	Skilled jobs increase	Reduction of cork waste in landfill	Increase of sector competitiveness	Increase of cork valorisation through gasification technology	Local economy boost	Competitiveness increase of cork industries	SCORE	AREA SCORE
ENVIRONMENTAL	Climate change	kg CO_2-eq.	186.14	40.86	-	456%	2	2	4	2	6	2	4	20	61.5
	Acidification potential	kg SO_2-eq.	1.53	0.30	-	511%	2	0	4	2	2	0	2	10	
	Photochemical ozone creation potential	kg NOx eq.	0.53	0.39	-	137%	1.5	0	1.5	1.5	1.5	0	1.5	6	
	Freshwater eutrophication	kg P-eq.	0.08	0.05	-	150%	1.5	0	3	1.5	1.5	0	1.5	7.5	
	Cumulative energy demand	MJ	4604.75	-1306.60	-	352%	2	0	4	2	6	2	4	18	
TECHNICAL	Plant efficiency	%	56.00	56.62	+	101%	1	2	3	3	3	2	3	16	61
	Energy consumed	kWh	-	43.51	-	-	1	0	2	2	3	1	2	10	
	Waste reduced	kg	-	1540.94	+	-	1	1	3	3	3	2	3	15	
	Electrical power	kWe	20.00	21.64	+	108%	1	0	2	2	3	1	2	10	
	Thermal power	kWth	10.00	9.52	+	95%	1	0	2	2	3	1	2	10	
ECONOMICAL	Treatment cost	€	76.61	68.58	-	110%	1	2	3	2	3	2	3	15	59
	Net present value	€	-	80315.05	+	-	1	0	1	2	1	1	2	7	
	Capital costs	€	51.16	58.41	-	86%	1	1	1	3	3	2	3	13	
	Benefit / cost ratio	---	-	2.14	+	-	1	1	2	2	2	2	2	11	
	Payback period	years	-	12.50	-	-	1	1	2	3	3	2	2	13	
SOCIAL	Potential local employment	new jobs	0.00	0.00	+	-	1	3	2	2	2	3	2	14	42
	Total human population to be affected by the project	No.	2100.00	2205.00	+	105%	1	1	3	2	2	2	1	11	
	Website visits	No.	1500.00	1500.00	+	100%	1	1	1	1	2	1	1	7	
	Companies implementing green circular economy	No.	6.00	6.00	+	100%	1	1	2	2	1	1	1	8	
	Implication of NGO	No.	0.00	5.00	+	-	1	0	1	0	1	0	0	2	
						CATEGORY SCORE		16	46.5	40	52	27	42	223.5	

Figure 45 - Socio-economic importance matrix for Ecorkwaste project.

In a broad view, the socio-economic impacts that scored higher were the *increase of cork valorization through gasification* with 52 points and the *reduction of cork waste in landfill* with 46.5. These were mainly due to the environmental and technical indicators. The *increase in competitiveness of cork industries* scored third (42 points) mostly due to the environmental factors, while the *increase of sector competitiveness* scored 40 points supported by the technical and economic indicators. The *local economy boost* depicted 27 points mainly based on the economic indicators. The *skilled jobs increase* presented the lowest socio-economic impact mainly because the environmental indicators showed little impact (2 points). The total score for this category was only 16 points, the main contributor being the social indicators (6 points). This may be supported by the main findings of Bong et al. [605] who remark some chief strategies to reach distinct audiences in the production of renewable energy. The authors highlight aspects such as collaborating with other sectors of activity and developing the human capital as significant contributions to propel the technology, which reinforces the results herein presented. In addition, this is also aligned with the European Commission “Strategy for a bioeconomy” [626]. Paredes-Sánchez et al. [627] also stress that the bioenergy sector triggers significant social benefits, especially when it concerns rural areas where there are limited job opportunities. However, there is dispute about this point, once some studies refer that depending on the jobs quality and duration their establishment by the renewable energies sector might be seen as a benefit or as a competitor for the creation of jobs in more productive sectors [623].

Overall, the environmental aspect is the predominant sphere in the socio-economic matrix, its performance indicators summing up to 61.5 points. Climate change was the major player within this area totalizing 20 points, followed by cumulative energy demand with 18 points. Regarding the technical indicators, a score of 61 points was achieved, mainly thanks to the *plant efficiency* and the *waste reduction* categories (16 and 15 points, respectively). The economic impacts scored 59 points, mainly due to the *treatment cost* indicator (15 points), followed by the *capital costs* and the *payback period* in “ex aequo” with 13 points. The social category depicted the fourth score (42 points), the *potential to create local employment* being the performance indicator that influenced the most the impact categories (14 points). According to literature [15, 605], attracting foreign investors and establishing government incentives would reinforce the settling of the renewable energy achieved from alternative methods. On the other hand, Ribeiro et al.

[623] mention the possible opposition of the local communities to the renewable energy sector, once population tends to relate these sources of energy with social discomfort and disamenity.

As the social component of this kind of projects is very difficult to access, its outcomes are hard to measure and to translate into numerical values [15]. Therefore, the contextualization of the results achieved for this section should be taken as indicatory of the capabilities of the project to reach aspects other than technique, environment and economy.

6.3.3. Two-stage plasma gasification economic impact

Table 23 presents the LCC results for scenario PG-1 and PG-2. In order to stand for a representative situation, the plant cost was normalized for the plant treatment capacity, to take into account possible scale-up issues [590, 601].

Table 23 - LCC summary for MSW two-stage plasma gasification.

<table>
<tr><th colspan="2">Cost categories</th><th>PG-1 (€)</th><th>PG-2 (€)</th><th>%</th><th>PG-3 (€)</th><th>%</th></tr>
<tr><td rowspan="3">CAPEX</td><td>Plant</td><td colspan="2">23.54</td><td>20.4</td><td>23.54</td><td>7.2</td></tr>
<tr><td>Others</td><td colspan="2">0.08</td><td>0.1</td><td>0.08</td><td>0.0</td></tr>
<tr><td>Sub-total</td><td colspan="2">23.62</td><td>20.5</td><td>23.62</td><td>7.2</td></tr>
<tr><td rowspan="6">OPEX</td><td>Overheads</td><td colspan="2">18.93</td><td>16.4</td><td>18.93</td><td>5.8</td></tr>
<tr><td>Staff</td><td colspan="2">2.30</td><td>2.0</td><td>2.30</td><td>0.70</td></tr>
<tr><td>Waste management</td><td colspan="2">5.35</td><td>4.6</td><td>218.99</td><td>66.5</td></tr>
<tr><td>Energy</td><td colspan="2">7.79</td><td>6.8</td><td>7.79</td><td>2.4</td></tr>
<tr><td>Maintenance</td><td colspan="2">57.29</td><td>49.7</td><td>57.29</td><td>17.4</td></tr>
<tr><td>Sub-total</td><td colspan="2">91.67</td><td>79.5</td><td>305.30</td><td>92.8</td></tr>
<tr><td colspan="2">Revenues</td><td>(-)92.29</td><td>(-)113.55</td><td>---</td><td>(-)92.29</td><td>---</td></tr>
<tr><td colspan="2">TOTAL</td><td>23.00</td><td>1.74</td><td>100</td><td>236.63</td><td>100</td></tr>
</table>

Comparing the scenarios presented in Table 23, the only difference between PG-1 and PG-2 relies in the revenues (presented with a negative sign, once they depict a negative cost – a profit). Scenario PG-2 reports higher revenues as it includes the commercialization of both electricity and vitrified slag originating from plasma gasification, while scenario PG-1 only accounts electricity as incoming receipt. This is directly connected to the final cost per functional unit which, in the case of scenario PG-1 is 23 €/t while for scenario PG-2 it is 1.74 €/t.

