Comparative analysis of WtE technologies based on multiple criteria analysis and life cycle considerations

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Abstract Nowadays, a range of alternative options and technologies for Waste to Energy are currently available and analytically discussed in the effort to promote energy production and rational waste management. In this paper, a generic methodological scheme is proposed for the comparative analysis of WtE (Waste-to-Energy) technologies based on multiple criteria analysis and life cycle considerations. The approach is based on Multi-Criteria Decision Analysis (MCDA). The methodological scheme simultaneously considers environmental, economic, and social criteria to support robust decision-making. Towards validating the methodology, the latter was demonstrated in a real-world case study taking for Greece, considering four main technological options i.e., incineration, gasification, pyrolysis, and anaerobic digestion. Questionnaires, both for a pool of fifteen experts and the public were disseminated and interesting results are analyzed and discussed. Based on the proposed methodological scheme, the results for the basic scenario (when social, environmental, and economic considerations have equal weighting factor) promote anaerobic digestion as a more preferred option for Greece, followed by incineration, gasification, and pyrolysis. However, the optimal solution puts forward a mixture of technologies (i.e., combination of anaerobic digestion and incineration or gasification), depending on the differentiations of the scenarios weighting factors. Life cycle thinking should also be considered to provide a more reliable analysis related to the estimation of environmental performance of alternative technological solutions.

Keywords: sustainable management; thermal treatment; decision support system; multi-criteria analysis; waste management;

1. Introduction

According to World Bank, global waste production is expected to grow to 3.4 billion t by the year 2050 (Kaza et al., 2018). Although, up until now, sanitary landfill remains the “business as usual” model in solid waste management, it places a heavy burden to the planet’s carrying capacity, also taking its toll to economic and social aspects, both globally and locally. In the context of sustainable waste management, novel practices have been introduced throughout the last decades, such as prevention, reuse, recycle and energy recovery, that can be combined to tackle the aforementioned problem. Energy recovery of MSW (Municipal Solid Waste) is steadily gaining ground, through the use of technologies like incineration, gasification, pyrolysis and anaerobic digestion. Furthermore, MCDA is being widely used as a tool of evaluating the optimum choice among a set of alternative options (i.e., technologies), where there are oftentimes, multiple conflicting criteria.

The main objective of this paper is to present a generic methodological framework for that matter, considering the three pillars of sustainability (social, economic, environmental) as a basis and in addition, to showcase its application in real case alternative scenarios for Greece, evaluating the optimum technologies in respect to various weighting factors.

2. Methodology

The overview of the applied methodological framework is depicted in Figure 1.

2.1 Set of alternatives

According to World Energy Council (WEC, 2016), there are three main categories of WtE processes that are being currently applied as technologies: chemical, biochemical, and thermochemical. Esterification belongs to the first category, anaerobic digestion, fermentation, and landfill with gas capture belongs to the second and incineration, gasification, and pyrolysis belong to the third. As is often the case, the feasibility of the applied technology depends on many factors, such as waste composition, LHV (Lower Heating Value) as energy content of the mixture, energy demand, chemical and thermodynamic conditions etc. (Vlachokostas et al., 2021). Within the aim of the current study, most widely used technologies are being selected, namely, incineration, gasification, pyrolysis, and anaerobic digestion.

