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Closing the Loop between Waste-to-Energy Technologies: A Holistic Assessment Based on Multiple Criteria

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Abstract: This paper puts forward a generic methodological framework to holistically assess WtE technologies based on the PROMETHEE approach. In addition to environmental and economic aspects, the method focuses on large-scale applicability and social preference, thus adopting economic, environmental, social, and technological criteria. Three data sources are selected, namely the scientific literature, a public survey, and an experts' opinion survey, which is a novel combination with the aim to cover public consensus, technological applicability, and to provide alternative data sources for the economic and environmental criteria, thus enriching the methodology with the input of location specific data. The demonstration of the applicability of the proposed methodology is realized at a national level for the case of Greece. Anaerobic Digestion is shown to be the most preferable choice, recognized for its cost-effectiveness and lower environmental burden to other WtE technologies (i.e., gasification, pyrolysis, incineration). When all criteria are evaluated with equal weights, anaerobic digestion greatly outperforms incineration (net flow 0.833 versus 0.1667), while incineration only becomes the most preferred choice if the social criterion is in high focus (i.e., over 63% weight).

Keywords: multi-criteria decision analysis; life cycle assessment; waste-to-energy; waste management; anaerobic digestion

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1. Introduction

According to the World Bank, waste generation is rapidly increasing worldwide, and it is estimated to reach 3.5 Gt/year by 2050 [1]. In the field of solid waste management, the established scenario until today has been sanitary landfilling. However, this practice remains environmentally harmful due to greenhouse gas emissions (GHG) and polluting agents affecting ground and aerial contamination [2]. Incineration for electricity production and anaerobic digestion with biogas production are two practices dating back to the industrial revolution, but innovative WtE methods such as gasification and pyrolysis have emerged in recent decades, producing solid, gaseous, and liquid fuels [3]. This has created the need for large-scale processing, especially for waste with an increased areal density, such as that of municipal solid waste (MSW). Moreover, the concept of sustainability introduced the participation of various stakeholders in decision making combined with different, often self-conflicting criteria. Multi-criteria decision analysis (MCDA) belongs to the broader scientific field of operational research and allows the synthesis of conflicting views concerning the three pillars of sustainability, namely the financial, the social, and the environmental [4].

Within the scientific literature, many methods of MCDA have been used to date to comparatively analyze different WtE technologies, such as Simple Additive Models (SAM) [5], the Analytic Hierarchy Process (AHP) [6], Multi-Objective Programming (MOP) [7], The Technique for the Order of Preference by Similarity to the Ideal Solution (TOPSIS) [8], the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) [9], among others. According to Vlachokostas et al. (2021) [4], the most widely used are AHP, SAM, and PROMETHEE. Regarding the criteria selection, although various frameworks exist in the scientific literature, such as the 3E model (Energy, Economic, and Environmental) [10], the majority of MCDA studies involve the three established criteria: social, environmental, and economic. In many cases, a fourth criterion is added, namely the technological, forming a framework for integration into an efficient management strategy [11]. As an example, Kheybari et al. 2019 [12] expanded the set of selected criteria for MCDA to include technical aspects like technical maturity, reliability, cleaning systems, energy efficiency, skilled personnel, etc. In addition, Thengane (2019) [13] included volume reduction, safety, user friendliness, and scalability potential among the technical criteria, as well as community acceptance and employment among the socio-political criteria, based on data from the literature and experts. However, in the studies above, public preference was not explored based on a public survey, rather than on experts' input. Furthermore, each criterion drew its data from a single source, being either the scientific literature or a questionnaire.

It should be noted that optimal waste management is based on the combination of a bundle of technologies that are dependent on the characteristics of each case under study and the waste under consideration. Thus, the mixture of thermochemical and biochemical technologies can be found in real life cases, in order to holistically manage a wide spectrum of waste categories. However, although some technologies may apply to different waste types, it is crucial to provide a platform for comparing economic, environmental, technological, and social criteria and parameters of alternative solutions, e.g., [14–17]. In particular, public preference and social consensus remain crucial factors and, oftentimes, a point of dispute when it comes to the implementation of such technologies [18]; thus, it is vital to be embedded in such a holistic approach. Data on public preference and social consensus can be obtained based on a public survey.

In this work, a complete MCDA methodological scheme for the selection of WtE technologies in the context of sustainability is proposed. Four criteria were selected, namely social, economic, environmental, and technological, while the collection of data for each criterion was based on the scientific literature and two types of surveys: an experts' opinion survey, with focus on the large-scale applicability of each WtE technology, and a public survey, with focus on the public preference and social consensus. To the best of the authors' knowledge, this combination of the scientific literature, public preference, and experts' opinions is novel, with the intention to cover both technological and social criteria, while the economic and environmental criteria were evaluated via multiple data sources (experts, the scientific literature), thus enriching the methodology with the input of location-specific data. Regarding the selection of the method, the PROMETHEE method was chosen as one of the most preferred techniques in similar problems also taking into account that it allows sensitivity analysis to be carried out in a tractable and flexible way for the user. Two alternative scenarios were examined, which involved variations in the weighting factors of the selected criteria. In the first alternative, the economic and environmental criteria were evaluated based on the scientific literature, while in the second alternative, they were evaluated by experts. In both scenarios, the social criterion was based on the results of the public survey, while the technological applicability was evaluated by experts. The presented method was subsequently used to comparatively analyze various technology rankings produced by the MCDA method, using alternative scenarios and location-specific data for the case of Greece. The application of the method produced evident data and valuable conclusions that can be used by local authorities in decision-making processes, to avoid "Not In My Back Yard" (NIMBY) syndrome and technical issues of scalability, especially for innovative and newly incorporated technologies.