Regarding the CAPEX costs both scenarios show that 20% of the total cost per tonne of MSW is allocated to the initial investment in the technology, in a ratio of approximately 172 thousand € /tonne per day. This is in the range of expected values regarding the total capacity of the plant and might be improved taking into account the economy of scale [590]. On the other hand, almost 80% of the costs per tonne of treated MSW are allocated to OPEX, approximately 50% of the total share being assigned to the maintenance of the plant. In fact, maintenance expenses have been reported as major costs in the thermal treatment of residues [621]. In a detailed economic evaluation, it may be noticed that the bigger portion of these costs is due to the auxiliary materials used in the MSW treatment, followed by the management of the equipment and the replacement of perishable parts. This is especially true regarding the fragile nature of the plasma torch, which constitutes a high cost but not as frequent as the daily consumable resources [575, 628]. Overheads represent nearly 20% of the costs, which agrees with what is expected for this type of facilities [628]. Energy and waste management represent lower costs, once the plant runs in an auto-consumption mode (part of the produced electricity feeding the system itself) and produces nearly no tars or chars. Nevertheless, these two components sum up a total of more than 13% of the total costs. Staff seems to be the lowest expense per tonne of MSW, mainly for two reasons: on the one hand, the EU-28 average workforce cost per hour is lower than the value for some of the participating countries [629]; on the other hand, the plant is highly automatized, obviating the need for a large number of available employees per shift.

Relative to scenario PG-3, revenues are the same as in scenario PG-1 but the waste management costs are much higher, as in this case the vitrified slag was considered as waste to dispose instead of a marketable by-product. Therefore, all the CAPEX and OPEX shares are significantly lower (in %), while the waste management contribution is the highest of all the allocations (reaching almost 70% of the total share). This cost partition is not recommended as it is completely unfavorable in terms of economic feasibility. From the assessed alternatives, scenario PG-3 depicts the least viable option, constituting the total opposite of scenario PG-2.

As this study concerns the socio-economic feasibility of implementing plasma gasification as an alternative to the landfilling of solid waste, the results for scenario PG-2 will be discussed in detail, as these reflect a more advantageous situation. The revenues totalized 113.55 € per tonne of MSW, which rebates the OPEX costs, enabling the final cost treatment to be settled at 1.74 € per tonne of MSW. In comparison to the conventional MSW landfilling, this is a competitive value, once the lowest landfill fee practiced in EU-28 is *circa* 3 € per tonne of MSW [612]. Therefore, a more detailed economic analysis is required in order to understand in which countries the plasma gasification plant would be a valuable investment when compared to the conventional system of landfilling or, in contrast, economically unfeasible.

As all the costs associated to the OPEX category were based on EU-28 values, major differences are expected when varying the landfill fees, once these diverge from country to country (in some cases even from municipality to municipality within the same country). Thus, a sensitivity analysis was performed varying the commissioning country for the plasma gasification plant, when compared to the traditional landfill. Figure 46 depicts the economic indicators for implementing the plasma gasification scheme proposed in this study.

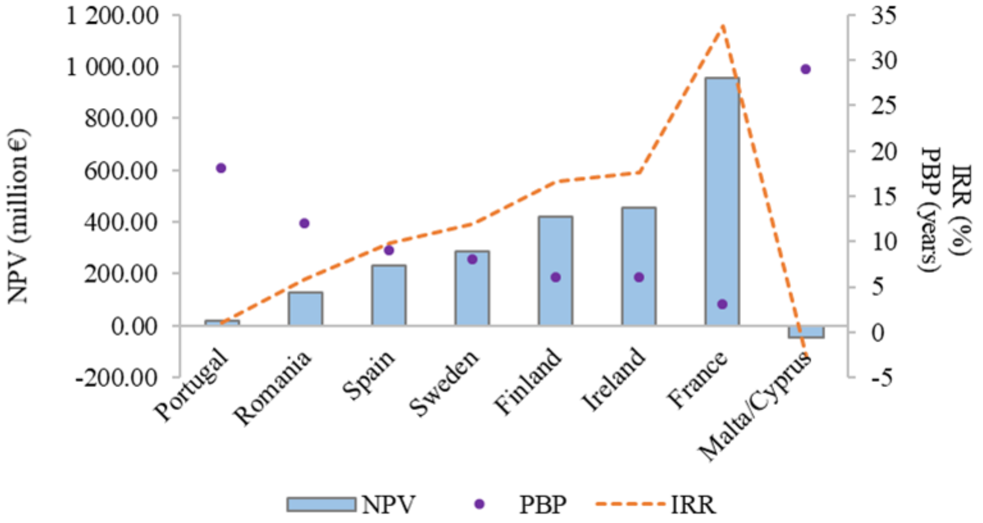


Figure 46 - Economic indicators for two-stage plasma gasification in different EU regions.

Recalling that a positive NPV indicates that the investment is economically viable, plasma gasification depicts a viable option for all the assessed countries except for Cyprus and Malta. For these countries a negative NPV was achieved, designating an unfeasible investment. This is justified by the fact that, in these countries there is no tax for landfilling waste. So, under a financial perspective, no stakeholder would be interested in investing their money in a project such as plasma gasification in these locations. Also, as seen in Figure 46, the PBP for these countries is 29 years, which means the initial investment (CAPEX) would only be payed after 29 years of operations. Thus, in Malta and Cyprus, a plasma gasification plant as described in this assessment would only be profitable 30 years after its construction. A possible strategy to change this is the establishment of the renewable energies scheme by the Government or the EU, in which investors would profit from green energy subsidies or fiscal incentives [601].

In contrast, France depicts a NPV of more than 956M € with a PBP of solely 3 years. This is due to the high landfill fees in this country, which reach 150 € per tonne of MSW. Hence, with a treatment capacity of more than 1100 tonnes of MSW/day at a cost of 1.74 € per tonne, the recovery of the CAPEX is easily attained and the profits maximized over the 20-year lifespan projected for the plant. On the other hand, within the considered countries, Portugal is the country where plasma gasification would be less viable. Thus, a PBP of nearly 18 years and a NPV of a little over 20M € make this investment unattractive for possible investors. Actually, an IRR as low as 1% is achieved, which is not enough to motivate shareholders. In comparison with Spain, this latter country has ten-times higher NPV and IRR, with half the PBP presented by Portugal, thus constituting a more attractive investment. The relation between these variables is in accordance to the expected, higher IRR leading to higher NPV and low PBP and vice versa [614].

The IRR is a profitability measure, as it determines the maximum rate of return for granted viability. Therefore, the higher the IRR, the more attractive is the project once the stakeholders have a higher financial return of their investment, also recovering the money more rapidly [614]. France is a good example of this, with an IRR of 33.7%, therefore granting a high economic viability and setting a strong appeal to investors. Between the extreme cases, countries such as Finland and Ireland also show interesting IRR (16.5% and *circa* 18%, respectively) and PBP (6 years in both cases), setting also good outcomes if plasma gasification is implemented under the conditions herein exhibited. Furthermore, NPV higher than 421M € and 455 M€ are foreseen for these countries.

