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Integrated early-stage environmental and economic assessment of emerging technologies and its applicability to the case of plasma gasification

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Abstract

Economic and environmental impact assessments are increasingly being adopted in the design and implementation of emerging systems. However, their emerging nature leads to several assessment challenges that need to be addressed to ensure the validity and usefulness of results in understanding their potential performance and supporting their development. There is the need to (i) account for spatial and temporal variability to allow a broader perspective at an early stage of development; (ii) handle uncertainties to systematically identify the critical factors and their interrelations that drive the results; (iii) integrate environmental and economic results to support sound decision-making based on two sustainability aspects. To address these assessment challenges, this study presents an alternative approach with the following corresponding features: (i) multiple scenario development to conduct an exploratory assessment of the systems under varying conditions and settings, (ii) global sensitivity analysis to identify the main critical factors and their interrelations, and (iii) trade-off and eco-efficiency analysis to integrate the economic and environmental results. The integrated approach is applied to a case study on plasma gasification for solid waste management. The results of the study highlight how the approach allows the identification of the dynamic relations between project settings and surrounding conditions. For example, the choice of gasifying agent largely depends on the background energy system, which dictates the impacts of the process energy requirement and the savings from the substituted energy of the syngas output. Based on these findings, the usefulness and validity of the proposed integrated approach are discussed in terms of how the key assessment challenges are addressed and how it can provide guidance for the development of emerging systems.

Key Words:

Ex-ante assessment, Integrated assessment, Global sensitivity analysis, Life cycle assessment, Life cycle costing, Plasma gasification

1. Introduction

In the context of technology development of emerging systems, sustainability assessments are acquiring greater importance (Foley et al., 2015; Hetherington et al., 2013; Thomassen et al., 2019; Van der Giesen et al., 2020; Wender et al., 2014a). Here, emerging systems refer to either an individual technology or an entire chain of several technological processes that lack large-scale applications. At the early stage of development, when there is more flexibility for change, assessments can significantly drive their design and implementation (Arvidsson et al., 2017; Thomassen et al., 2019; Wender, 2016;). Such assessments may also vary in terms of intended use. Decision-oriented studies aim to support specific project approval based on potential economic and environmental performance. On the other hand, learning-oriented analyses aim for a fine-grained understanding of the critical factors and their interrelations that build up the performance (Buyle et al., 2019; Esguerra, 2020; Laner et al., 2019). Regardless of the intended use, such assessments incur several challenges due to the emerging nature of the systems (Arvidsson et al., 2017; Van der Giesen et al., 2020; Villares et al., 2017). Among these, the focus of this study is on the need to overcome three challenges when performing environmental and economic assessments of emerging systems: (i) spatial and temporal representativeness, (ii) the handling of large uncertainties, and (iii) the integration of economic and environmental results.

With the lack of full-scale applications of emerging systems, current assessment approaches typically aim to compare emerging technologies at an industrial scale and consider their application at a specific future point in time (Arvidsson et al., 2017; Buyle et al., 2019; Cucurachi et al., 2018). While uncertainties are inherent to any assessment, they are exacerbated in assessments of emerging systems due to large knowledge deficits of the modeled process and considering both the spatial and temporal aspects of development. Multiple scenarios are used to model potential future conditions, and the focus is on comparing the new technology with the incumbent one it aims to replace. However, these studies typically target environmental and economic performances of case study-specific project settings (Danthurebandara et al., 2015b; Delpierre et al., 2021; Joyce & Björklund, 2019). Consequently, the understanding of the new technologies' performance is limited in the consideration of possible wider variations not just in project settings. Surrounding conditions such as background energy, market situation, and other socio-economic factors vary in different spatial considerations and evolve through time (Bisinella, 2017; Laner et al., 2019; Thomassen et al., 2019). Failure to include such wide variations influences the validity of the results when assessing the potential economic and environmental performance of emerging systems.

The variability and uncertainty of the results should be consistently addressed for a better understanding of the result, and to support future assessments and decision-making (Cucurachi et al., 2018; Saltelli et al., 2019). By allowing a fine-grained assessment of the output variability, assessments can lead to understanding the underlying mechanisms that drive the economic and environmental performance under variable conditions (Laner et al., 2016, 2019). This can increase the usefulness of the results to better support system development and implementation.

In addition, environmental assessments of emerging systems are often performed separately from the economic assessments. Results of the economic and environmental assessments can be contradictory, or the improvement of the technology performance in one direction could penalize it in the other. In this regard, eco-efficiency indicators have been used to promote the maximization of product/process value and minimization of the environmental burden by measuring the relationship between economic growth/activity and environmental impacts to decouple them (Baptista et al., 2015; Muller & Sturm, 2001). The integration of the environmental and economic results in assessing emerging systems could allow an integrated understanding that better supports decision-making towards more sustainable choices.

This study aims to present a learning-oriented approach to assessing the integrated environmental and economic performance of emerging systems. More specifically, the main features of the approach address the aforementioned assessment challenges allowing (i) a broad perspective by accounting for spatial and temporal variabilities at an early stage of development; (ii) the systematic handling of uncertainties for a fine-grained analysis of the critical factors and their interrelations that influence the environmental and economic results; (ii) the integration of environmental and economic results to provide sound decision-making based on two sustainability aspects. The integrated assessment approach is applied to a case study on plasma gasification for solid waste management. The technology offers an innovative solution for its combined material and energy valorization potential, but remains under research, or only tested at a pilot scale (Bosmans et al., 2013; Materazzi & Holt, 2019a; Ramos et al., 2019). Based on the assessment findings of the case, the usefulness and validity of the proposed approach are discussed in terms of how the key assessment challenges are addressed and how it can provide guidance for the development of emerging systems.

2. The integrated framework and its application

In this section, plasma gasification is presented in the context of integrated solid waste management, highlighting the need for an early-stage and integrated assessment of its economic and environmental performances. The integrated framework is then introduced in relation to the factor-based approach developed by Laner et al. (2016, 2019), from which it is adapted and modified. The proposed framework is different as it aims to address both economic and environmental perspectives and at integrating respective results in terms of trade-off analysis and eco-efficiency analysis.

2.1 Plasma gasification for integrated solid waste management

Plasma gasification is gaining increasing attention for the thermal treatment of waste due to its potential for both energy (waste-to-energy, WtE) and material (waste-to-material, WtM) recovery (Bosmans et al., 2013; Oliveira et al., 2022; Ramos et al., 2019), as well as the treatment of heterogeneous waste streams (Kaushal et al., 2022; Paulino et al., 2020; Pei et al., 2020). The main products of plasma gasification include a tar-free synthesis gas (syngas), composed mainly of hydrogen

(H_2) and carbon monoxide (CO), and an inert and vitrified slag. The syngas can potentially be used for energy production or the production of chemicals, such as bio-hydrogen (Amaya-Santos et al., 2021; Materazzi et al., 2019b), bio-syngas (bioSNG) to replace natural gas (Materazzi et al., 2018), as well as other biofuels (Materazzi, 2019; Materazzi et al., 2019a). The vitrified slag can instead be processed for the production of aggregates or higher value-added construction products such as inorganic polymers (Danthurebandara et al., 2015b; Evangelisti et al., 2015a; Materazzi et al., 2016). Compared to conventional gasification, of great interest in plasma gasification is the use of an external heat source, the plasma torch. This allows the decoupling of heat generation from the feedstock composition, leading to higher flexibility and the potential to treat highly heterogeneous waste streams.

Nevertheless, the current lack of industrial-scale applications leads to limited knowledge and high uncertainties on its performance, as challenges for commercial-scale applications have been discussed in terms of operational scale and technology design, as well as costs and feedstock availability (Materazzi et al., 2019b; Ramos et al., 2019; Willis et al., 2010). Moreover, its application for solid waste treatment inevitably leads to the temporal and spatial variation of the feed characteristics, project, and system-level factors, influencing its performance and the technology set-up (Bisinella, 2017; Laner et al., 2019). Therefore, the plasma gasification process demands an assessment that covers varying system conditions, feedstock characteristics, process set-ups, and (by)product valorization alternatives, and provides an understanding of which factors drive its performance for the thermal treatment of waste. Previous studies on the environmental and economic aspects of plasma gasification have mainly addressed variations in project settings or comparisons with other technologies, maintaining a specific system design and background system (Danthurebandara et al., 2015b; Evangelisti et al., 2015b). Recommendations for improvement or implementation are in isolation, excluding the dynamic relations between upstream variations of input feedstock, downstream variations such as residual slag management, and system variations such as substituted background energy and output market prices. The assessments of such technologies call for more learning-oriented approaches that can address the large uncertainties that arise. The application of the framework to the case study aims, therefore, to further support technology development and its future implementation in different project settings.