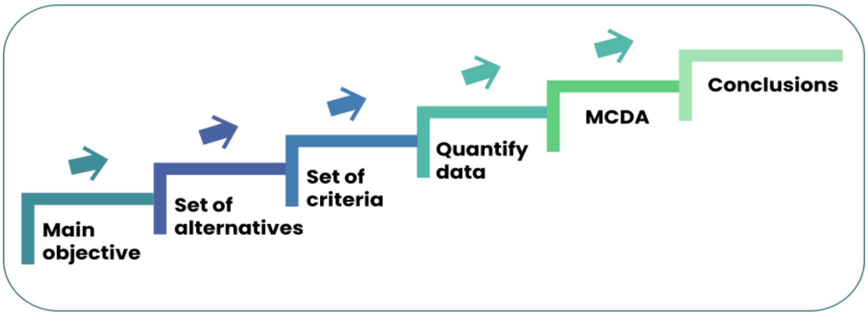

Figure 1. MCDA methodological framework

2.2 Set of criteria

The three-pillar conception of sustainability (economic, social, and environmental) emerged gradually in the academic literature through an attempt to reconcile economic growth with various ecological and social problems that grow in parallel (Purvis et al., 2019). Taking this into consideration, the three criteria formed the basis of the third step of the methodological framework. It needs to be underscored that apart from the economic and environmental aspects of sustainability, social acceptance is of equal importance. In that aspect, the reluctance of the general public towards the application of WtE technologies came to be known as "NIMBY" (Not In My Back Yard) syndrome (Achillas et al., 2011). Furthermore, a fourth criterion was included to be examined, that is the feasibility of the selected technologies from the scope of economies of scale, in Greece.

2.3 Research and quantification of data

From the standpoint of economic considerations, CAPEX (Capital Expenditure) was chosen to be the variable examined in relation to the plant's annual process capacity. For that reason, the selected index was €/t of MSW. CAPEX is a widely used type of data, especially in techno-economic assessments. The process of extraction of data involved extended study of the current bibliography.

In the plethora of environmental assessments, the most widely used tool is LCA (Life Cycle Assessment). LCA methods are considering all the various stages of a product's life cycle by applying a set of systematic processes which aim to collect and quantitatively analyze input data (natural resources, energy etc.), intermediate flows (materials, production, and consumption processes) and output data (waste, residues), to estimate the overall environmental criterion (Vlachokostas, 2022). As it was in the case of the economic criterion, LCA studies concerning incineration, gasification, pyrolysis, and anaerobic digestion were thoroughly studied to determine the environmental impact of each technology. The selected impact category was GWP (Global Warming Potential) in kg CO_2 eq./t MSW.

To determine the degree of social acceptance to WtE technologies, a survey aimed to the public was designed and distributed online. The format of the survey consisted of three main themes, estimation of public awareness, disposition and public opinion about the advantages and disadvantages of each technology. All the questions involved 5-scale qualitative multiple-choice answers that were quantified assigning a corresponding value and calculating the weighted average.

Finally, a pool of fifteen experts from academia and public sector was chosen to assess the feasibility of large-scale application for these technologies, in Greece. Once more, a survey was designed and distributed online, involving 5-scale qualitative multiple-choice answers that were quantified similarly to the survey for the public.

2.4 Multi Criteria Decision Analysis

To the purpose of this study, PROMETHEE (Preference Ranking Organization Method for Enrichment of Evaluations) was selected to be applied to the extracted data. This method uses pair- wise comparison according to preference functions and outranking techniques among the alternatives, resulting in an overall ranking. The final model of quantified data that was used as an input in the MCDA software is depicted in Table 1. CAPEX and GWP were set to minimize while the public preference and the expert's opinion were set to maximize. Finally, different "what-if" scenarios were examined, depending on the variation of each weighting factor corresponding to the four criteria that were established.

3. Results

3.1 Scenario 1

In the first scenario, all weighting factors are considered equal, sharing 25%, each. The overall ranking is depicted in Figure 2. Anaerobic digestion is the preferred option, followed by incineration, gasification, and pyrolysis.

3.2 Scenario 2

In the second scenario, emphasis is given in the environmental criterion. It is noted that when the corresponding weighting factor increases to 47%, all other being equal, the preferred option remains anaerobic digestion, followed by gasification, incineration, and pyrolysis, as it is depicted in Figure 3.

Table 1. PROMETHEE input data

	CAPEX	GWP	Public preference	Applicability
Units	**€/t MSW**	**Kg CO_2 eq/t MSW**	**5 grade scale**	**5 grade scale**
Incineration	600	584	4.31	3.8
Gasification	700	443	4.05	3.1
Pyrolysis	800	482	4.07	2.5
Anaerobic digestion	113	360	4.16	4.6

3.2 Scenario 3

In the third scenario, emphasis is given in public preference. As it is depicted in Figure 4, when the corresponding weighting factor is set to 51%, all other being equal, the preferred option remains anaerobic digestion, followed by incineration, pyrolysis, and gasification.