6.3.4. LCC for two-stage plasma gasification in Portugal

6.3.4.1. Economic indicators

From Figure 46, Portugal is suggested as the less feasible country to commission a plasma gasification plant. Therefore, as it constitutes the worse-case scenario, a closer look at the financial indicators for this country was held to serve as an indicator for countries where the conditions are more favorable for the investment. Results are detailed in Figure 47.

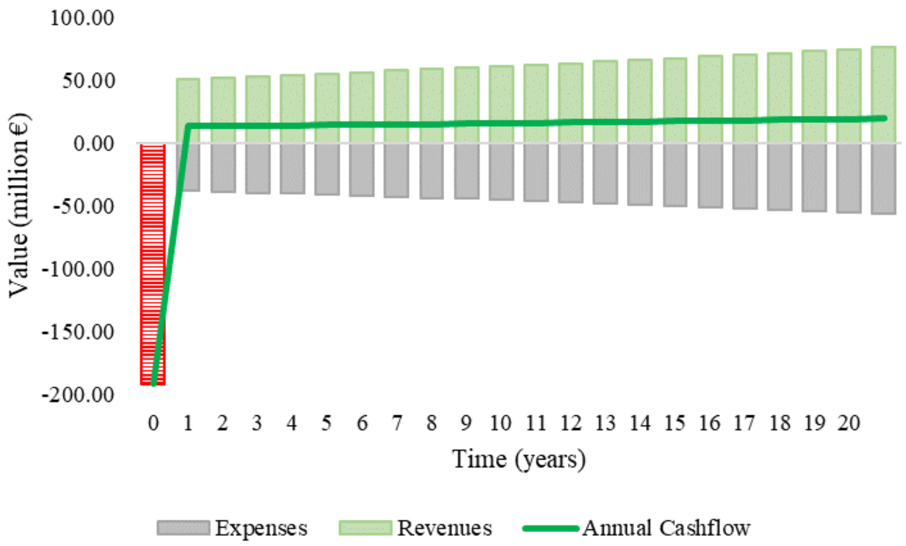


Figure 47 - Annual finances for plasma gasification strategy in Portugal.

According to Figure 47, the annual cashflows for the plasma gasification plant depict a viable project for the 20-year lifespan. Although a high investment is required in the year 0 (red bar), the annual revenues are always higher than the expenses (mainly due to the marketable products but also to the savings in the landfill fees). Revenues show a gradually increasing behavior along the project lifetime, while the expenses illustrate a symmetrical profile, nevertheless at a slower pace. As no borrowed capitals were considered, no expenses related to amortization of debts are seen. This is one of the possible approaches to take in the case of WtE when the market is not motivated to invest and bank loans are difficult to achieve [601]. An industry or technology partner could be the solution but, high interest rates would be required and this may compromise the project viability [614].

After determining the annual results of the plant, the project acceptability may be determined using the economic indicators previously mentioned. Figure 48 represents these indicators for varying discount rates.

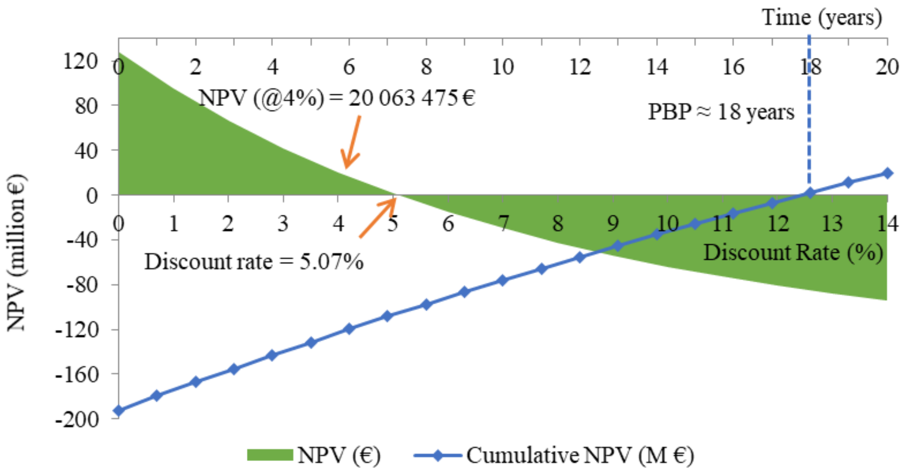


Figure 48 - Financial indicators for two-stage plasma gasification strategy in Portugal.

From Figure 48 it is observed that at a discount rate of 4% (as considered in the conditions used), the NPV of the project is positive (higher than 20M €), meaning that the project may be accepted. Besides that, this value is under the limit rate of 5.07%, which represents the situation where NPV is zero. This is considered the IRR, from which the project should not be accepted as a lower NPV entails economic risk [602]. Figure 46 also corroborates the previous finding relative to the PBP: approximately 18 years after the start of the plant, the cumulative cashflows are finally above zero restoring the CAPEX costs.

As rule of thumb, when the three economic indicators considered are met the project is viable, as seen here: the NPV is positive, the IRR is higher than the discount rate applied and the PBP is lower than the project's lifetime [601]. The PBP obtained may be the first big drawback, as investors are commonly seeking to recover the initial investment as fast as possible and, in this case, it would only happen in the last 10% of the project lifetime. Also, the margin between the discount rate applied and the IRR accomplished is not too wide (only 1.07%), which means that if some variable is put into stress, the return may be put at risk. Nevertheless, a lower discount rate may be utilized, which would also enhance the NPV at the end of the project's lifetime.

Table 24 depicts the economic indicators calculated for the assessment of the plasma gasification scheme proposed.

Table 24 - Economic indicators for plasma gasification plant.

Economic indicators	Real case
Payback period (years)	18
Internal Return Rate (%)	5.07
Net Present Value (€)	20 063 455

In order to reinforce the results presented, the concept of economy of scale should be applied [614]. The technology dissemination may be supported by different circumstances namely stricter environmental legislation (which empowers more sustainable techniques), wider waste treatment fees for conventional treatments (such as landfill), pressure to improve the public image of the waste management companies and also the hypothetical price drop due to the establishment of the plasma gasification technology. Therefore, if the technique is implemented it is worth to perform a susceptibility study considering different reduction rates over the initial investment [614]. This will also aid at seeking a reasonable CAPEX value, so that the initial investment effort is not so demanding. Figure 49 shows the results for CAPEX variations between 100% and 50%.

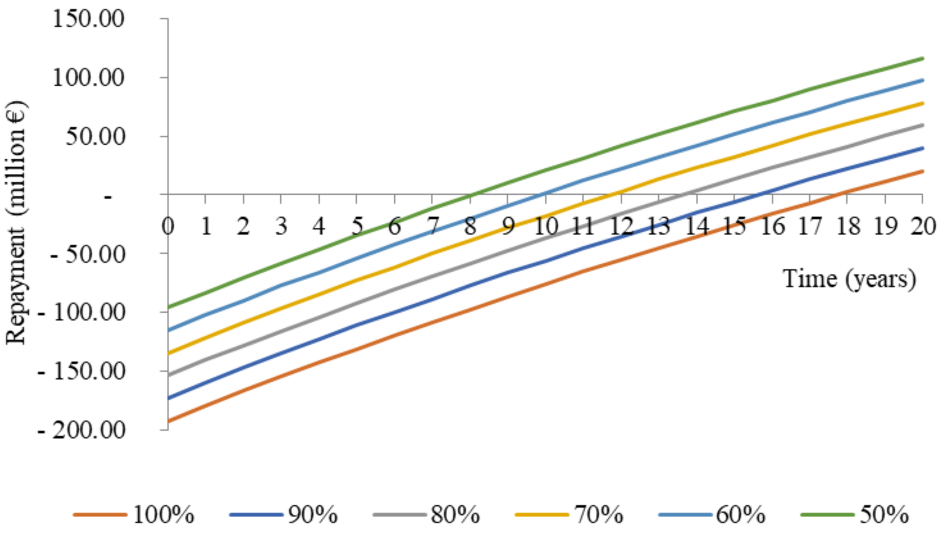


Figure 49 - Repayment of the plasma gasification plant for variable investment costs.