The case study addresses a specific application of plasma gasification in the context of enhanced landfill mining (ELFM), to maximize the valorization of the excavated waste streams, as both materials and energy (Danthurebandara et al., 2014; Jones et al., 2012, 2013). Such waste is very heterogeneous, with a high content of soil-like material, high moisture content, and low calorific value (Danthurebandara et al., 2015b; Jones et al., 2013; Quaghebeur et al., 2013). Given the characteristics of plasma gasification, it represents an interesting thermal treatment alternative to incineration for ELFM. The study is based on the analysis of a two-stage plasma gasifier that combines a fluidized bed gasifier and a plasma rector (Bosmans et al., 2013; Evangelisti et al., 2015b; Materazzi et al., 2016). The utilization of high-quality syngas is limited to power production via a combined gas turbine cycle with a steam turbine (Uytterhoeven, 2017). Based on the conducted review on the plasma gasification of solid waste, the causal/mathematical relations between process parameters, the materials and energy input requirements, and the resource recovery potential of the technology were defined. In particular, the waste composition (site-level) and the gasifying agent (project-level) determine the syngas yield and composition. Parameters such as carbon content, moisture content, ash content, and calorific value (LHV) affect the syngas quality and composition, the other by-products, and the environmental and economic performances. The choice of gasifying agent and the amount of oxygen used also influence the composition, and quality, of the syngas (Agon et al., 2016; Arena, 2012; Lemmens et al., 2007; Materazzi et al., 2016; Mountouris et al., 2006). While oxygen (O_2)-based gasification could lead to a high syngas heating value, around 28 MJ/Nm^3, the expensive oxygen production processes could outbalance the benefits of increased syngas quality. On the other hand, air is the cheapest alternative but yields syngas with a lower calorific value and lower quality. Steam gasification, or steam and O_2, is an intermediate alternative that can lead to syngas heating values from 10-18 MJ/ Nm^3 (Singh et al., 2017). In plasma gasification, the high temperatures reached in the process lead to the vitrification of the solid residues. The characteristics of the vitrified slag could allow for its valorization in higher-added value products, avoiding the production of primary materials and minimizing the landfilling of this by-product (Danthurebandara et al., 2015b; Evangelisti et al., 2015b). The choice of the above-mentioned factors, coupled with the constant variability of system-level conditions, such as the background energy system or market characteristics, could lead to a wide range of environmental and economic results (Danthurebandara et al., 2015b). To this end, the assessment of the technology via the integrated framework could provide relevant insights for project development.

2.2 The proposed framework

The framework proposed in this study adopts, extends, and applies the concepts of statistic design of experiment (DOE). DOE is a step-wise procedure that accounts for the effect of the variation of different process input variables on the process output variables within the system boundaries considered (NIST/SEMATECH, 2012). By doing so, efficient planning of process experiments can maximize the amount of gathered information for the amount of experimental effort. The factor-based approach, in particular, focuses on the full factorial design method to screen critical factors for the performance of emerging concepts and technologies (Figure 1). Overall, the main features of the approach can be summarized in (Step A) generating a multitude of technological design scenarios through factorial combination, (Step B) assessing environmental and economic performance through LCA and life cycle costing (LCC), respectively, and (Step C) systematically determining the critical performance factors through global sensitivity analysis.

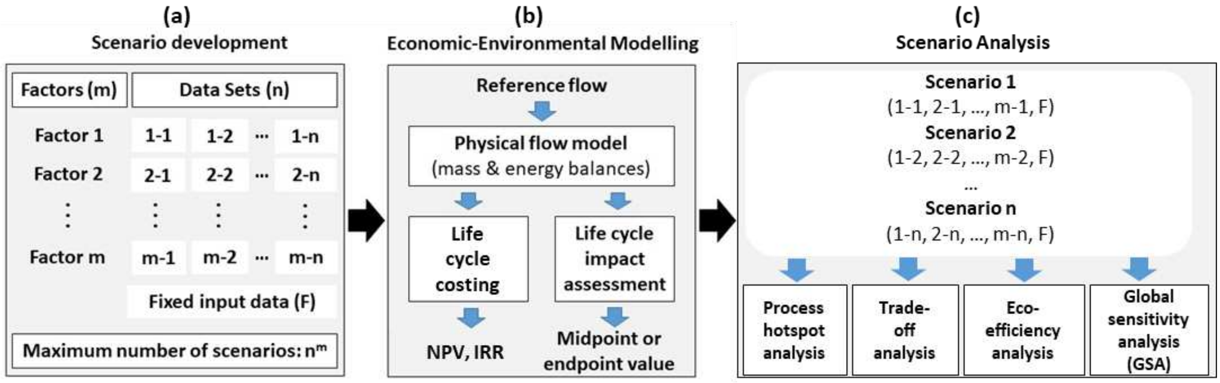

Figure 1. Schematic illustration of full factorial design approach for the integrated assessment of the critical factors for the economic-environmental performance of emerging concepts and technologies, consisting of three main steps: (a) scenario development, (b) economic-environmental modelling and (c) scenario analysis. The approach was adapted from Laner et al. (2016, 2019)

The novelty of the proposed integrated framework, compared to the factor-based approach of Laner et al. (2016, 2019), lies in the integrated economic and environmental assessment (Step B) and, more importantly, in the subsequent analysis of results (Step C). This final step includes (i) process hotspot analysis, to understand the main contributing processes to the overall impacts; (ii) trade-off analysis to compare scenario results from the economic and environmental perspectives; (iii) eco-efficiency analysis, to integrate the results and (iv) global sensitivity analysis for developing an in-depth understanding of what factors and conditions that build up both the individual and integrated environmental and economic results.

2.2.1 Scenario development

In this step, a systematic scenario generation is performed by first selecting relevant factors (m) and data sets (n). Factors are the system variables, which can be interpreted as modules or conditions. They can refer to overarching conditions, including site level (local context), project level (technological and organizational aspects, upscaling possibilities), and system level (background and exogenous conditions, such as policy and regulation aspects) that are relevant to the environmental and economic assessments. Data sets, on the other hand, refer to several possible alternatives for the parameters that define each factor. Data sets can be exploratory or extreme, the latter considering the best and the worst cases. The choice of the factors (m) and data sets (n) is strictly related to the goal and scope of the study. In the studied case of plasma gasification, they are determined based on the literature review, which also accounts for case studies, companies' reports, and existing models, and is iteratively developed with the knowledge from various experts. The full factorial combination of all the data sets (n) in each factor (m) corresponds to the multiple generations of scenarios (n^m). In the case of unrealistic combinations, factorial constraints can be introduced to eliminate these scenarios. This is also part of the iterative process involving the experts. Similarly, fixed factors are also determined based on the goal and scope of the study. These represent those processes or factors whose variation is either considered as not critical for the performance of the system or not included in the scope of the study.

To assess the performance of plasma gasification and its potential for resource recovery from excavated landfill waste, 7 factors were identified based on the reviewed studies (Figure 2). The 7 factors with their 3 related data sets are provided in Table 1 and lead to a total of 3^7 (2187) scenarios. Each factor is further defined by a set of parameters that characterize the factor itself and give the possibility to build energy and mass balances. The values of the parameters vary within each dataset. A description of the factors and data sets chosen is provided below, and further details are reported in the Supplementary Materials (SM).

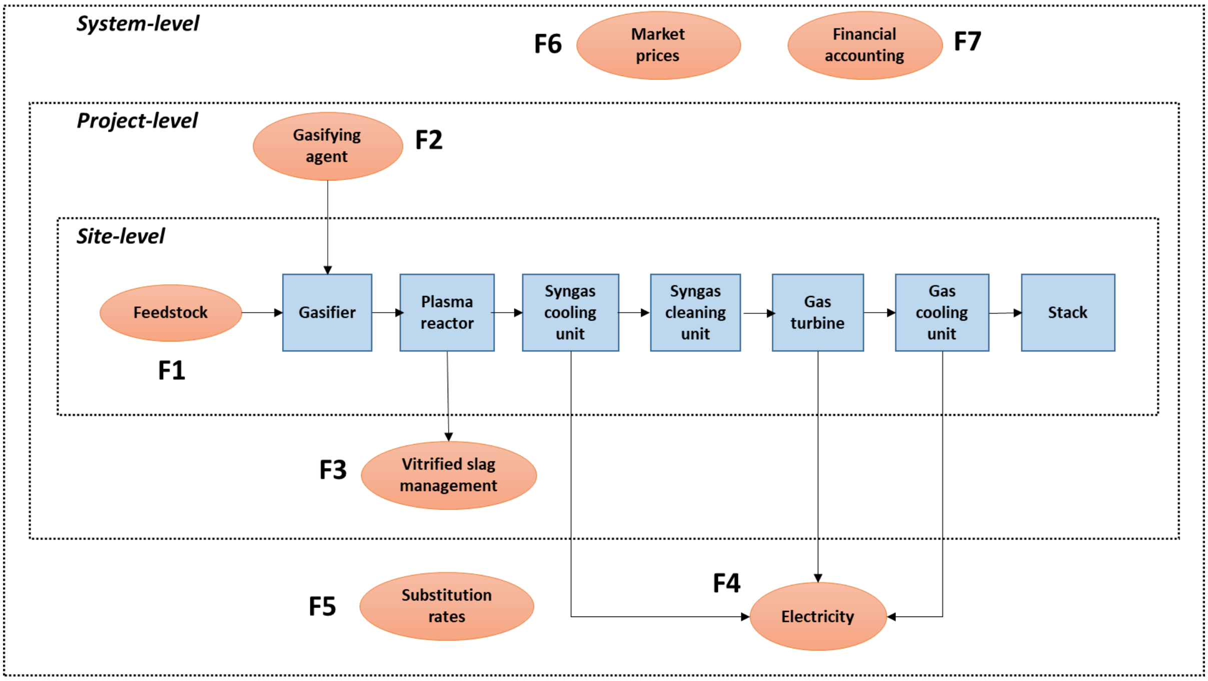

Figure 2. Schematic overview of the system design and processes included in study, and the identified factors. The factors (F1-F7) are highlighted in orange. The process design is adapted from Uytterhoeven (2017) and includes all processes, from the thermal processing of the feed to the syngas valorization and the vitrified slag treatment.