The structure of this work is as follows. In the second section, the basic structure and components of the developed methodological framework are meticulously described. In the third section, the applicability of the methodology is presented, and the main results are critically discussed for the case study of Greece. In the final section, important conclusions are summarized and future challenges are considered.

2. Methods

The general methodological scheme developed and demonstrated for the purpose of this study comprises of 6 consecutive steps, as depicted in Figure 1. Firstly, the strategic scope of the MCDA analysis was defined. This is crucial towards the efficient realization of sustainability's assessment of the technological mixture (i.e., combination of different technologies) under consideration. As a second step, the researcher defined the set of alternatives that would be compared (3rd step) based upon the selected criteria that represent the three pillars of sustainability. The majority of MCDA methods require quantitative data (4th step). With the completion of the data model, application in selected software (5th step) yielded various rankings/solutions according to the number of scenarios. Sensitivity analysis is considered a useful technique in MCDA, especially in the context of sustainability. Alteration of each criterion's weight often leads to different solutions that must be taken into consideration to have a broader and clearer understanding of various parameters (criteria, alternatives, stakeholders, etc.) and the way that these inter-relate and interact to produce a well-defined result.

Figure 1. Basic structure of the methodological framework.

2.1. PROMETHEE Method

PROMETHEE method for MCDA was originally developed by J.P Brans and Ph. Vincke in 1985 and is based on the outranking approach, using pairwise comparison between alternatives (actions) and utilizing preference functions [19]. Three main steps comprise the PROMETHEE method [20]:

1. Calculation of preference degrees for each pair of alternatives.
2. Calculation of unicriterion flows.
3. Calculation of global flows.

Preference degrees are scores between 0 and 1 that indicate how much an alternative is preferred compared to another. Preference degree of 1 indicates total preference while preference degree of 0 means no preference at all. This is accomplished by using preference functions of various forms (usual, linear, level, u-shape, gaussian, etc.). Preference threshold p is the difference of two alternatives, beyond which, the decision maker shows clear preference to an alternative over another, while indifference threshold q is the difference of two alternatives, beneath which, the decision maker shows indifference to either [19]. For each pair of alternatives (c_i, c_j), a unicriterion preference degree $P_{i,j}^m$ is calculated, based on criterion g_m, where m is the number of criteria. Let $g_i(c_j)$ be the performance of action c_j on criterion g_i. Linear function can be shown in Equation (1) [20]

$$P_{i,j}^m = \begin{cases} 0 & if \quad g_m(c_i) - g_m(c_j) \leq q \\ \frac{[g_m(c_i) - g_m(c_j) - q]}{|p-q|} & if \quad q < g_m(c_i) - g_m(c_j) < p \\ 1 & if \quad g_m(c_i) - g_k(c_j) \geq p \end{cases} \quad (1)$$

The global preference degree π_{ij} indicates the global preference of action c_i on action c_j according to all criteria, where $\mathrm{w_m}$ is the weight of each criterion Equation (2) [20].

$$\pi\left(c_i, c_j\right) = \sum_{m=1}^{q} w_j \cdot P_{i,j}^{m} \quad (2)$$

The next step in the PROMETHEE method is the calculation of unicriterion flows, which is the summarization of the total pairwise preference degrees. Unicriterion flows consist of the positive, negative, and net flows. The positive flow indicates how an alternative is preferred over all other alternatives, for a certain criterion, using a score between 0 and 1. The negative flow, on the contrary, indicates how all other alternatives are preferred to this alternative, using a score between 0 and 1. The net flow is produced by the substruction of the negative flow from the positive and it is indicated by a score between −1 and 1 [20].

Lastly, for the calculation of global flows, which takes into consideration all the criteria simultaneously, the decision maker must specify the weight of each alternative, i.e., the relative importance of the alternative in comparison to all the others. As in unicriterion flows, positive and negative flows return values between 0 and 1 and net flows between −1 and 1. Global net flows produce the final result in the form of ranking. By denoting $\Phi^{+}(c_i)$ and $\Phi^{-}(c_j)$ as the positive and negative flows of action c_i, respectively, the global flows are produced by Equations (3) and (4) [20].

$$\Phi^{+}(c_i) = \frac{\sum_{j=1}^{n} \pi_{ij}}{n-1} \quad (3)$$

$$\Phi^{-}(c_i) = \frac{\sum_{j=1}^{n} \pi_{j_i}}{n-1} \quad (4)$$

One of the main advantages of PROMETHEE software (v 1.1.0.0) is the capability for implementing sensitivity analysis. It allows the decision maker to produce dynamic results (rankings) while changing various parameters, e.g., weight. Additionally, this method requires fewer inputs compared to other techniques and it has a clear and easy-to-use structure [21].