This analysis shows that when the price of the plant decreases, the repayment is higher and the PBP is reduced, as expected. Considering a 10% reduction in the initial investment is enough to decrease the PBP in 2.5 years and to double the repayment at the end of plant working period (roughly 40M €), while considering a 50% reduction leads to half the payback period and 6 times the 20-year repayment (almost 120M €). If higher discounts are considered, even lower PBP would be achieved as well as higher overall profits. These are interesting conditions for stakeholders and chief points to raise the attention from the governments in order to settle the required strategies to attract investors.

As Portugal represents the worse-case scenario, higher economic performances are foreseen for the other countries considered in Figure 47 (except Malta and Cyprus), which is a good indicator for the enforcement of this type of technique.

6.3.4.2. Sensitivity analysis

As the decisive parameter to accept or reject a project is the NPV [602], after investigating the influence of some variables in the financial aspects of the plasma gasification plant, a sensitivity analysis was performed to verify the relative impact of each of them in the NPV. The variability of the NPV was assessed by the standard error as follows: the higher the deviation the higher the investment risk. Figure 50 illustrates the results for the initial investment, the vitrified slag sales price, the discount rate, the landfill fees and the electricity sales price.

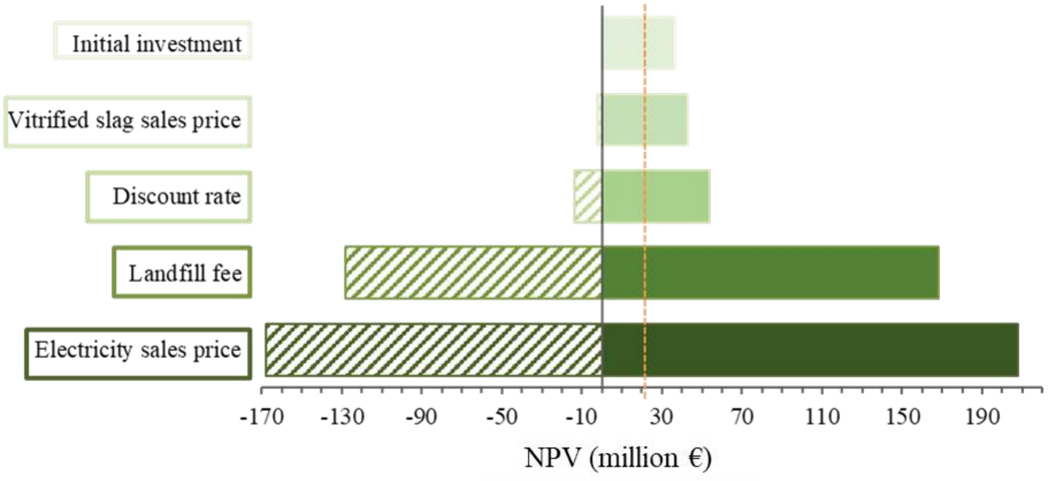


Figure 50 - Sensitivity analysis for NPV.

Figure 50 demonstrates that, regarding NPV, the project of installing a plasma gasification plant is more sensitive to the electricity sales price, followed by the landfill fees applied, the discount rate, and then the vitrified slag sales price and the stake of the initial investment. Similar profiles for some of the parameters were reported by other authors [602, 624]. This last parameter is the only variable that does not compromise the project viability, accomplishing positive NPVs throughout the range.

Hence, varying the electricity sales price would compromise the project's NPV, the profitability ranging from approximately -170M € to 210M €. Changing the landfill fees, as for instance within the values applied in Figure 44, the profitability of the project may vary between -128M € and 168M €. In the case of Portugal, these variations could lead to NPV's ranging from approximately -108M € to 188M €. The negative NPV's would lead to the rejection of the project, yet the maximum revenues could also be significatively raised. As far as the discount rate is related, a lower risk is assumed when ranging this parameter. NPV may vary approximately from -14M € to 54M €, which also poses some undesirable scenarios, however the project's actual revenue may also increase by almost three times. Relative to the vitrified slag sales price, a minor risk in the project acceptability is predicted, when NPV reaches values near -2.4M € (if the price is lowered to half the initial value). Nevertheless, if the vitrified slag sales price is increased, the profitability of the project may be raised to more than 42.5M €. Regarding the partition of the CAPEX costs, varying the initial investment between 50% and 100%, poses no major risk to the project's feasibility in terms of NPV, as the worst situation is the reduction of the NPV to less than 4M € under extreme conditions. Within the evaluated variables, the reduction of the initial investment depicts the least challenging situation, always accounting for a viable NPV. This is a consequence of having already accomplished a positive 20-year NPV when 100% of the CAPEX is considered, therefore when this initial cost drops, only better results may be foreseen.

6.3.5. Two-stage plasma gasification socio-economic assessment

Regarding the socio-economic study, Figure 51 shows the final matrix, after assessing the impact of each category over each indicator and vice-versa and after implementing the accomplishment factor, which compares the results achieved with the goal scenario for each indicator. Almost all the indicators performed better than expected, as seen for the high accomplishment percentages and magnitude factors, the environmental perspective presenting higher accomplishment for all the indicators. Few indicators depict low accomplishment, as is the case for the *energy consumed* in the technical sphere and the *capital costs* and *operational costs* in the economic perspective. These features show

								SOCIO-ECONOMIC IMPACT CATEGORIES					INDICATOR SCORE	
PERFORMANCE INDICATORS		Units	Goal	Result	Expected trend	Accomplishment	Magnitude	Skilled jobs increase	Reduction of MSW in landfill	Increase of sector competitiveness	Economic benefits	Waste management sustainability increase		
ENVIRONMENTAL	GWP	kg CO_2.eq. / t	7.01E+02	-3.10E+01	-	204%	2	0	6	4	2	6	18	74
	AP	kg SO_2.eq. / t	3.21E-01	-3.97E-01	-	324%	2	0	6	2	0	6	14	
	EP	kg PO_4^{3-} eq. / t	1.72E+00	-1.55E+03	-	90261%	2	0	6	2	0	6	14	
	MAETP	kg DCB-eq. / t	5.22E+03	-2.14E+05	-	4303%	2	0	6	2	0	6	14	
	ODP	kg R11-eq. / t	1.20E-06	-2.13E-08	-	202%	2	0	6	2	0	6	14	
TECHNICAL	Energy consumed	kWh / t	5.08	123.06	-	-2222%	0	0	0	0	0	0	0	56
	Mass reduction	kg / t	72.20	866.80	+	1201%	2	2	6	4	0	6	18	
	Electricity produced	kWh/ t	42.17	839.33	+	1990%	2	4	6	4	6	6	26	
	By-products produced	kg / t	---	79.42	+	---	1	1	3	2	3	3	12	
ECONOMIC	Final cost	€ / t	28.78	1.74	-	194%	2	2	4	6	6	4	22	46
	Capital costs	€ / t	21 893 312.00	191 642 261.00	-	-675%	0	0	0	0	0	0	0	
	Revenues	€ / t	10.9	113.55	+	1042%	2	4	4	4	6	6	24	
	Operational costs	€ / t	10.97	91.67	-	-636%	0	0	0	0	0	0	0	
SOCIAL	Potential local employment	No.	-	3	+	---	1	3	2	1	1	0	7	40
	Total human population affected	No.	1 000 000.00	1 000 000.00	+	100%	1	1	3	2	0	1	7	
	New stakeholders involved	No.	-	3	+	---	1	2	1	2	1	0	6	
	Companies implementing CE	No.	3	3	+	100%	1	1	2	3	1	3	10	
	Buildable area	m^2	0	80000	-	---	2	0	6	0	2	2	10	
							CATEGORY SCORE	20	67	40	28	61	216	