Table 1. Summary of the factors and data sets used for the integrated environmental and economic assessment of plasma gasification. A further explanation of the factor choice and description of the data sets can be found in the Supplementary Materials.

Factors	Type	Description	Set 1	Set 2	Set 3
F1	**Site**	Feedstock composition	Unsorted excavated waste	Average-sorted excavated waste	Highly sorted excavated waste
F2	**Project**	Gasifying agent	Air	O_2	Steam + O_2
F3	**Project**	Slag management	Landfill	Aggregates	Inorganic polymer
F4	**System**	Background energy system	Coal-based energy mix	Average EU mix	Highly renewable energy mix
F5	**System**	Substitution rates	Low	Average	High
F6	**System**	Market prices	Low	Medium	High

F7	**System**	Financial accounting	Low	Medium	High

Factors 1-3 represent the site- and project-level factors, including variations in waste feedstock composition and the technology design and set-up of the plasma gasification process. The parameters that define the factors consist of energy and material flows that allow energy and mass balances. Factors 4-7 represent system-level factors instead, referring to the background energy mix and the market and policy conditions or potential future evolutions that can influence the resource recovery potential of the technology. The parameters that define these system-level factors include environmental and economic parameters that serve to define the final economic and environmental results.

Feedstock composition (F1), and its data sets, reflect the potential spatial and temporal variation of excavated landfill waste composition. The aim is to understand to what extent the waste composition can influence the process performance and resource recovery potential of plasma gasification. The three alternative data sets for F1 were defined with different carbon and ash content based on three potential levels of pre-treatment of excavated waste, from minimum mechanical processing to advanced processing plants.

The choice of **gasifying agent (F2**) reflects the trade-off between syngas quality and the upstream processing required. The data sets chosen include parameters on the electricity required to produce the oxygen via the cryogenic process, the amount of gasifying agent required, and the different syngas compositions and amounts obtained. They also include other process requirements strictly related to the gasifying agent choice, such as the plasma torch power required and the need for pressure swing absorption in the case of air-gasification before the gas turbine.

Slag management (**F3**) alternatives include three possible treatment solutions that could lead to significant differences in the environmental and economic results: landfilling, aggregates production as a substitute for natural gravel, and inorganic polymer production as a substitute for OPC cement (Danthurebandara et al., 2015a). The parameters included in the data sets represent the material and energy requirements for the different treatment options.

The **background energy (F4)** refers to the background processes for conventional power and heat generation. The alternative data sets range from a heat and electricity mix with a high fossil share, to the European average mix, to a mix with a high renewables share. This factor addresses geographic variations (country-related) and potential future variations in the background energy system due to policy interventions.

Substitution rates (F5) are related to the market acceptance of the products and thus to socio-economic conditions and trends. In particular, the marketability of the products is defined by market quality standards and by country-specific regulations for their use (Hernández Parrodi et al., 2019; Šyc et al., 2018, 2020). Moreover, market saturation could further impede their marketability in terms of low demand. Therefore, substitution factors are defined to consider the quality of the product and the potential spatial and temporal variation of its marketability.

Market prices (F6) for the recovered resources such as materials and energy refer to the volatility of the market. The factor addresses the variability of the market by assigning low, medium, and high market prices to the recovered resources. This includes immediate valuable resources such as valorized slag, heat, and/or electricity. The market prices for the secondary resources are estimated by including their market value and the costs for their treatment up to the market gate.

Financial accounting parameters (F7) refer to the risk level of the market. The parameters are the discount rate, the interest rate, and the depreciation rate. These, in one way, can be interpreted depending on whether a certain asset is privately or publicly owned with corresponding high and low rates, respectively.

2.2.2 Environmental and economic modelling

In this step, the mathematical relations between factors are defined. This allows the building of material and energy flows in combination with fixed factors. The material and energy flows defined in this step serve as the common basis for calculating both the economic and environmental results.

A simplified model of the plasma gasification process was built in Aspen Plus v11 to define the relationship between the waste composition, gasifying agent, and syngas composition (Byun et al., 2012; Materazzi et al., 2013; Zhang et al., 2012). It was used to model the process in the minimization of Gibbs free energy, and included the RYield and RGibbs processes as main components (figure and more detailed description of the model can be found in SM). For each combination of factors F1 and F2, the model allowed to estimate the amount of gasifying agent, the amount and resulting composition of the syngas in terms of CO, H2, CO_2, CH_4, H_2O, N_2, and O_2. Moreover, the plasma power required to heat the syngas and crack the tars was estimated. The results obtained for the main operating parameters are reported in Table 2. The results are somewhat in line with the literature (Evangelisti et al., 2015a; Materazzi et al., 2016; Mazzoni & Janajreh, 2017; Paulino et al., 2020), although differences exist due to the different feedstock used and goal of the studies, as well as the assumptions and simplifications made in this study. In the estimation of the vitrified slag amount, a mass balance approach was instead adopted, assuming that all input ash would be converted into it. For the other processes, thermodynamic and chemical relations were used to model the energy and mass balances. These calculations were based on the work of Uytterhoeven (2017) and were performed on MATLAB and MuPAD Notebook, with Excel used as support. The use of such models, with simplifications and assumptions, is considered well-suited in an early assessment, or, as in this case, when the influence of several parameters needs to be discussed and the process and technological design optimized (La Villetta et al., 2017; Tsoy et al., 2020; Van der Giesen et al., 2020). It allows to increase the representativeness and reproducibility of the data and reduces the related uncertainties due to upscaling and data availability in ex-ante LCA (Van der Giesen et al., 2020). A more detailed description of the system model can be found in the SM.

For the estimation of the economic and environmental performances, LCC and LCA are adopted, respectively. LCA and LCC assess the impacts and costs over the life cycle of a product or system following the same framework (ISO 14040:2006). The definition of the functional unit (FU), system boundaries, and time frame common to both assessment tools allow comparability between the results and ensure their consistency. Common indicators for economic performance are the net present value (NPV) through discounted cash flow analysis and the internal rate of return (IRR) from the perspective of certain investors (Brealy et al., 2011). Environmental results can instead be defined in terms of midpoint or endpoint impact categories through an LCA.

The goal of the study was to assess the environmental and economic performance of plasma gasification for resource recovery from excavated landfill waste under varying conditions. The FU chosen for the study is the thermal treatment of 1 kg of pre-treated excavated landfill waste, here referred to as refuse-derived fuel (RDF). The choice allows comparability with related assessments of landfills and other waste management systems. The reference flow, which is the flow used to estimate mass and energy balances throughout the system operation, is instead considered as 36 t/h, which represents an average processing capacity of 285 ktons/year. This is defined according to an average industrial-scale WtE plant that processes around 860 tonnes per day (tpd) of waste (Ducharme et al., 2010). The choice of a time-related reference flow is linked to the aim of integrating environmental and economic assessment, thus harmonizing their scope. The technology is assessed over 10 years, with a 90% availability rate, leading to 7920 h/year of operation. For the LCA, substitution is applied by expanding the system boundaries and including the avoided burdens of primary production to account for the multifunctionality of the system (JRC, 2010). Moreover, a distinction is made between foreground and background systems, where foreground refers to the processes under study, while background refers to the processes that interact with the foreground system by providing materials and energy (Clift et al., 2000). The resulting system boundaries (Figure 3) include the processes for the thermal valorization of the waste and power generation, cleaning of the syngas, treatment of residues, and avoidance of production of the recovered resources (materials and energy). In the case of slag management, a simplified approach was adopted, addressing only the production of the aggregates and IP and the avoided production of the corresponding primary materials. No further impacts are included related to the use phase of the materials. This simplified approach was based on Danthurebandara et al. (2015b) and was motivated by the lack of data on the performance of the vitrified slag during the use phase. For the LCC, similar system boundaries are considered, except for the inclusion of investment costs for the technologies in the economic assessment. The impacts of capital goods are not taken into account in the environmental assessment. This choice was made as it represents a common approach in previous studies (Arena et al., 2015; Danthurebandara et al., 2015b; Evangelisti et al., 2015b), and for comparability purposes with the same studies. These considerations, coupled with the often lack of data on emerging systems, have further motivated the choice.