2.2. Criteria and Data Collection

For the case of Greece, four criteria were analyzed: economic, environmental, technological, and social. A thorough study of the scientific literature was needed for the economic and environmental criteria, and the design of two surveys, specially customized to assess public preference and experts' opinion, for the social and technological criterion, respectively (Supplementary Materials). Criteria selection was accompanied by the proper selection of the corresponding index for each criterion in order to provide the MCDA model with the necessary quantitative data. Several case studies were studied, concerning either real case scenarios of WtE plants or model applications.

In this work, 2 different scenarios were analyzed. In Scenario 1, the indices for the economic and environmental criteria were extracted by calculating the mean values reported in the literature for the 4 WtE processes with similar technological characteristics and by considering particular type of feedstock (MSW for thermal technologies and biodegradable waste for Anaerobic Digestion) and the same functional unit (1 kg of feedstock). More specifically, mean values for CAPEX in EUR/Mg were calculated for the economic criterion based on [10,22–28], while Global Warming Potential (GWP), in kg CO_2 eq./Mg feedstock, was calculated for the environmental criterion based on [10,26–38]. Regarding social preference, the overall grade of each of the 4 WtE technologies was produced by calculating the normal weighted average for each technology in the 1–5 qualitative scale based on the answers of the public. The same method was used for the technological criterion also, based on the experts' answers for the applicability of each technology in Greece (in 1–5 qualitative scale). In Scenario 2, data concerning the economic and environmental dimension were based on the experts' responses to the respective questionnaire. More specifically, the experts were asked to comparatively rank the 4 WtE technologies (given the same plant capacity) (i) from the least to the most expensive and (ii) from the most to least environmentally friendly, respectively. Both of the above criteria were normalized using the weighted average method for each technology. The social preference in Scenario 2 is the same as in Scenario 1.

Figure 2 depicts the applied framework used for the scope of this study, in the context of Scenario 1.

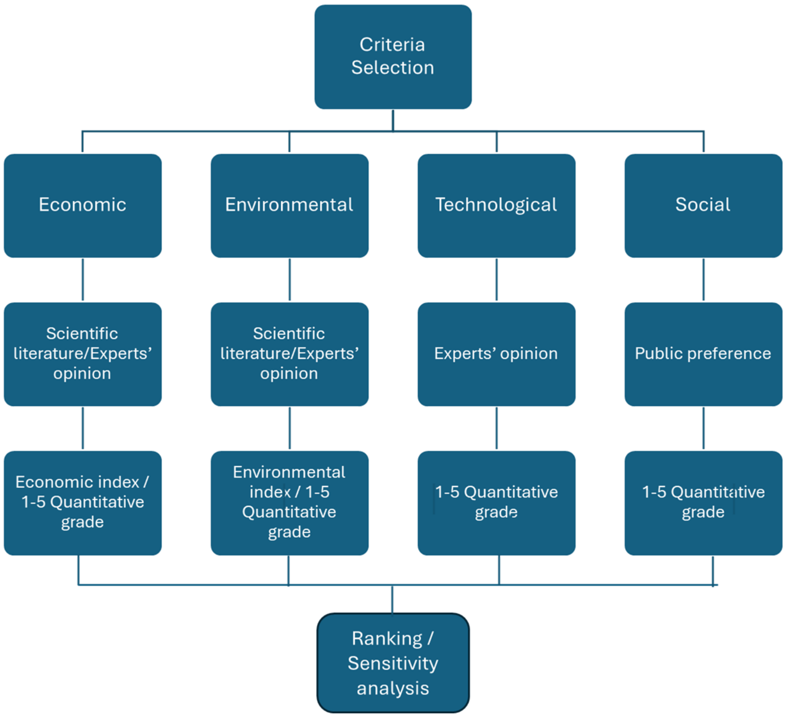

Figure 2. Detailed MCDA methodological framework for the selection of the optimal WtE technology, using multiple data sources.

2.2.1. Economic Criterion

Capital Expenditure (CAPEX) mainly consists of construction costs, equipment and installation, land use and preparation, loan interest, etc. External costs are another factor that is usually taken into consideration in sustainability issues and consists of direct and/or indirect consequences of a plant operation in stakeholders not directly related to the plant owner or operator, e.g., costs related to healthcare from harmful emissions in the area, or social costs related to the mechanization of labor and the concurrent job losses [22]. For the purpose of this study, CAPEX (EUR/Mg of feedstock) for the 4 types of plants (incineration, gasification, pyrolysis, and anaerobic digestion) was chosen as an indicator, mainly due to the greater availability of data in the scientific literature. Especially in the case of incineration and anaerobic digestion plants, data analysis was conducted based on data from the scientific literature, that reveal a strong positive linear correlation between CAPEX (M/EUR) and plant capacity (Gg/year), as it is shown in Figures 3 and 4, with R^2 = 0.9133 and 0.9216, respectively [22–25,29].