Figure 51 - Socio-economic importance matrix for two-stage plasma gasification.

negative accomplishments once the trend achieved was opposite to the expected (higher energy consumption and higher costs in plasma gasification whereas landfill presents lower results). Upon adjustment with the correspondent magnitude factor, these indicators will present null results over the impact categories, nonetheless this should be taken as a negative contribution from these indicators, meaning a disadvantageous situation. Except for the negative accomplishments, the lower impacts were majorly seen in the social perspective, indicators such as *total human population affected* and *companies implementing CE* presenting 100% match among the goal scenario and the final result.

The category that scored higher was the *reduction of MSW in landfill* (67 points) mainly due to the environmental indicators, which reached a sub-total of 30 points, followed by the technical and the social aspects (sub-totals of 15 and 14 points, respectively). The economic indicators were the least impacting in this category, contributing with only 8 points. This was somehow expected since the environmental impacts associated to this technique are highly beneficial when compared to other options [11, 574] and, as seen in section 6.3.3., one of the economic scenarios posed reveals a final treatment cost higher for plasma gasification than for the MSW landfill, explaining the lower contribution of the economic sphere. The technical indicators which contributed more were the *mass reduction* and the *electricity produced* which are also environmentally advantageous, reinforcing the global outcome of this category.

Following *reduction of MSW in landfill*, the *waste management sustainability increase* category scored 61 points, as a result of the environmental and the technical indicators (30 and 15 points, respectively). The economic and the social impacts in this category were lower (10 and 6 points, respectively), as sustainability is commonly more difficult to account under these perspectives. The European Commission reports related societal challenges under the strategy "Innovating for sustainable growth: a bioeconomy for Europe" [626]. Under the technical perspective, the *mass reduction* and the *electricity produced* are again the major players, while in the economic sphere, *revenues* is the most impacting indicator. This is in accordance to the economic results accomplished in section 6.3.4, plasma gasification leading to considerable high incomes. Dedicated literature also supports the revenues as an important contributor to the overall profitability of the projects [602, 614, 630].

In third place, the *increase of sector competitiveness* recorded 40 points, majorly attributed to the environmental category (sub-total of 12 points), where GWP was the leading indicator. In fact, GWP is the most used impact category, when relating the environmental concerns to climate change [21, 588, 631]. The technical and the economic perspectives scored 10 points each, the *mass reduction* and the *electricity produced* showing in “ex aequo” shares (4 points) and the *final cost* indicator reflecting the most important economic contribution to the economic domain (accounting 6 points). The social sphere reached 8 points, mostly due to the contribution of the indicator *companies implementing circular economy* (3 points).

The category *economic benefits* is ranked in the fourth place with a total of 28 points, mainly due to the 12 points accounted in the economic perspective (the *final cost* and the *revenues* showing in “ex aequo” shares). The technical aspects contributed with 9 points attributed to the *electricity produced* and the *by-products*, as these are the direct sources of income for the plasma gasification plant. The social indicators depicted a sub-total of 5 points, mainly attributed to the *buildable area* (possibly related to the construction of private or community facilities), whereas the environmental sphere appeared in the last position (2 points), as sometimes it might be seen as the major drawback for higher economic benefits. Bong et al. [605] stress that the renewable energies sector should make use of key strategies to reach broader audiences in order to surpass constrains like these. In fact, the authors suggest multisector collaboration as a way to develop the human capital and preconize the implementation of new technologies under a more social-related perspective.

Lastly, the *skilled jobs increase* scored only 20 points, performing worse than the other assessed categories. The environmental indicators did not contribute at all to the outcome of this category (0 points), while the technical and the social aspects accounted 7 points each, the *electricity produced* and the *potential local employment* being the chief contributors. Controversy about this theme is found in literature, some authors pointing out the social benefits of the bioenergy sector [627], while others highlight the dispute between job quality and job duration [623]. The economic perspective achieved only a sub-total of 6 points, again attributed to the *revenues* indicator.

Overall, the environmental sphere was the predominant aspect of the system, its performance indicators summing up to 74 points. The GWP had the most important role, totalizing 18 points, all the other indicators depicting 14 points each. As far as the technical sphere is concerned, a score of 56 points was achieved, mainly thanks to the *electricity produced* (26 points), followed by the *mass reduction* (18 points) and the *by-*

products produced (12 points). The *energy consumed* indicator has a negative influence, presenting a drawback in this sphere. The economic impacts accounted a total of 46 points, the *revenues* and the *final cost* contributing the most (24 and 22 points, respectively) and *capital costs* and *operational costs* accounting for a bad performance within this perspective. The social category was ranked in the lowest position (40 points), the *buildable area* and the *companies implementing circular economy* contributing with 10 points each, followed by the *potential local employment* and the *total human population affected* (7 points each), and the *new stakeholders involved* (6 points).

6.5. Partial conclusions

In this chapter two distinct WtE techniques were evaluated, regarding also two different feedstocks as well as two dissimilar functional units. Hence, the final goal was not to compare them, but to take advantage of the lessons learned from the assessment of regular gasification (environmentally less viable) to conduct a thorough study on the potential implementation of a two-stage plasma gasification plant, previously confirmed as a promising WtE technique in what regards its environmental performance.

After the thermal conversion of the cork wastes through gasification, a LCC study was carried out in order to evaluate the techno-economic impact of the valorization strategy as well as the potential social effects in the involved communities. The obtained results represent the whole cost cycle of one MWh of energy, and a comparison to the cost from the conventional Spanish electrical mix. The major findings were that besides the sustainable energy production, Ecorkwaste scheme also enables the achievement of marketable by-products, which generate considerable revenue, reducing the OPEX costs. The avoided landfill fees for the cork residues are also considered a big saving. A lower nominal cost per MWh was achieved through the gasification strategy (24.74 €/MWh in the continuous regime and 39.73 €/MWh in the real plant case), when compared to the conventional electrical grid mix (76.40 €/MWh), inferior cost per MWh being achieved. At the end of the project lifespan, gasification scenarios allow hundreds of thousands of € saved when compared to the conventional energy production scheme. Also, the economic indicators of the project reflected a (rather lean but) positive performance, NPV reaching 113 000 € in the continuous operation regime, with a payback period of 10 years.

About the socio-economic matrix, different levels of impact were seen for the considered indicators. The increase of cork valorization was the most important effect, mainly thanks to the environmental and the technical components of the evaluation, followed by the economic sphere. The skilled jobs increase was the least pronounced category, most of the indicators presenting a low result. From the exposed above, the developed valorization strategy may be stated to have positive high socioeconomic impacts.