For the economic assessment, data is obtained from similar processes from the literature. It is then adapted to the production capacity, as well as according to geographical and temporal variations (for market prices). Economic results for all scenarios are calculated as the difference between the discounted revenue and cost items per scenario (Eq. 1), whereC_0 represents the initial investment, C_t is the cash flow in a specific year (t), i [%] is the inflation rate, and d [%] the interest rate. The NPV is calculated over the 10 years operation period (T=10).

$$NPV = -C_0 + \sum_{t=1}^{T} \frac{C_t * (1+i)^t}{(1+d)^t} \qquad \text{(Eq. 1)}$$

Foreground data for the LCA was derived from the modeling of the technology and the literature, and main parameter datasets are provided in the SM. Background data was instead based on the Ecoinvent database (see SM). To provide the temporal and spatial representativeness of different geographical settings and future variations to the background processes, ranges of processes were used (Thomassen et al., 2019). The environmental impacts, or savings, were then calculated in Matlab based on the input data and the results of the modeled energy and mass balances. Five midpoint impact categories were considered: climate change (GWP) [kg CO_2 eq.], acidification potential (AP) [Mol H+ eq.], resource depletion, mineral and fossil (AD) [kg Sb eq], ecotoxicity (freshwater) (ET) [CTUe] and human toxicity (HT) [CTUh]. These categories were chosen for comparability as they are commonly used categories in literature studies related to either slag management or plasma gasification and WtE (Danthurebandara et al., 2015b; Evangelisti et al., 2015b, 2015a). The ILCD methodology was chosen for the impact assessment (European Commission - JRC, 2011).

Table 2. The table summarizes the results of the Aspen model for the main parameters. Values are reported per kg of feedstock, in line with the FU chosen and to allow comparability with previous studies. The results are more or less in line with the literature, where the W_{torch} is expected to vary with the calorific value, ash and moisture content of the feedstock and has been estimated to have value of around 0.15-0.2 kW/kg. Regarding the CGE, reported values range from above 70% to around 90% (Materazzi et al., 2016; Paulino et al., 2020)*. Such values are in line with the ones for scenarios with O_2 as GA. This is due to the feedstock and GA used in the study, which lead to higher LHV for the syngas (*Materazzi et al., 2016)*. The net plant efficiency is lower than previous literature studies (Evangelisti et al., 2015a; Mazzoni et al., 2017; Uytterhoeven, 2017) due to the assumptions and simplifications made in the modeling of the system in this study.*

F1	**F2**	**Cold Gas Efficiency (CGE) [%]**	**$LHV_{feedstock}$ [MJ/kg]**	**LHV_{syngas} [MJ/kg]**	**GA/Fuel ratio**	**W_{torch} [kW/kg]**	**P_el net [kW]**	**Net plant eff. [%]**
1	1	56%	15.64	3.03	2.36	0.28	0.44	10%
1	2	71%	18.55	10.22	0.42	0.15	0.58	13%
1	3	61%	23.43	6.75	0.78	0.19	0.72	17%
2	1	58%	15.64	3.34	2.64	0.30	0.52	10%
2	2	72%	18.55	10.95	0.47	0.16	0.68	13%
2	3	62%	23.43	7.18	0.89	0.21	0.84	16%
3	1	59%	15.64	3.66	3.06	0.34	0.63	10%
3	2	72%	18.55	11.95	0.57	0.17	0.82	13%
3	3	65%	23.43	8.22	1.03	0.23	1.01	15%

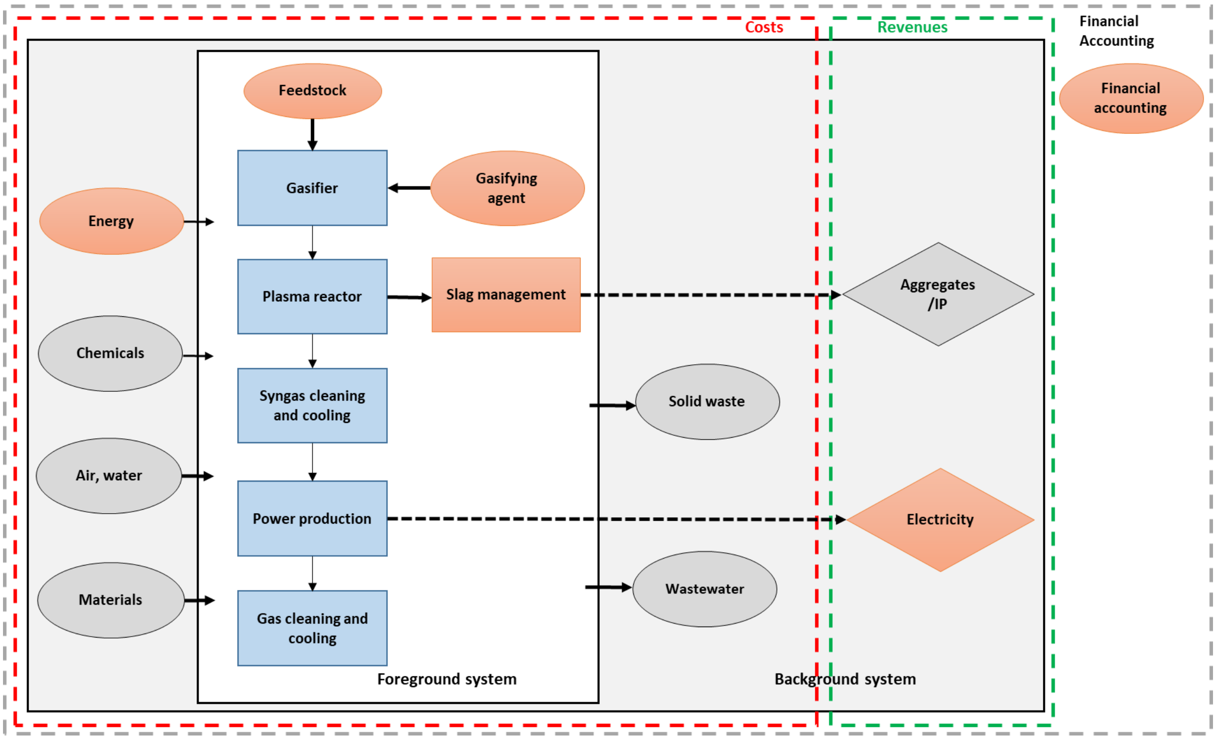

Figure 3. System boundaries considered for the LCA and LCC models. For the LCA, a distinction is made between background and foreground system, while for the LCC the distinction is based on costs, revenues and financial accounting. The circles represent flows, the rectangles represent the processes addressed in the study, and the diamond-shaped figure the output products. The orange color refers to the processes or flows considered as critical factors in the analysis.

2.2.3 Analysis of scenario results

In this step (C), four analysis procedures are proposed highlighting the added value of each step to the overall understanding of the technology performance. The increasing depth of analysis is shown from the net economic and environmental performance to a more fine-grained understanding in terms of hotspot analysis, trade-off analysis, eco-efficiency analysis, and the identification of important underlying factors through global sensitivity analysis (GSA).

The hotspot analysis allows for the partitioning of the total scenario results, both environmental and economic, in terms of the main contributing processes. GSA, specifically variance-based sensitivity analysis in which the choice of alternative data sets of a factor is addressed, is instead used to investigate the criticality, or relative importance, of each factor to the variance of the scenario results (Laner et al., 2016, 2019; Saltelli et al., 2019). This addresses the assessment challenge of systematically handling the uncertainties and identifying the critical factors and their interrelations to understand the wide variations of the results. Two types of sensitivity indices are calculated. The first-order sensitivity index represents the contribution of one-factor variation to the output variation. The total effect sensitivity index, in contrast, represents the effect of factor *i* on the results while also integrating its interactions with all other factors. With these indices, it is then possible to show the relevance, or not, of specific factors in the environmental and economic performance of the process under study. This analysis enables a fine-grained assessment of the environmental and economic performances and what drives the results and is the core of the factor-based approach presented by Laner et al. (2016, 2019). Further information on the concept and calculations can be found in Laner et al. (2016, 2019).

To comply with the objective of the study of integrating environmental and economic results, two further analysis procedures are included in the framework. In the trade-off analysis, total scenario results are mapped in a two-dimensional economic-environmental plot allowing the observation of the distribution of either economically- or environmentally favorable scenarios, or both. Eco-efficiency indicators, defined as the ratio between the economic influence (EI) and environmental impact (EN), are then considered. This perspective, as also defined by the World Business Council for Sustainable Development (WBCSD), aims to estimate the environmental productivity or improvement cost of the system under study (Baptista et al., 2015; Cha et al., 2007; Michelsen et al., 2006; Saling et al., 2002; Verfaillie & Bidwell, 2000). The equation for the estimation of the eco-efficiency scores is provided below.

$$Eco-efficiency\ indicator(i) = EE_i = \frac{EI}{EN_i} \qquad \text{(Eq. 2)}$$

EI is the economic indicator, *EN* the environmental result for the *i*th impact category. Differently from previous studies, where environmental impacts are aggregated into a single score following normalization and weighting steps (Hermann et al., 2016a, 2016b; Kicherer et al., 2007; Saling et al., 2002), different eco-efficiency indicators are estimated within the framework for different impact categories (EE_i, with *i* referring to the impact categories chosen). The subjectivity of normalization and weighting factors can substantially increase the uncertainty of the results and assessment (Saling et al., 2002; United Nations, 2009). Considering different environmental indicators enables to address different impacts and targets, leading to a broader overview of effects. GSA is further performed on the eco-efficiency scores to provide additional information on the main contributing factors and the extent to which they influence them. This allows for an understanding of which factors or conditions to improve to achieve better-integrated performance.