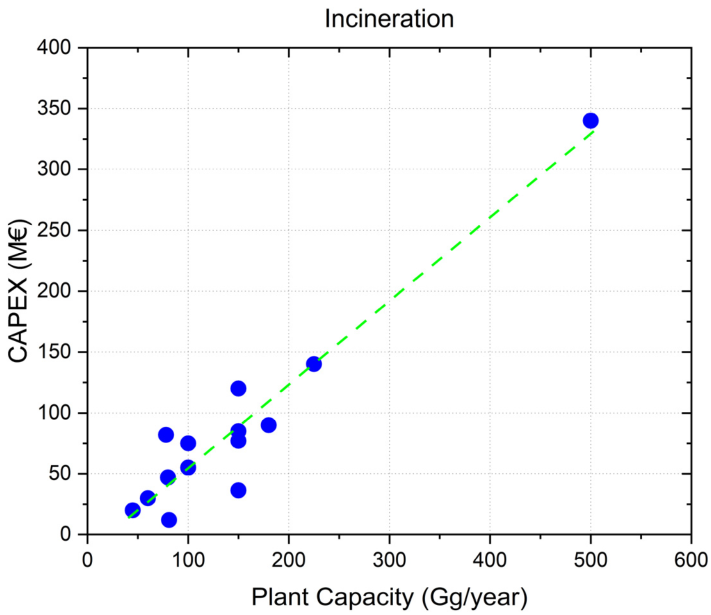

Figure 3. CAPEX as a function of plant capacity for incineration of MSW.

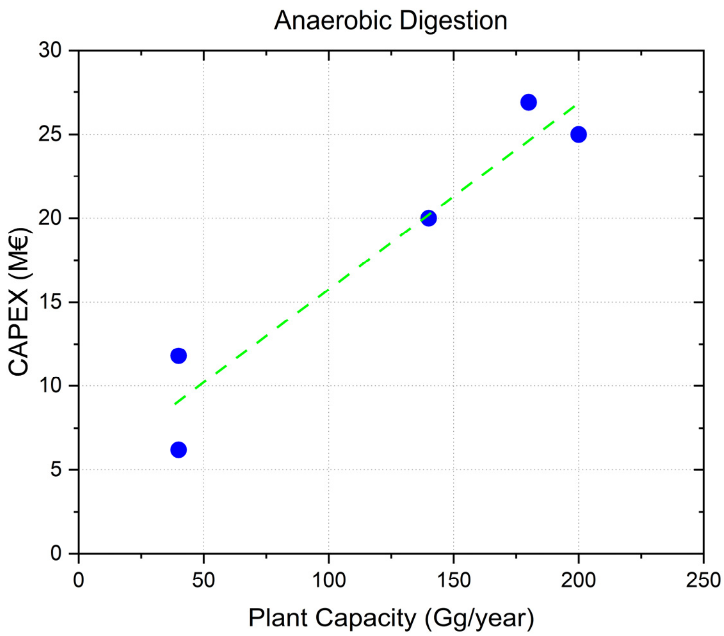

Figure 4. Correlation of CAPEX and plant capacity for anaerobic digestion of organic waste.

2.2.2. Environmental Criterion

According to ISO 14040, LCA (Life Cycle Assessment) is a methodical process of gathering and analyzing material and energy inputs and outputs, as well as the related environmental effects that are directly related to the operation of a system of goods or services over the course of its life cycle, and has been widely used during recent decades as an environmental support system [39]. The assessment covers the entire life cycle of the product or activity, including, for example, extraction and processing of raw materials, manufacturing, distribution, use, maintenance, recycling, and final disposal, as well as transportation between the aforementioned stages. Through the comparison of environmental burdens of various options, it provides a valuable tool in decision making and management [40]. Conducted through dedicated software, LCA provides a plethora of environmental indicators that stem from the defined system. The most widely known Life Cycle Impact Assessment Methodologies currently used, especially in Europe, are IPCC

GWP (carbon print), CML-IA (midpoint), ReCiPe (midpoint and endpoint), and Ecoindicator 99 (endpoint) [26]. The results of the LCA though are affected by parameters that are up to the researcher's assumptions such as system boundaries, functional unit, availability and accuracy of data, type of waste, etc. Moreover, geographical and seasonal variability of the composition of waste adds more uncertainty to the expected results. Table 1 highlights the variability of LCA results of selected studies, taking into account also the work of Mayer et al. (2019) [41] and Dastjerdi et al. (2021) [42].

For the scope of the present study, GWP was chosen as an indicator to be gathered and analyzed from various LCA papers, mainly due to the plethora of these types of data in the scientific literature. GWP was used to compare the amount of thermal energy absorbed by a gas without directly measuring its concentration in the atmosphere and it is defined as the ratio of the impact on Earth's energy balance from 1 kg of a GHG to the impact from 1 kg of CO_2 [43]. In recent years, due to heightened efforts to combat climate change, GWP has gained prominence as a quantified metric that aids researchers in understanding the overall environmental impact of human activities.