Regarding the commissioning of a plasma gasification plant over 20 years, although the project depicted feasibility, Portugal was seen as the least favorable country (from some European countries) and therefore, a thorough economic analysis was held, as a worse-case approach for the implementation of this WtE technique. Two scenarios were posed, the only difference being the inclusion of the by-product (vitrified slag) commercialization, besides the electricity sales. The most advantageous situation was the combination of selling electricity and vitrified slag (rather than electricity alone), which afforded revenues over 113 € per tonne of treated MSW, lowering the final treatment cost from 23 € to 1.74 € per tonne. Therefore, it is possible to conclude that the plasma gasification of MSW with commercialization of the vitrified slag affords a competitive scenario when compared to the conventional landfilling of these residues (9.9 €/tonne in Portugal). For this scenario, a NPV of roughly 20 million € and a PBP of 18 years were achieved, other countries presenting enhanced results for these economic indicators. Nevertheless, a sensitivity analysis showed that the electricity sales price and the landfill fees significantly impact NPV, whereas parameters such as the discount rate and the vitrified slag sales price depict a lower effect, still also posing some risk situations. The initial investment has shown not to affect the final decision of accepting or rejecting the project.

As far as the fulfilment-importance matrix is concerned, the environmental sphere showed to be the most relevant, scoring higher in performance indicators such as reduction of MSW in landfill and waste management sustainability increase. The technical sphere ranked second, also accounting major effects over the referred impacts, while the economic perspective ranked third mostly due to the economic benefits of the technique. Last but not least, the social sphere presented lower impacts, although the goal scenario was accomplished for all the performance categories. The social aspects were seen to be mainly influenced by the reduction of MSW in landfill, higher scores being attained for the buildable area indicator as a societal advantage over the land area occupied by the common landfill.

As may be seen from the study held, plasma gasification has benefits over the current landfill option, lower environmental and technical impacts being observed for the conditions herein applied. As far as the economic perspective is concerned, lower or similar costs are envisioned, depending on parameters such as the landfill fees or the economic situation of the commissioning country, for instance.

Chapter 7 – Main Conclusions and Future Work

7.1. Overview

In this work two chapters were dedicated to the state-of-the-art of the groundwork topic for the thesis: the co-gasification of different feedstocks and the strategies to accomplish the numerical modelling of such type of experiments. After understanding what the research gaps were, three other chapters were developed as an effort to complete the outlook reported in the state-of-the-art. The works reported were conducted under the main big driver for this study: performing an integrated assessment of the environmental, technical, economic and social domains of the referred waste-to-energy techniques.

This chapter is the closing part of the presented thesis, and aims to resume the thorough work held during four years, into simple overall remarks with high impact for the general readers. Hopefully this work constitutes a contribution to the pursuit of a more sustainable society, which is able to understand and accept the pressing requirement to adapt their daily activities and needs to the existing reality of natural resources scarcity.

7.2. General conclusions

An interesting major conclusion could be drawn from this work, namely that regular gasification was seen to bring forth higher environmental burdens than incineration (although with positive results for some of the assessed impact categories), nevertheless it is cleaner and more energetically-efficient, producing lower amounts of residues and higher yields of electricity when compared to incineration. This study has shown that two-stage plasma gasification is a sustainable and clean WtE technique, proving to perform better than the commonly used methods nowadays. Regarding the overall efficiency of the techniques, two-stage plasma gasification proved to be the most effective, depicting higher mass reduction and producing lower amounts of air pollution residues. Moreover, when compared to incineration, plasma gasification almost doubles the energy generated, affording higher electricity production than reported in literature. Comparing the three techniques, material resources, energy resources and emissions to fresh water were the main savings, especially from incineration and two-stage plasma gasification, which portrayed more than 500 tonnes of environmental credits per functional unit. This represents a decrease in the environmental impacts as well as an improvement of the quality of life, with less polluted air, water and soil. Thus, the wellbeing of the exposed populations is improved and a higher degree of sustainability is achieved. In fact, summing up the overall results per environmental compartment the following outcomes are achieved per tonne of MSW treated:

- Incineration avoidances: (-)2.70x10^4 kg of emissions to air, (-)0.14 kg of emissions to freshwater and (-)0.0485 kg of emissions to agricultural soil;
- Regular gasification burdens: 2.16x10^5 kg of emissions to air and 0.0281 kg of emissions to industrial soil;
- Plasma gasification avoidances: (-)5.83x10^3 kg of emissions to air, (-)1.28x10^5 kg of emissions to freshwater and (-)0.632 kg of emissions to industrial soil.

Regarding the two-stage plasma gasification viability, although the project depicted economic feasibility in Portugal, investors may find it not interesting due to circumstances such as plant location, feedstock availability and access to the solid waste supply chain. These drawbacks might explain why there is a scarce implementation of this technique, few plasma gasification plants being known in Europe. However, if general government incentives are established by the means of fiscal exemptions or green energy subsidies, some of the technique limitations may be overcome or at least reduced. This type of support is generally well received by the stakeholders as it may be faced as a sort of revenue or expense avoidance, ultimately prompting stakeholders to rethink their decision. The presented socio-economic methodology had the final goal to determine explicitly the considered impacts based in the fulfilment of certain conditions and the performance of specific economic, social and environmental indicators. Two-stage plasma gasification presents a very favorable set of results, practically all the indicators performing above the set goal. The environmental perspective depicted the highest accomplishment for all the indicators, whereas sectors such as the technical and economic had some indicators presenting performances which were opposite to the expected outcome. The lowest impacts were seen in the social perspective, nevertheless the indicators related to the affected population and to the implementation of the circular economy principles were met. As energy is one of the cornerstones of the actual society, the social welfare is directly connected to the capability of producing electrical power from our own residues. As seen, the ratio of electricity consumed per waste generated might serve as a basis for the strategic development of waste management options or even for the electrical grid planning. Moreover, plasma gasification depicted superior efficiency results in the process of converting residues into energy and, if applied, could be settled as an optimum sustainability foundation in regards to positive socio-economic results, leading to higher viability and enhanced sustainability.

Relative to the Ecorkwaste project, the main benefits of the valorization of cork residues through the gasification scheme herein proposed were the reduction of landfill practice supporting circular economy, the production of clean energy at a fraction of the price of the conventional option, the recovery of some by-products which can further be utilized in the production of other materials, also promoting sustainability and the enhancement of the industrial development and sector efficiency. In fact, the replacement of raw materials by the produced resources allows to decrease some impacts beyond national borders since some of the raw materials produced have a trans-boundary character, such as the produced electricity, which would replace the electrical grid mix composed of the different renewable and fossil resources from different points of the world. The reduction of landfilling allowed also to avoid environmental impacts at regional and country level, relative to the acidification and eutrophication potential.

The conversion of cork wastes into energy has raised the competitiveness of this treatment, granting lower waste management fees, as well as higher revenues from the products achieved. Therefore, both waste management and resource efficiency were tackled, enforcing higher environmental and economic performances. Overall, the gasification scheme proposed proved to be a key basis to the economic and social development at a regional scale.

In an overall view, the current study provides a critical analysis of the advantages and disadvantages of three different WtE technologies and thus is able to contribute to the decision or policy making process. Sustainability is a priority and other core perspectives (technical, social and environmental) were seen as critical elements contributing to an integrated knowledge in favor of renewable and sustainable energy solutions with direct benefits to the environment and people.