To graphically analyze the eco-efficiency results, adjustments are required for a clearer representation and understanding of the results (Hermann et al., 2016a). If the eco-efficiency score has a negative sign, it means that the ratio has an opposite sign quotient. This would lead to no clear preference again. The results would then not allow an understanding of which, between the numerator and denominator, has a negative value, leading to limited interpretation. As in Hermann et al. (2016a), scenario results (x_i) are adjusted by adding a fixed amount, which in this study is two times the absolute value of the minimum result (x_{min}) This allows the shifting of all indicators to positive and non-zero values, maintaining the same results distribution and enabling the comparison (eq. 3).

$$x_{adj} = x_i + 2 * |x_{min}| \qquad \text{(Eq. 3)}$$

Although the adjusted eco-efficiency scores do not represent the actual results in terms of absolute value, they enable comparison between scenarios and allow a graphical analysis of the results. As the aim of the framework is not to identify the best-performing scenario but the driving factors behind them, this approach is considered adequate. In particular, better performance efficiency is achieved with large economic values and small environmental impacts. Considering the definition of eco-efficiency, higher scores for the adjusted indicators indicate better integrated performance efficiency.

Nevertheless, it must be considered that the use of eco-efficiency indicators to support decision-making entails limitations. As for LCA, results are relative to the scope of the system and the modeling (Ehrenfeld, 2005). Moreover, eco-efficiency is limited to only two of the three dimensions of sustainable development, neglecting the social dimension. This would call for additional approaches to integrating the results to support decision-making (Park & Kumar, 2014). Additionally, eco-efficiency indicators help identify the better choices among a set, giving a relative value to the results. This could shift the focus away from more effective solutions (Ehrenfeld, 2005).

3. Results and interpretation

3.1 Net environmental and economic results

A summary of the environmental and economic results for the 2,187 generated scenarios is provided in Table 3 in terms of maximum, average, and minimum. The environmental impacts for each category are estimated as the difference between the environmental burdens (positive value) and environmental savings (negative value). Contrarily, the economic results are estimated as the difference between the total costs (negative value) and the total revenues (positive value). The wide range of results can be attributed to the variation of the factors addressed. This highlights the contribution of multiple scenario development in covering the possible variations in terms of site, project, and system levels, addressing the assessment challenge of accounting spatial and temporal variations. Such broader knowledge contribution provides more information on risks by showing how much can the environmental and economic performances vary. However, the presented net results only provide a general understanding of the system performance as they do not provide any additional information on the main influencing processes and factors. This limits the value of the results in identifying measures to improve the performance and assess how this performance changes under the varying site, project, and system conditions.

Table 3. Summary of results for the five environmental impact categories. The results are expressed in unit per kg of waste. Moreover, only the maximum (max), minimum (min) and average (ave) values of all scenarios are reported. [GWP= climate change; AP = acidification potential; AD= resource depletion; ET= ecotoxicity; HT = human toxicity].

	GWP [kg CO2 eq.]	AP [Mole H+ eq.]	AD [kg Sb eq]	ET [CTUe]	HT [CTUh]	NPV [Euro]
Maximum	0.0419	0.0085	0.0000	1.3496	0.0000	-0.7103

Minimum	-0.9272	0.0022	-0.0007	-6.8724	-0.0007	-5.6448
Average	-0.2776	0.0057	-0.0001	-1.5112	-0.0001	-2.5021

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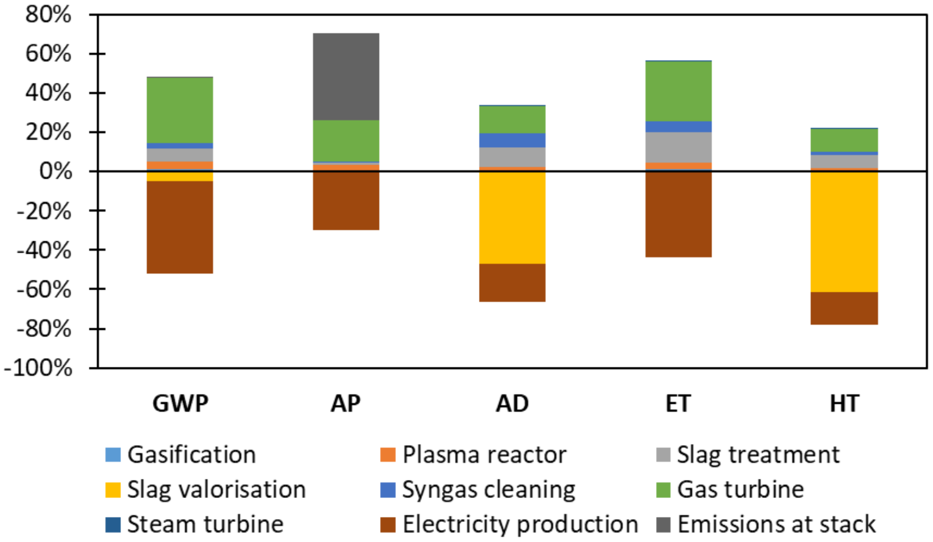
3.2 Hotspot analysis

The analysis is extended to identify the critical factors through a hotspot analysis, which specifies the contribution of processes to the overall environmental and economic performance. Such information provides a good basis for which processes should be addressed to improve the results. The hotspot analysis conducted on the environmental impact highlights the influence of energy-intensive processes on the results of GWP, AP, and ET (Figure 4). In particular, the main contributing processes, with shares between ± 21% (AP) and 33% (GWP) are the gas turbine (between 21% for AP and 33% for GWP), due to the energy required for the compression of the combustion air, and the electricity production of the process (between 19% for AP and 47% for GWP). Different results are obtained for AD and HT, where the main contributing processes are related to slag management, with high avoided impacts obtained in both categories (47% and 62% respectively). Slag management and energy requirements for the gas turbine step are also the main contributing processes to the economic results (Figure 4). The revenues from electricity production and slag management do not compensate for the corresponding costs, as also shown in Table 3. For slag management, the re-landfilling costs are more significant than the revenues from slag valorization, either as aggregates or inorganic polymers.



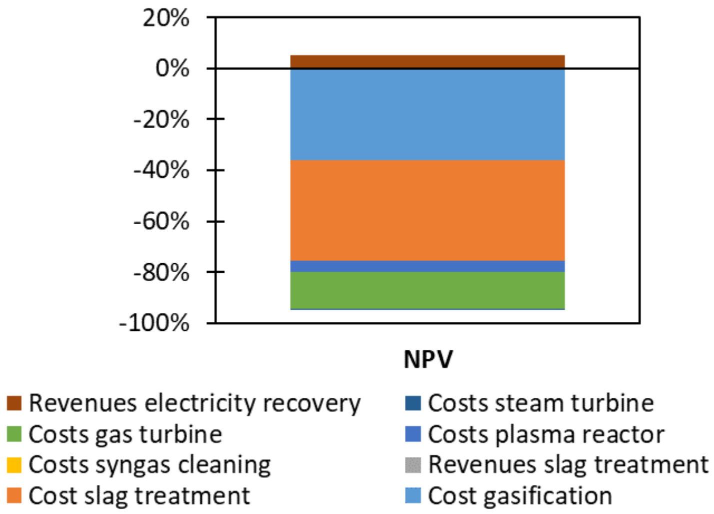


Figure 4. Hotspot analysis for the environmental and economic results. The average contributions are expressed as a percentage (%) of the total. The results are plotted to show the main processes influencing the negative results (avoided environmental burdens and costs) and the positive-valued results (environmental impacts and revenues).

Nevertheless, in both cases, average contributions are estimated on the average results of the 2,187 scenarios. Variations in the results of the hotspot analysis are expected among scenarios based on the considered variations among the factors. Moreover, the hotspot analysis limits the understanding on an aggregated level by only specifying the more influential processes over all the 2,187 scenarios, generalizing the results and consequently reducing their temporal and spatial representativeness. It does not allow a fine-grain understanding of which factors and their interrelations that build up and drive these results.

3.3 Global sensitivity analysis

The total order sensitivity indices obtained for all results categories are reported in Table 4. Across different impact categories, it is shown that different factors are accountable for the variation of the respective results. For example, the main factors influencing climate change results are the background energy system, gasifying agent, slag management, and quality of the feedstock. In contrast, the categories of resource depletion and human toxicity are mainly influenced by the slag management and substitution factors, and to a lesser extent, by the quality of the feedstock. The other categories also differ. For the proceeding discussion, only climate change and NPV will be analyzed in more detail. However, results for all other impact categories are reported in the SM.

Table 4. Summary of the results of the global sensitivity analysis. The total order sensitivity indices are reported for all result categories and adjusted eco-efficiency indicators. It should be considered that the double-counting of the effects of the interactions between factors leads the sum of the total order sensitivity indices for each category to be >1.