Table 1. GWP of various waste feedstock for MSW, according to the scientific literature.

Study	Feedstock	Functional Unit	Technology	GWP (kg CO_2 eq./Functional Unit)
[30]	MSW	1 Mg of waste	Pyrolysis–Gasification	1017
[31]	Mixture of waste	1 kg of waste	Incineration	1.91
			Gasification	0.94
			Anaerobic digestion	1.7
[32]	MSW	1 kg of waste	Incineration	0.7
			Pyrolysis	0.6
			Gasification	0.55
[44]	MSW	1 Mg of waste	Gasification	−96
[45]	MSW	1 Mg of waste	Incineration	496
[46]	MSW	1 Mg of waste	Incineration	593
[27]	MSW	1 Mg of waste	Incineration	372
			Anaerobic digestion	324
			Gasification	376
[33]	MSW Refuse	1 Mg of waste	Incineration	−725
[34]	MSW	1 Mg of waste	Incineration	430
			Gasification	27
[47]	MSW	1 Mg of waste	Incineration	271
			Anaerobic digestion	−164
[48]	MSW	1 Mg of waste	Pyrolysis	250
[49]	MSW	1 Mg of waste	Gasification	566

2.2.3. Social Criterion

For the successful implementation of any waste management system within the framework of sustainability, social consensus is required. This is also evident in the last decade's literature which indicates an increase in the incorporation of social criteria in the MCDA for WtE technologies [4]. According to Assefa et al. (2007) [50], the factors influencing information collection concern how easily these data can be quantified, as well as temporal or geographical constraints. For the needs of this research, a questionnaire was implemented as a tool and distributed in electronic format through email and social networks. In total, 225 responses were received.

Figure 5 depicts the age distribution among the respondents of the questionnaire to the public. The majority of respondents (47.6%) were in the ages between 40 and 64, while 28.4% were between the ages of 25–39. In addition, 12.4% were in the ages over 65 and, lastly, 11.6% were below the age of 24.

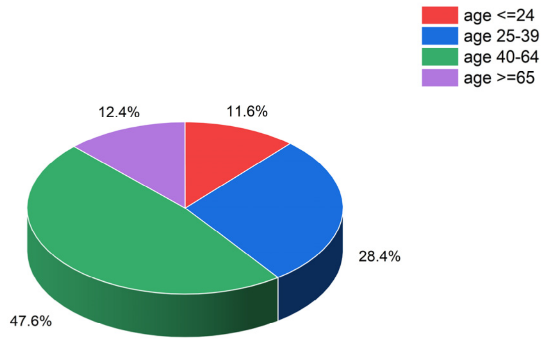

Figure 5. Age distribution among the respondents of the public questionnaire.

Figure 6 depicts the distribution of the education levels of participants in the public questionnaire: 51% of the responders had Master's or PhD title, 40% had a university degree, while 8.4% had a high school degree, and 0.5% had a primary school degree.

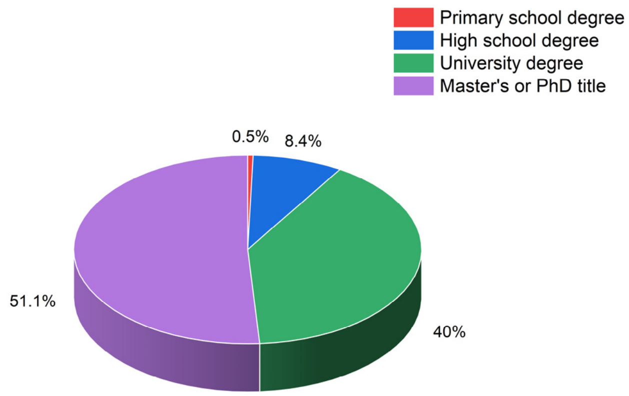

Figure 6. Distribution of the education level of participants in the public questionnaire.

The questionnaire's structure revolved around three axes. The first focused on public knowledge about the four examined technologies, the second involved the preference for constructing a plant near the respondent's place of residence, and the third sought public opinion on the advantages/disadvantages of WtE technologies and the degree of trust in auditing and pollution control procedures. An additional objective was to facilitate the quantification of results, primarily regarding public preference. For this reason, five qualitative choices were presented as responses, corresponding to those used in the PROMETHEE model (qualitative 5-point scale). Subsequently, in each technology, a preference grade was assigned in a quantitative 5-point scale. Ultimately, four performance evaluations emerged, using weighted average method, corresponding to the four technologies introduced into the model. It is worth noting that during the last decade, social considerations are being increasingly incorporated in MCDA studies, despite the difficulties of the quantification of public preference. Public consensus is considered crucial in sustainable waste management [4].