7.3. Future work

Regarding the numerical simulations of the WtE alternatives, the prospective growth in computational knowledge and devices is yet to promote even superior progress in the construction of faster and advanced numerical models, making the design of reactors easier and more precise according to the desired syngas characteristics. Although several aspects of gasification modeling are already understood and their effect on the overall system is known, there are many others that still need to be explored such as the blending of different fuels. These constitute challenges for the technique that need to be overcome so that more widespread and rapid acceptance and implementation may take place in the future. An example of this is the lack of assessments of a larger number of waste and coal blends in fixed beds, which have not yet even been considered for modeling purposes. This is probably due to technical difficulties regarding the heterogeneity of the feedstock, which will ultimately lead to low efficiency. Another flaw which may sometimes hinder the development of more sophisticated and productive methods is the need for powerful computers and software that could allow a broader scale-up from lab- or pilot-scale studies to the industry level. Large-scale plants have different technological needs which are difficult to tackle by simply magnifying the results achieved at a smaller level. This creates an obstacle for the use of regular and affordable laptops or personal computers since the simulations held in these kinds of structures would not accurately recreate real facilities.

After the accomplishment of this first task, the optimization of the operational conditions for different biomass and waste blends should be performed in order to test the ideal set of conditions in a real plant. If high levels of agreement between the numerical and experimental runs are achieved, the obvious follow-up will be to conduct the respective LCA and LCC analysis for these new feedstock blends, to try to improve the outcomes of the regular gasification scheme. The LCC assessment is a very delicate question as when dealing with sources of biomass and/or MSW (for instance) at a more regional or local scale, other barriers may potentially hinder the process. This involves issues such as institutionalized policies, rules or legislation that might have to be altered, possibly entailing modifications in long-term relations among strategic partners or the inclusion of different stakeholders. Therefore, a closer collaboration in policy-making and regulatory decisions is also envisioned aiming to promote a prompter sustainability enhancement and trying to fit the maximum goals for all the intervening parties.

As far as the plasma gasification is concerned, the promotion of the LCA results should be reinforced so that more countries or organizations could start taking this as a potential option in a near future. Again, the LCC assessment plays a major role in this task, specific and detailed analysis being required for each country who decides to implement it. A case study similar to the Ecorkwaste project should be accessed so that intrinsic life cycle costing could be applied and understood within the real conditions of a plasma gasification plant.

Also, taking advantage of the assumptions and limitations done for the gasification-based techniques, using distinct electrical grids and waste compositions would provide a new opportunity to further develop this work. This would enable the creation of different scenarios, new comparisons and conclusions being drawn.

This being said, opportunities are open to solve the detected issues and promote a faster evolution for the gasification-based technologies towards an advanced integrated approach.

Annexes

Annex 1 – Impact categories description

CML 2001 methodology

Global Warming Potential (GWP): concerns the effect of increasing temperature in the lower atmosphere namely quantifying greenhouse gasses such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons (CFC's), among others. Possible consequences of the greenhouse effect include the increase of temperature at Earth surface (which leads to melting of the ice caps and glaciers, elevating sea levels), as well as regional climate changes. GWP for greenhouse gasses is expressed as CO_2-equivalents and is normally quantified for time horizons of 20, 50, 100 or 500 years.

Ozone depletion potential (ODP): is related to the breakdown of ozone by substances present in the stratosphere such as long-lived chlorine and bromine compounds methane, nitrous oxide and water vapor. These are sufficiently stable in the atmosphere to allow a substantial fraction to reach the stratosphere participating in the chemical decomposition of ozone. Ozone molecules absorb the UV radiation coming from the sun, therefore the depletion of this layer may cause damage to plants, animals and humans potentially leading to consequences in the aquatic food chain and skin cancer, respectively. The reference unit for ODP is CFC-11, as it is the substance with the largest effect in ozone depletion.

Photochemical Ozone Creation Potential (POCP): relates to the formation of ozone in the troposphere, which occurs in the presence of nitrogen oxides and volatile organic compounds (VOC's). This originates peroxy radicals which are highly reactive and toxic leading to the increase of ozone yield, as a secondary pollutant. Tropospheric ozone is one of the major environmental threats at regional scale, hazardous to human health and to flora, namely crops. Its transboundary abilities enhance even further its harmfulness during transport over long distances. The principal precursors for tropospheric ozone are nitrogen oxides (NOx), VOC's and carbon monoxide (CO). POCP is expressed in kg C_2H_4-equivalent as ethene is one of the most potent ozone precursors of all VOC's.

Acidification Potential (AP): concerns the release of protons to the terrestrial and aquatic ecosystems, contributing to an increased mobility of heavy metals and aluminium. Acid gases that are released into the air or resulting from the reaction of non-acid components of the emissions are taken up by atmospheric precipitations forming “acid rain”, which has widespread noxious effects. At terrestrial level the main consequence is the inefficient growth of forests while in the aquatic level lakes are becoming acidic putting at risk any wildlife. All the substances releasing hydrogen ions to the environment and leaching the corresponding anions from the concerned system are considered to have acidification effect, the primary ones being as sulphur oxides (SOx), NOx, ammonia, and hydrochloric acid (HCl). AP is quantified in SO_2-equivalents.

Eutrophication Potential (EP): comprises all the potential impacts with high environmental levels of macronutrients (nitrogen and phosphorus) causing increased production of aquatic plants, reducing water quality and oxygen depletion in the bottom layers. This is due to the increased production of plankton, algae and higher aquatic plants which break down and consume the oxygen in the bottom layer, gradually leading to the death of organisms. Substances containing nitrogen or phosphorus in a bioavailable form are potential contributors to EP. EP is expressed in kg PO_4-equivalent.

Human Toxicity Potential (HTP): is related to the acute toxicity at which the human being is exposed when outdoors, and seen as a local and regional impact. As the substances contributing to this effect are countless and belong to several different categories (heavy metals, NOx, SO_2, VOC’s, chlorinated compounds, persistent organic pollutants -POP’s, particulate matter among many others), a sub-quantification is believed to be held, although in the right order of magnitude. These can provoke irritative, corrosive, allergenic, irreversible and carcinogenic effects. HTP is expressed in kg DCB-equivalent, reference to the compound 1,4- dichlorobenzene.

Ecotoxicity: refers to the acute and chronic toxicity on different species in soil and water and therefore is distinguished in **Marine Aquatic Ecotoxicity Potential (MAETP), Freshwater Aquatic Ecotoxicity Potential (FAETP) and Terrestrial Ecotoxicity Potential (TETP)**. As mentioned in the case of HTP, the same problem concerning the multitude of substances that contribute is seen in this case so impacts from organotin compounds, metals, POP’s and pesticides are the main considered. Again, MAETP, FAETP and TETP are expressed in kg DCB-equivalent, reference to the compound 1,4- dichlorobenzene.

Abiotic Depletion Potential (ADP – fossil or elements): includes the scarcity of all fossil and mineral resources, and therefore is distinguished in ADP_{fossil} and $ADP_{elements}$

respectively. This indicator is derived from the extraction of fossil fuels and elements from Nature and might be regarded as an indicator of the primary energy usage, to evaluate the efficiency of the resources. ADP_{fossil} is expressed in MJ and $ADP_{elements}$ in kg Sb-equivalent.

ReCiPe methodology (Ecorkwaste project)

Global Warming Potential (GW): similar to the description of Global Warming Potential in the CML 2001 methodology.