	F1 Feedstock	F2 Gasifying agent	F3 Slag valorisation	F4 Background energy	F5 Substitution factors	F6 Market prices	F7 Financial accounting	Total
GWP	0.0404	0.1256	0.0466	0.8491	0.0257	-	-	1.0874
AP	0.4769	0.2357	0.0037	0.4046	0.0049	-	-	1.1259
AD	0.1427	0.0005	0.8531	0.0005	0.3063	-	-	1.3031
ET	0.0673	0.1201	0.0148	0.8648	0.0005	-	-	1.0674
HT	0.1437	0.0005	0.8533	0.0005	0.3029	-	-	1.3007
NPV	0.0177	0.5542	0.0005	-	0.0005	0.5364	0.0554	1.1093

The results of the global sensitivity analysis for the climate change impacts show that the main factor influencing the results is the background energy mix (Figure 5). Scenarios with a coal-based energy mix result in higher climate savings due to the higher benefits associated with the avoided production of electricity. The environmental benefits are then higher for scenarios where steam + O_2 is used as gasifying agent. The choice of gasifying agent, the second main influencing factor, influences the yield and composition of the syngas, and therefore the energy recovery potential. With air gasification, the energy recovery potential is lower than for the other scenarios. While oxygen-based gasification would result in syngas with higher LHV, the electricity requirements for the production of pure O_2 reduce the benefits, making steam-based gasification better performing. This is expected to be related to the higher syngas quality obtained compared to air gasification, the lower O_2 requirements compared to O_2-based gasification, and the use of recirculated steam produced within the process. However, it can be seen how, with the variation of the background energy mix, the difference between scenarios decreases due to the lower influence of the recovered electricity in scenarios with a renewable energy mix.

The third and fourth factors are slag management and feedstock quality. The results show the benefits obtained from the production of IP from vitrified slag. However, such benefits are also strictly connected to the background energy system and to feedstock quality. In particular, for a renewable energy mix, the benefits obtained from the production of IP are higher than for other scenarios, due to the lower influence of energy recovery. This is also confirmed by the fact that in these scenarios a low-quality RDF is preferred, as it represents a higher ash content and slag produced. For scenarios with a coal-based energy mix, instead, the production of IP leads to higher benefits than other slag management options, but the differences are not as extended. This is because, in these scenarios, energy recovery is the main contributing factor to the climate change impact, leading to a preference for high-quality RDF. This type of RDF, with a high carbon (C) content, leads to the production of a higher amount of syngas. For the scenarios with an average electricity mix, IP production leads to great benefits, but the choice between RDF types is not as strict, although low-quality RDF seems to have a slightly better performance. The scattered results for scenarios with IP production are then due to the substitution rates, which determine the extent of the avoided production of the primary OPC cement.

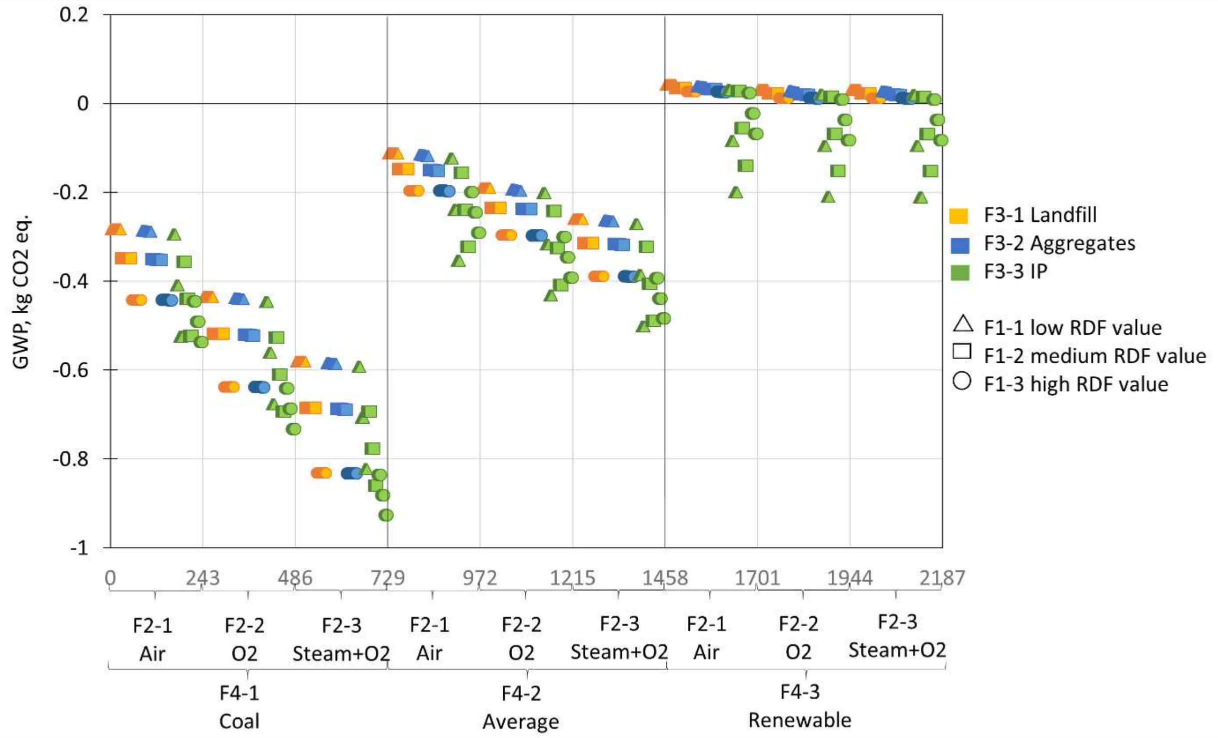


Figure 5. Results for the climate change category, plotted according to the four main contributing factors resulting from the global sensitivity analysis. In particular, the results are plotted to show the influence of, in order of criticality, the background energy mix (F4), gasifying agent (F2), slag management alternative (F3) and quality of RDF (F1). Three colors are used to distinguish between datasets for the 3rd influencing factor. Shapes allow distinguishing between the datasets of the 4th influencing factor.

Results of the global sensitivity analysis for the economic impacts highlight the influence of the choice of gasifying agent, followed by, in order, the market prices, level of financial accounting, and RDF quality. As shown in Figure 6, the economic results are mainly driven by the first two factors. The importance of the gasifying agent is strictly related to the market prices, particularly for O_2- and steam +O_2-based gasification. In these scenarios, the high costs for the production of O_2 are not compensated for by the revenues from the electricity produced by the process. O_2-based gasification presents overall higher costs, with the latter increasing with increasing price ranges. Steam gasification presents a similar trend, with slightly lower costs. For air gasification, the scenarios instead present the lowest costs and overall better NPV results due to the lower costs for GA compared to the other scenarios. The influence of the feedstock quality is instead minor, although the higher the price range, the higher the influence of the RDF quality and its corresponding carbon content. In O_2- and steam-based gasification, this is due, as mentioned for the climate change impacts, to the higher O_2 requirements to sustain the gasification of high amounts of C. In general, high value-RDF is preferred due to the higher amount of syngas that can be obtained. Moreover, as costs generally dominate the economic performance, the high discount rate is shown to improve the NPV with a reduced present value of the costs.

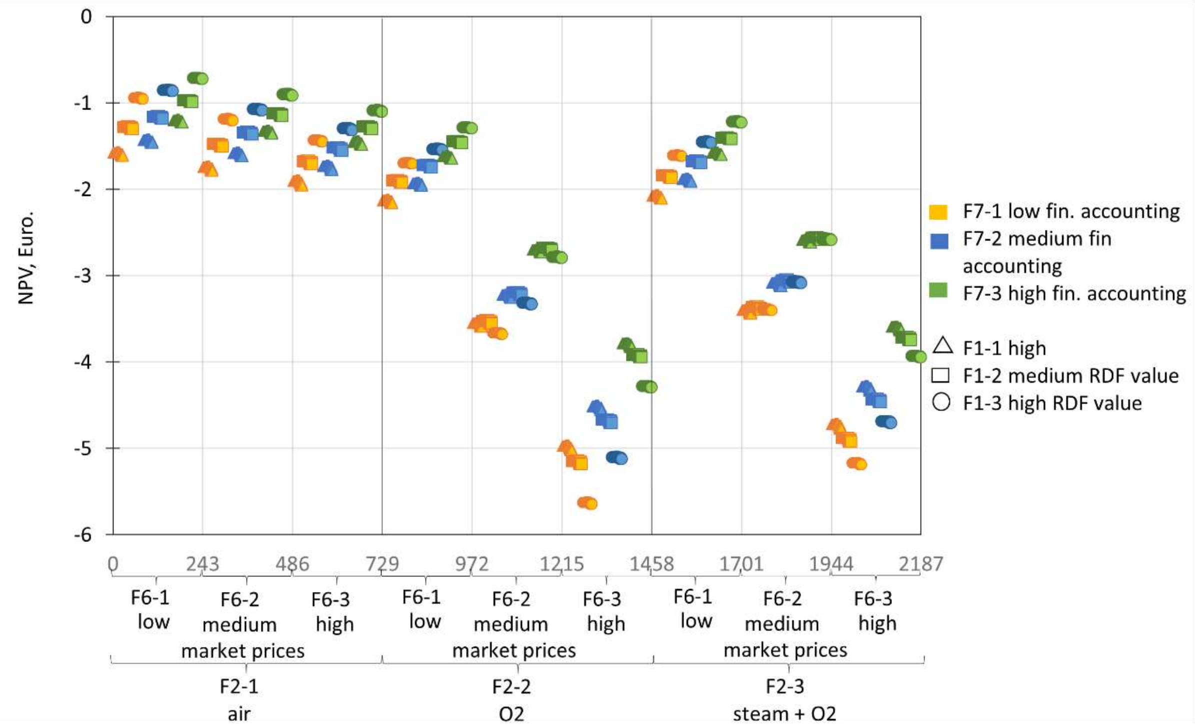


Figure 6. NPV results plotted according to the four main contributing factors resulting from the global sensitivity analysis. In particular, results are plotted to show the influence of, in order of criticality, the gasifying agent (F2), market prices (F6), level of financial accounting (F7) and quality of RDF (F1).