2.2.4. Technological Criterion and Alternative Economic and Environmental Indices

The fourth criterion considered was the technological one, which concerned the degree to which these technologies can be realistically applied in Greece, with unit capacity characterized as large (>150 Gg/year). For this purpose, an additional questionnaire was structured, concerning the opinion of experts on these technologies, and distributed via email and social networks. The questionnaire's structure was as follows: The first axis concerned experts' opinions on ranking technologies based on economic and environmental criteria. Its purpose was to verify and enrich the literature research and be used on alternative scenarios in this work (Scenario 2). The second axis focused on the primary concern, the realistic application of technologies. The third and final axis revolved around respondents' judgment regarding the reasons for hindering the development of such units in Greece. As it was in the questionnaire for the public, the type of responses in this survey were given in a qualitative scale and subsequently converted into a quantitative 1–5 scale, using weighted average method. This questionnaire targeted a specific sample of 17 experts from academia, public, and private sector, whose opinions hold significant weight, particularly due to the interdisciplinary nature required to thoroughly examine the subject. Figure 7 depicts the experts' opinions for the large-scale applicability of the 4 technologies to Greece. Among those with wide probability of application were anaerobic digestion and, to a lesser degree, incineration. "High probability" was shared among all the 4 technologies and medium probability concerned mostly thermochemical processes. Finally, as the probability of large-scale application lowers, a prevalence of pyrolysis in the experts' choices can be seen.

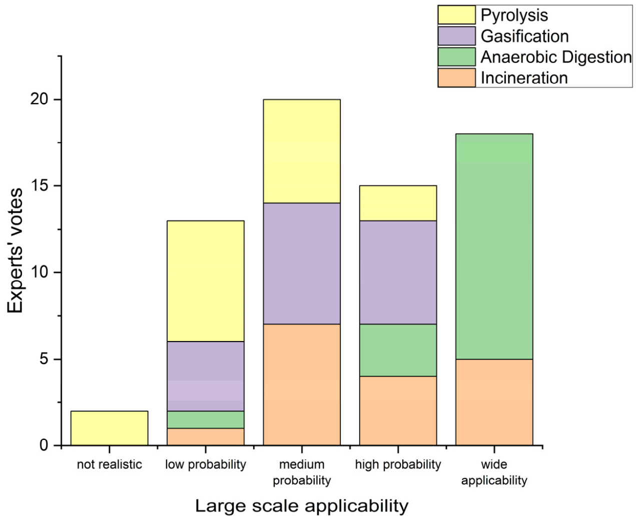

Figure 7. Experts' votes on large-scale applicability of the 4 technologies.

Figure 8 depicts the experts' ranking of the technologies in relation to the cost of application. As it is shown, the least expensive technology (1st place) was considered to be anaerobic digestion and, to a much lesser degree, incineration and gasification. The votes for the second least expensive technology were shared between all of the 4 technologies, with emphasis on incineration. Finally, the most expensive technologies were considered to be gasification and pyrolysis (3rd and 4th place), as it is shown in the distribution of the experts' votes.

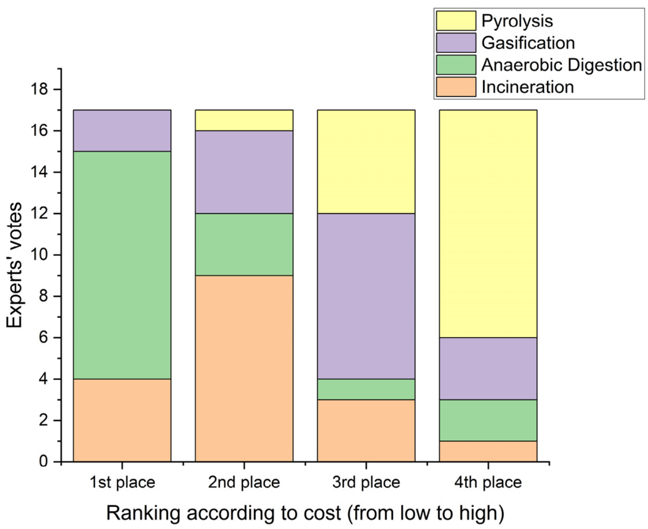

Figure 8. Experts' votes on the ranking of the technologies in relation to cost (from high to low).

Figure 9 depicts the experts' ranking of the technologies in relation to the degree of environmental burden. As shown, most environmentally friendly technology appeared to be Anaerobic Digestion, ranking in 1st place. In 2nd and 3rd place (medium environmental burden), the votes, in majority, highlighted gasification and pyrolysis. Finally, in 4th place, as least environmentally friendly, came incineration, according to experts' votes.