Terrestrial Acidification (TA): is characterized by changes in soil chemical properties following deposition of nutrients in acidifying forms (namely nitrogen and sulphur). This corresponds to a pH decline and consequently, the increase in acidifying nutrients leading to a decline in base saturation, which decreases soil fertility. This may ultimately lead to plant yellowing and seed germination failure, reducing photosynthesis and plant diversity.

Freshwater Eutrophication (FE): refers to the excessive growth of aquatic plants or algal blooms, due to high levels of nutrients in freshwater ecosystems such as lakes, reservoirs and rivers. Nutrient pollution in the form of phosphorous from agricultural fertilizers, sewage effluents and urban storm waters are the main causes for this. This can substantially impact ecosystem services affecting fisheries, recreation, aesthetics and health.

Marine Eutrophication (ME): refers to the increase in organic matter supply in marine ecosystem, generally attributed to the increase of nutrient loading from agricultural and urban sources. This promotes adverse ecological and economic effects as the creation of anoxic zones and toxic cyanobacteria blooms.

Fossil Resources scarcity (FRS): measures the availability of the fossil resources based on their increasing demand, especially due to their dominant component in energy production and industrial capacity. The impacts of climate change and resources scarcity are often similar and interdependent, ultimately leading to supply constraints and affecting population worldwide.

Cumulative Energy Demand (CED): calculates the primary energy input for the generation of a product, taking into account the pertinent front-end process chains. It is related to the primary energy-efficiency of the energy supply and points out the energy resources demand.

Annex 2 – Life cycle inventory for MSW treatment by incineration and regular gasification

Table A2.1 – Life cycle inventory assessment for MSW treatment.

Main Flows	Incineration	Regular Gasification	Two-stage plasma
Main Inputs			
Waste, t	1		
Water, m^3	0.486	0.584	0.358
Diesel, cm^3	3.56	---	---
Natural gas, dm^3	30.85	---	---
Electricity, kWh	66.8	53.1	70.8
Auxiliary materials			
Limestone, kg	4.22	7.76	2.62
Activated charcoal, kg	181.3	0.10	0.10
Urea, kg	1266	1.34	0.47
Sodium Hydroxide, kg	14.4	1.86	0.79
Main Outputs			
HCl, g	1.18	0.60	0.57
NOx, kg	4.05	0.23	0.23
NH_3, g	17.7	16.5	16.3
HF, g	24.5	5.2	4.95
SO_2, kg	2.04	0.15	0.064
Particulate matter, kg	42.0	24.9	15.1
CO, kg	0.98	0.13	0.13
Neutralized ashes, kg	79.7	15.1	9.80
Produced electricity, MWh	0.407	0.790	0.839

Annex 3 – Ecorkwaste gasification plant functioning

1. **Gasification reactor**: The cork feed to the reactor is carried out by means of a hopper located in its upper part. The cork is loaded into the reactor by a vertical screw driven by a motor, which ensure the cork feed is correctly performed. The air inlet is made by two pipes and is regulated by two fans in order to ensure oxygen presence. In order to avoid preferential channels, the reactor has a motor which continuously mixes the content of the reactor. In the reactor there are a series of balls or ceramic filling that are intended to prevent the leakage of fine material. Thus, if it is drawn through the air, when it comes in contact with the filling, due to the high temperature reached at the balls, this material is gasified immediately and is prevented from escaping with the flow of syngas.

2. **Exchange reactors**: The output gas goes through the first tubular air-to-air heat exchanger where atmospheric air circulates by natural convection. The interior of the exchanger has the shape of a cyclone so that the solid particles and some of the tars that are dragged with air will be collected in the bottom of this equipment. The next step is the tubular exchanger (an air-water exchanger) where the gas temperature drops to 50 ºC. Syngas moves forward to the tar cleaning tower, and after this phase, into another tubular exchanger using the same system as the previous exchanger, temperature dropping to 25 ºC.

3. **Gas cleaning**: after the first tubular exchanger, the gas is subjected to a pressurized water wash through nozzles in order to draw all the particles of tar that it may contain, following the same principles of a washing tower. Once the gas is clean and pressurized, it goes to the second tubular exchanger.

4. **End system**: as a last treatment, a mesh filter with cork support is placed that is intended to retain any solid particle that the gas may contain. A regulating valve and a rotameter are located in the filter outlet pipe. This system controls the flow of primary air to be introduced into the gasification reactor and thus the total syngas produced.

5. **Control system**: The monitoring of the produced syngas is carried out from a gas analyzer and a laptop.

6. **Gas motor**: A theoretical approximation of a motor has been introduced in the system. This motor burns the produced syngas in order to produce electricity and heat.

Annex 4 – Life cycle inventory for Ecorkwaste gasification strategy

Table A4.1 – Inputs and outputs for the valorization of cork residues in the gasification plant.

Inputs	**Value**	**Unit**
Electricity	10.3	kWh
Outputs	**Value**	**Unit**
CO_2 biogenic	19.2	kg
CH_4 biogenic	6.97	kg
NMVOC	5.82E-02	kg
Air emissions (diesel)		
CO_2 fossil	1.90E-02	kg
CH_4 fossil	3.30E-04	g
CO fossil	6.43E-02	g
NOx	1.97E-01	g
NMVOC	2.03E-02	g
N_2O	8.10E-04	g
NH_3	4.80E-05	g
SO_2	1.20E+01	mg
PM	1.30E-02	g

Table A4.2 - Atmospheric emissions from syngas burning in the CHP engine.

Emission	**Amount**	**Unit**
CO_2	35	kg/m^3
CO	7	kg/m^3
HC	0.01	kg/m^3
NOx	0.025	kg/m^3
SO_2	0.5	kg/m^3

Table A4.3 - Inventory for cork landfilling (avoided burden).

Inputs	**Value**	**Unit**
Electricity	10.3	kWh
Outputs	**Value**	**Unit**
CO_2 biogenic	19.2	kg
CH_4 biogenic	6.97	kg
NMVOC	5.82E-02	kg
Air emissions (diesel)		
CO_2 fossil	1.90E-02	kg
CH_4 fossil	3.30E-04	g
CO fossil	6.43E-02	g
NOx	1.97E-01	g
NMVOC	2.03E-02	g

N_2O	8.10E-04	g
NH_3	4.80E-05	g
SO_2	1.20E+01	mg
PM	1.30E-02	g

Table A4.4 – Inventory for tar management as a product from the gasification of cork residues.

Inputs	**Amount**	**Unit**
Energy		
Heavy fuel oil	13.64	kg
Steam	2.8211	GJ
Electricity	0.1804	MWh
Water		
Tap water	1.28	m^3
Groundwater	3.05	m^3
Rainwater	0.8	m^3
Additives		
Sodium hydroxide (50%)	0.22	kg
Lime	0.423	kg
Ammonium	0.77328	kg
Hydrochloric acid (30%)	0.01728	kg
Poly electrolyte	0.03	kg
Brown coal	0.91	kg
Outputs	**Amount**	**Unit**
Incineration ash	192	kg
Boiler ash	8.9	kg
Fly ash	21.2	kg
Filter cake	26.1	kg
Brown coal (coal filter)	0.91	kg
Energy		
Steam production	451.44	MJ
Electricity production	47.52	MJ
Water		
Wastewater	1.48	m^3
Emissions		
NOx	1.965	g
Dust	6.1	g
CO	0.072	kg
CxHy	9.2	g
Dioxins	1.62E-10	kg

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