The overall environmental and economic results show different trends, as for climate change a high RDF quality and steam+O2-based gasification would perform better, differently from the economic results where air-based gasification with low-quality RDF could be more economically viable. The differences in results would then lead to difficulties in decision making, penalizing either one of the perspectives while improving the other.

3.4 Trade-off and eco-efficiency analyses

To avoid the crossroad and support the development of emerging systems considering both perspectives, the framework includes two further analysis procedures: trade-off and eco-efficiency analyses. The trade-off analysis results were analyzed for a first assessment to graphically situate the scenario results in the four quadrants (I-IV in Figure 6) and understand the overall combined economic and environmental performance.

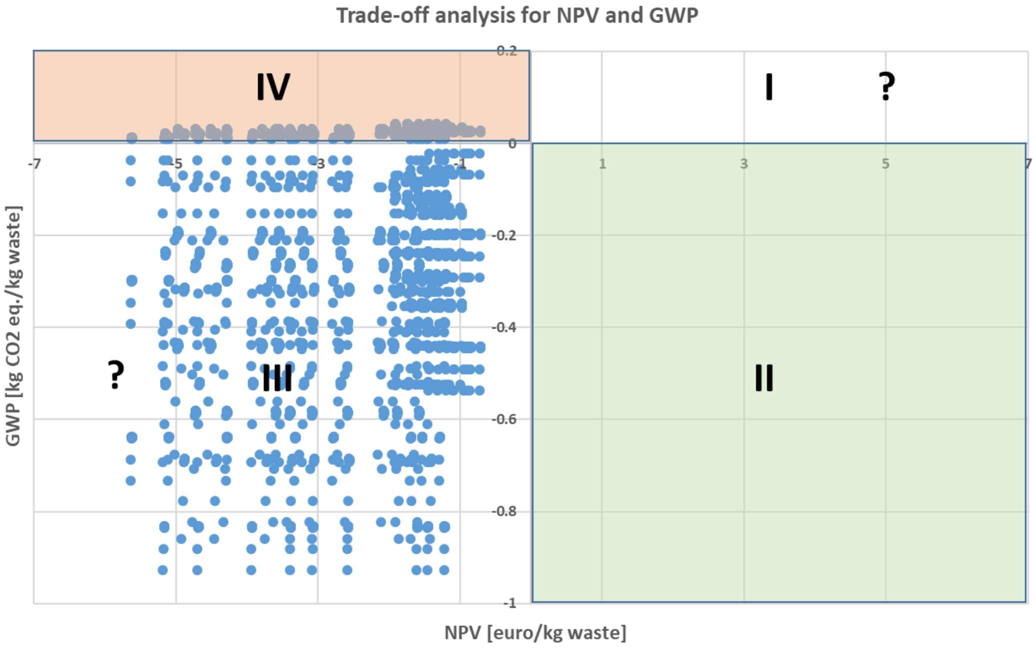


Figure 7. Trade-off analysis between climate change (GWP) and economic (NPV) results.

However, trade-off analysis has limited applicability to support decision-making and technology development (Hermann et al., 2016a; Saling et al., 2002; Vercalsteren et al., 2010). The information provided in the graph (Figure 7) is limited to identifying scenarios that are overall performing positively or negatively in both categories (Quadrants II and IV, respectively). The scenarios in Quadrants I and III indicate scenarios that only have a positive performance from either the economic or environmental perspective. Scenarios in these quadrants are more complicated to be used as a basis for decision-making, as they result in “limited preferability” and require additional analysis (Hermann et al., 2016b, 2016a). Furthermore, the goal of the framework is not to identify the best performing scenario but to understand under which conditions, design/set-up, and waste composition the adoption of technology could be environmentally and economically feasible and preferable. To this end, eco-efficiency indicators are computed for all impact categories and coupled with the global sensitivity analysis. The aim is to support the graphical interpretation to identify the influencing factors for the combined environmental and economic results.

The results of the global sensitivity analysis for the eco-efficiency defined as NPV/GWP show the influence of, in order of importance, the background energy system, the slag management, the substitution rates, and the gasifying agent. To help in the understanding of how these factors influence the integrated performance, the graphical analysis of these results is performed on the adjusted eco-efficiency values, plotted as a function of the mentioned factors (Figure 8). The background energy system appears to be the main influencing factor, highlighting the higher benefits associated with energy recovery in the case of the fossil-based energy mix. However, these scenarios also show a higher variation in the results due to also the higher impacts associated with input (energy) requirements for the processing of the waste.

Regarding slag management, better results are obtained in the case of IP production and the benefits are higher for high substitution rates in all cases. On the other hand, depending on the background energy mix, different gasifying agents are preferred. In particular, for scenarios with a coal-based mix, there is a net higher benefit in the case of steam +O_2-based gasification. This is still true for an average mix, although with a lower difference from other cases. For a renewable mix, air-based gasification appears instead to be preferred, due to the lower costs and impacts associated with the production of the GA. Of interest in the analysis of the eco-efficiency scores, is the increased importance of the substitution rates. These represent the actual marketability of the recovered resources, particularly in this case of the valorized slag. High substitution rates lead to higher environmental and economic benefits due to the higher avoided impacts from the production of the respective primary raw materials, as well as to higher revenues. The significant influence of the factor shows the importance of the actual marketability of the recovered products for the WtM potential of plasma gasification.

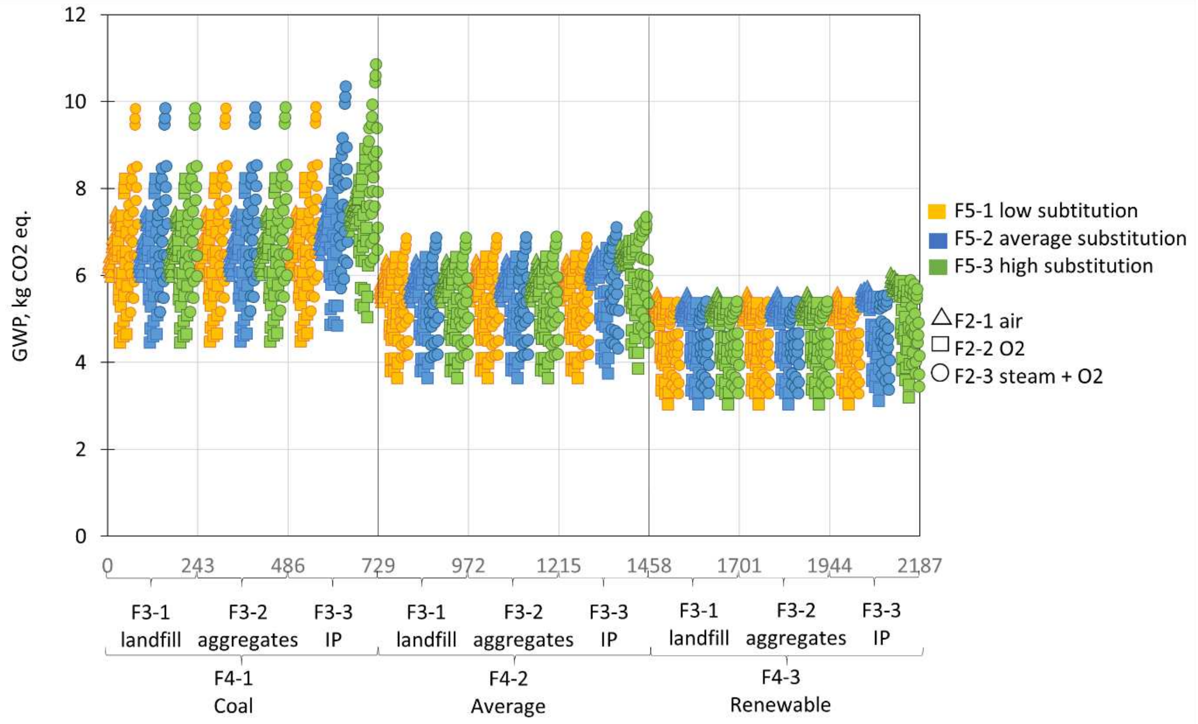


Figure 8. Results for the adjusted eco-efficiency calculated as NPV/GWP, plotted as function of the GSA results for the eco-efficiency scores. The results are therefore plotted for all scenarios according to the four main factors influencing the integrated performance. In order, these are the background energy system, the slag management, the substitution rates, and the gasifying agent. These adjusted results do not aim to represent net results but rather to graphically represent the variation in performance under varying conditions and the preferable combination of factors.