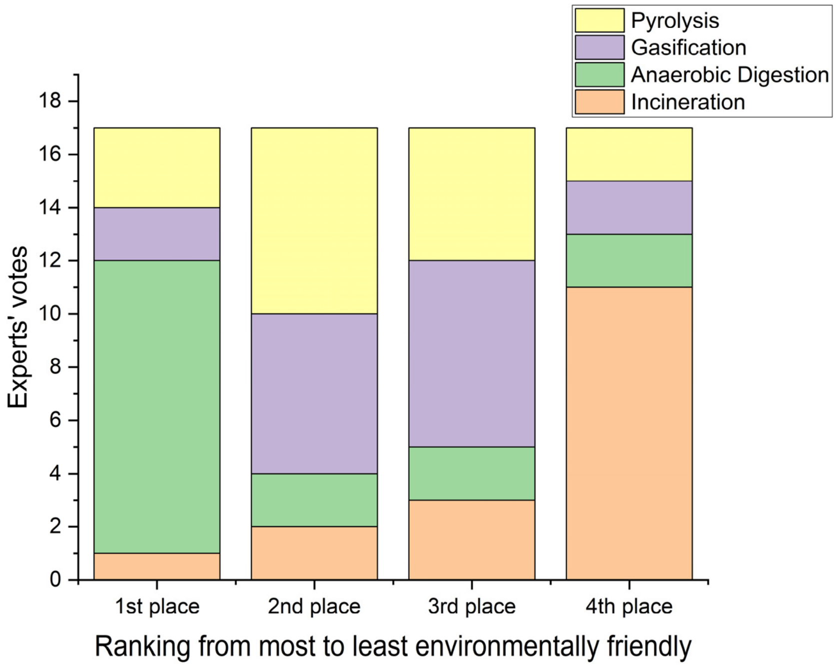

Figure 9. Experts' votes on the ranking of the technologies in relation to the degree of environmental burden.

2.3. Current State of MSW Management in Greece

Greece is an exceptional case study to demonstrate the applicability of the proposed methodological scheme. The need to promote WtE technological options is imperative, not only for MSW, but also for other types of waste (agricultural, industrial, sewage, etc.). Currently, the main MSW management method used in Greece is landfilling, as 80% of MSW ends up in landfills [51]. The legislative framework for waste management in Greece closely follows the corresponding European framework. Over recent years, all relevant EU Directives have been transposed into national law. It should be noted that, in 2021, law 4819/2021 imposed a landfilling fee for the unprocessed MSW and the residues of MSW management facilities. This legislation paves the way for the implementation of the Pay-As-You-Throw (PAYT) system, in compliance with the "polluter pays" principle. The final target of MSW management is the reduction of MSW landfill disposal down to 10% by 2035 [52]. EU Waste Framework Directives are also incorporated in the National Waste Management Plan (NWMP). According to the NWMP, organic waste represents more than 40% of the total generated MSW in Greece, most of which will be separated at source in the near future due to the installation of urban brown bins for biodegradable waste collection exclusively. This provides a great opportunity for the implementation of organic waste treatment facilities, with anaerobic digestion being at the forefront of biowaste valorization technologies. Optimal decision making in bio-WtE can increase the value of biowaste to bioproducts and improve the efficiency of bioenergy production [4].

It should be underlined that in Greece's co-capital, Thessaloniki, the estimation of local MSW production ranges to about 180 Gg/year [53], hence providing a viable application of a potential MSW management facility, as it fits the typical capacity of large-scale WtE units that start in the range of 150 Gg/year [54].

The location of an MSW management facility is of critical importance, especially to the viability of the project, since it influences economic and social factors [55]. No MSW incineration facility exists in Greece so far, and the only operational unit is a medical waste incineration facility in Attica. The unlikelihood of an MSW incineration unit construction in Greece is due to the lack of economic viability as well as social acceptance (NIMBY syndrome), despite the significant energy recovery [56]. A WtE incineration facility can be promoted as a preferable option in contrast to landfilling, but only under specific conditions of minimizing external costs of health impacts [53].

As for implementation of WtE technologies in Greece, only hypothetical case studies exist regarding MSW gasification, such as a MSW plasma gasification plant in Greece by [57] and biomass gasification in the region of Messenia, Greece [58]. Concerning pyrolysis, no MSW pyrolysis units exist in Greece, but up-to-date information presented by [59] shows future plans for an innovative pyrolysis–anaerobic digestion biomass residues processing plant. In any case, there is still effort to be realized towards implementing waste prevention principle, which seeks to reduce the total volume of waste and the harmful effects on health and the environment through re-use and recovering of materials on the basis of circular economy, taking into account economic costs and social predisposition.

2.4. Waste-to-Energy Technologies

2.4.1. Incineration

During the process of incineration, MSW is combusted in a chamber, in a temperature range between 900–950 °C. The process is exothermic and it is used to heat up water for steam generation. Electricity production is usually carried by turbines that use the generated steam for energy production [60]. Volume and mass reduction of MSW may reach up to 90% [61]. Apart from energy production and waste management, incineration of MSW may be useful for other sectors like road construction, recovery of ferrous materials and cement industry, mainly through the utilization of fly and bottom ash [62].

2.4.2. Gasification

Gasification is another example of a technology that belongs to thermal treatment methods. The organic compound is partially oxidated in the presence of a gasifying agent (air, oxygen, or steam). The main product is syngas, a gaseous fuel comprised of CO_2, CH_4, CO, H_2, etc. Typical operating temperatures are 1000–1600 °C when the agent is pure oxygen and 550–900 °C when air is used [35]. Advantages of gasification as WtE technology are reduction in polluting emissions, significant reduction in waste volume and mass, co-generation compatibility, etc. [60], among others.