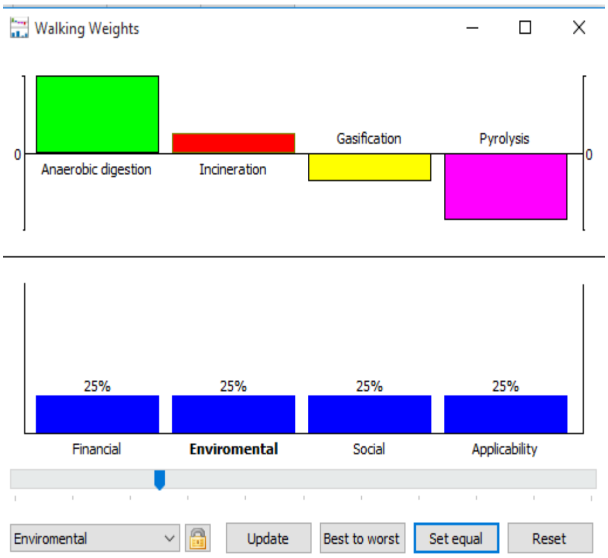

Figure 2. Scenario 1

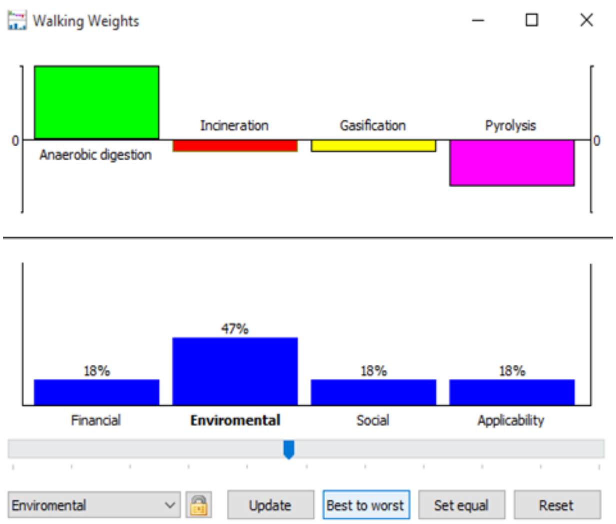

Figure 3. Scenario 2

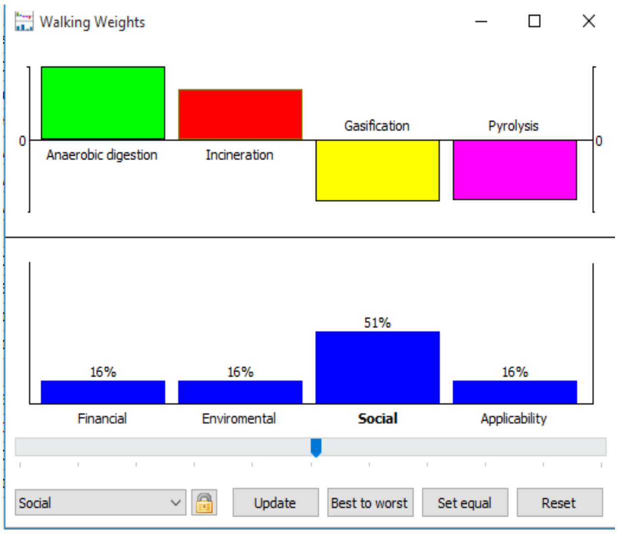

Figure 4. Scenario 3

4. Conclusion

In this study, a MCDA was performed to comparatively analyze four WtE technologies in respect to four criteria, economic, social, environmental, and large-scale applicability in Greece. Although anaerobic digestion is identified as the optimum solution among all four, whether the weighting factor is distributed evenly, or emphasis is given in the environmental or social aspect, evidence seems to be wanting a differentiation among the thermochemical processes to overall ranking. Particularly, in scenario 1, incineration is preferred comparatively to gasification and pyrolysis. Considering the environmental criterion, gasification is preferred among the rest and finally, with regards to social preference, incineration outranks gasification and pyrolysis.

This conclusion puts forth the notion of combination of different technologies in the framework of sustainable waste management which is also enhanced by the fact that biochemical processes involve solely the conversion of biodegradable fraction of MSW, whereas thermochemical (incineration, gasification, pyrolysis) cover a wider spectrum, such as mass burning, RDF (Refuse Derived Fuel) etc.

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