4. Discussion

The results show the additional information that can be obtained via the integrated framework in the assessment of emerging systems such as plasma gasification. The additional information directly corresponds to the assessment challenges that were addressed, such as (i) accounting for spatial and temporal representativeness, (ii) the handling of large uncertainties, and (iii) the integration of economic and environmental results. By addressing the challenges, such an approach allows to improve the usefulness and validity of the results for the development and further implementations of emerging technologies under varying conditions and project settings.

By addressing the uncertainties arising from the spatial and temporal variability of the factors at the site-, project- and system levels that define the system, the approach allows for increasing the spatial and temporal representativeness of the assessment. This leads to a significantly wide range of results (Table 3, Figure 5, Figure 6), differently from previous studies that cover specific cases (Danthurebandara et al., 2015b; Evangelisti et al., 2015a; Ramos et al., 2019). Further, it avoids the risk of early discrimination of the emerging system based on limited, case-specific, assessments. It should be noted, however, that the variations to be covered are dependent on the objective of the individual study. For studies that assess only the overall performance of a specific case study, it may not be relevant to account for wider variations and understand the underlying mechanisms of what factors drive the results. However, by addressing such uncertainties, the approach allows for increasing the validity of the assessment for different conditions and project settings.

The framework further provides the tools to identify the main influencing factors for the environmental and economic potential of the emerging technologies and understand the influence of their variation and their interconnections on the system's performance. Understanding how, and to what extent, these factors influence the performance allows to have a deeper knowledge of the underlying mechanisms that drive the performance under variable conditions. At an early stage, this increases the usefulness of the results in supporting technology development, as it allows for adapting the system to different conditions and settings, thus promoting a flexible and sustainable system design. While previous studies identified the main influencing factors for their cases, such as the background energy system, the gasifying agent, and the slag management for the environmental performance (Danthurebandara et al., 2015b; Evangelisti et al., 2015a), they did not address the dynamic relations between factors under varying conditions. The results of this study stress the importance of considering the variation of system conditions, as these dictate the environmental and economic potential of the technology, as well as the choice of preferable project conditions, such as the gasifying agent. The market prices, in the economic assessment, as well as the background energy system in the environmental and integrated performance, greatly influence the performance of the system due to trade-offs between costs/burdens and benefits.

The use of eco-efficiency and global sensitivity analysis allows for identifying the main influencing factors for the integrated environmental and economic performance. While the environmental and economic results show contradicting trends when considered separately, the integrated analysis of the results highlights the critical importance of system-level factors (background energy system and substitution rates), as well as the choice of slag management and the gasifying agent (project-level factors) on the results. Compared to previous studies that address both environmental and economic performances (Danthurebandara et al., 2015b), the integrated approach highlights the potential shift of importance of some factors over others when economic and environmental factors are considered together.

Overall, the study does not aim to give absolute environmental and economic results on plasma gasification of solid waste. Results are strictly dependent on modeling choices and assumptions made, and should therefore be treated with care and interpreted in consideration of the relevant uncertainties (Cucurachi et al., 2018; Saltelli et al., 2019). The goal of the study is, instead, to show the potential of the approach in analyzing the performance of the technology under different conditions. The analysis represents a screening approach with the overall goal to support R&D in more sustainable design and technology development. The identification of critical performance factors and their dynamic relations could support a better development process by identifying the operating parameters that, coupled with specific geographic and temporal conditions, could provide better performance. It is then important, for subsequent and future assessments, to further assess the technology with specific data, including technical experiments at pilot and commercial scales. For example, current challenges for the implementation of plasma gasification at a commercial scale have not been considered in the assessment, but are of great importance. The design and implementation of a commercial WtE, waste-to-fuel (WtF), or waste-to-hydrogen (WtH$_2$) plant, based on plasma gasification, should further address the analysis of future markets for the product, the identification of an appropriate scale for the plant, and the development of specifications for process design and output streams to optimize the process (Materazzi et al., 2019b; Ramos et al., 2019).

Limitations are inherent to all assessments and models (Saltelli et al., 2019). In the presented approach they are related to the modeling choices made, and data quality and availability. While modeling choices are inevitable and should be acknowledged in the assessment and analysis of the results, improvements can be made in the framework itself regarding the eco-efficiency scores, and data quality. Eco-efficiency indicators help identify the more efficient choices within a set and are therefore relative to the obtained results. The analysis allows to understand and improve the performance relative to the scope of what is considered possible, and thus within the set of factors and datasets considered. It does not allow, instead, to understand how to shift to more effective solutions in absolute terms (for example, shift towards Q2 in Figure 6). The eco-efficiency approach represents therefore a first step in the integrated analysis of the results. Further research should then be conducted to address this limitation. On the other hand, while the use of eco-efficiency indicators allows the assessment of the integrated environmental and economic performance to avoid trade-offs between the two perspectives, different eco-efficiency indicators for different environmental categories could still lead to the need for multi-criteria decision analysis or trade-off analysis among environmental results.

Another limitation is also related to the graphical analysis of the eco-efficiency scores. The adjusted eco-efficiency scores were computed by adding a fixed amount to the EI and EN constituents of the indicator (Eq. 2). This choice was made to help in the graphical representation of the eco-efficiency results by shifting all results to positive values. The main aim was to allow understanding in which direction the critical factors drove the results, and therefore which datasets would be preferable. Nevertheless, the addition of a fixed amount to both the numerator and denominator of the eco-efficiency scores leads to a change in the results and therefore in their relations. This could lead to a bias in the choice of datasets and thus in the interpretation of the results. In Figure 8, the effect of such adaptation is reflected in the interpretation of the GSA results. In particular, from the graphical analysis, the gasifying agent would appear to have a higher effect compared to the results of the GSA. Further research should be conducted to favor a better graphical analysis and interpretation of the results.

Data quality is also a critical issue in the comparability between environmental and economic results and their integration. Environmental and economic modeling depends on the available knowledge and data related to the system under study. For emerging technologies, the emerging nature of the technologies and the limited knowledge of their performance at pilot and commercial scale leads to high uncertainties that need to be addressed (Delpierre et al., 2021; Van der Giesen et al., 2020). Moreover, data quality usually varies disproportionally for economic and environmental factors (Kicherer et al., 2007). In this study, multiple scenario analysis and GSA were used to address the uncertainties due to the spatial and temporal variability of the factors and parameters. Further work should also focus on parameter uncertainty propagation. Probability distributions can be associated with parameter values, and Monte Carlo simulations can be conducted to assess the propagation of the uncertainties and the effects on the results (Laner et al., 2016). This would provide an even broader overview of the variability of system conditions and the influence on the results.

5. Conclusions

Early-stage assessments of emerging technologies are acquiring increasing importance to support their design and implementation. However, challenges still exist due to the emerging nature of the systems under study, the inherent variability of spatial and temporal conditions and the related large uncertainties, as well as the limited integration of environmental and economic results. Current assessment approaches are commonly applied to specific projects and contexts, limiting the analysis to the economic and/or environmental hotspots, or the comparison with similar and incumbent technologies/processes. The assessment of emerging technologies requires further addressing different levels of uncertainties and to understand the underlying mechanisms that drive the performance. This would allow increasing the validity and usefulness of the results in supporting a more flexible and sustainable system design. The study presents a framework for an integrated evaluation of new concepts and technologies, with a specific application to plasma gasification as WtE technology in the context of ELFM. The overall goal of the framework is to better support decision-making towards the sustainable development and implementation of emerging systems, by understanding the main performance drivers and their interactions, as well as limiting trade-offs between environmental and economic results.

The results of the study highlight the added value of the framework in the analysis of emerging technologies, such as plasma gasification. The wide range of results reflects the influence of site, project, and system-level conditions, and the need to account for their spatial and temporal variability to analyze the potential performance of the technology under different project settings. Moreover, GSA allows a fine-grained assessment of the system's environmental and economic performance and a deeper understanding of what drives the results. This, in turn, allows for promoting a flexible and sustainable system design, improving the technology's applicability to different projects. For example, the climate change results have shown how the variation of the background energy system can influence process design, such as the choice of the gasifying agent. Steam + O_2-based gasification is preferred in the case of a coal-based background energy mix, as the higher recovered energy leads to higher environmental benefits. In case of a renewable background mix, instead, energy recovery does not influence significantly the results, and the climate impact is not influenced by the choice of gasifying agent. On the other hand, the high costs associated with the production of O_2 do not balance the revenues from the recovered energy, resulting in air-based gasification as more economically feasible. The framework further addresses the integrated environmental and economic analysis of the technology via eco-efficiency. GSA applied to the results shows a shift in importance for the main influencing factors. This result highlights the importance of integrated approaches to avoid potential trade-offs and further support more sustainable development and implementation of the studied system.

Overall, the study does not aim to draw any absolute conclusions on the environmental and economic potential of plasma gasification. The still emerging nature of the technology and the lack of commercial-scale applications lead to large uncertainties that need to be taken into account when interpreting the results. Nevertheless, the results highlight the potential of the framework as a screening tool to support the design and implementation of the technology, and generally emerging systems, in different projects and settings. For plasma gasification, further assessments are required on pilot or commercial applications to validate the results for specific cases.

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