2.4.3. Pyrolysis

Pyrolysis is a relatively novel thermal treatment WtE technology that usually operates in 3 distinct temperature ranges, always in absence of oxygen. In ranges between 400 and 800 °C, it mainly produces oil, char, and gaseous products that depend upon the process temperature, heating time, and residence time [63]. At ranges close to 500 °C, the main products are tar, wax, and pyrolysis oil, and at higher temperatures (>700 °C), the main product is pyrolysis gas. Usually, the type of waste that is best suited for pyrolysis is plastics, tires, electric waste, etc., [62]. Compared to incineration and gasification, pyrolysis shows the least production of SO_2 and NO_x [64].

2.4.4. Anaerobic Digestion

Anaerobic digestion belongs to the biochemical processes. It involves several stages of biodegradation of bio-waste by methanogenic bacteria, in absence of oxygen. Initially, simple molecules and organic components are produced. The second stage is the hydrolysis of these products into acetic acid, hydrogen, and volatile fatty acids (VFA). The third stage is the conversion of H_2 and organic acids into CH_4 and CO_2 [65]. Biogas is composed mainly of 25–50% CO_2, 50–75% CH_4, and 1–15% other gaseous products (NH_3, H_2S, water vapor, etc.) [66]. Eliminating contaminants and especially H_2S are of crucial importance due to the fact that they may produce corrosion problems and negatively influence the process [67].

2.4.5. Other Technologies

Hydrothermal carbonization (HTC) is a novel WtE technology that is performed usually at mild temperatures (up to 524 K), utilizing biomass as feedstock, with reaction times that can hold several hours and produce mainly value-added products, like hydrochar, with content very similar to lignite [68]. HTC carbon materials can be utilized in a variety of applications. Hydrochar with high specific surface area can be used in anti-pollution technologies due to greater contact with pollutants and in adsorption of heavy metals, greenhouse gases, organic pollutants, and soil amendment [69,70].

The methodological framework proposed by the authors is applicable to other technologies as well, such as HTC, but in the application of the method for the use case of Greece, incineration, gasification, anaerobic digestion, and pyrolysis were considered due to data availability. However, examining large-scale applicability and social preference of HTC in a MCDA framework, remains a future challenge in waste management decision making.

3. Results

Results were obtained for two different scenarios. In Scenario 1, the index selected for the economical criterion was CAPEX (EUR/Mg), based on the calculated mean values reported in the literature. Similarly, the index selected for the environmental criterion was GWP (kg CO_2 eq./Mg feedstock), also based on the calculated mean values reported in the literature. The index used for the social criterion was social preference, based on the answers of the public survey, while the index used for the technological criterion was the large-scale applicability of each technology in Greece, based on experts' opinions. In Scenario 2, while the social and technological criteria remained the same, the data concerning the economic and environmental dimensions were based on the experts' responses to the respected questionnaire. Table 2 summarizes the collected data from the scientific literature and from the data analysis of the survey's responses, that were used as the input in PROMETHEE.

Table 2. Initial data model from the scientific literature and social and experts' surveys for the 2 scenarios.

	Incineration	Gasification	Pyrolysis	Anaerobic Digestion
Scenario 1				
CAPEX (EUR/Mg feedstock)	610	705	800	113
GWP (kg CO_2/Mg feedstock)	584	443	482	360
Scenario 2				
Economic criterion (1–4 scale)	2.06	2.7	3.6	1.65
Environmental criterion (1–4 scale)	3.41	2.53	2.35	1.70
Scenario 1 and 2				
Public preference (1–5 scale)	4.31	4.05	4.07	4.16
Large-scale applicability in Greece (1–5 scale)	3.80	3.10	2.50	4.60

In Scenarios 1 and 2, the economic and environmental criteria were set to minimize in PROMETHEE, while the social and technological were set to maximize. Overall, four sub-scenarios were examined for each of the two scenarios by implementing a sensitivity analysis according to various weights of the criteria.

3.1. Scenario 1

The positive, negative, and net flows for Scenario 1 are presented in Table 3, with all weights being equal (25%). Based on the results, it was observed that anaerobic digestion has the biggest net flow produced, thus gaining the first place in the ranking, while incineration, gasification, and pyrolysis hold the second, third, and fourth places, respectively.

Table 3. Positive, negative, and net flows for Scenario 1.

Technology	Phi	Phi^{+}	Phi^{-}	Ranking
Anaerobic digestion	0.8333	0.9167	0.0833	1
Incineration	0.1667	0.5833	0.4167	2
Gasification	−0.3333	0.3333	0.6667	3
Pyrolysis	−0.6667	0.1667	0.8333	4

In Figures 10–13, the relative rankings of the four technologies, depicted as dimensionless quantities, are presented when special emphasis, in the form of weight, is given to each of the four criteria. More specifically, in Figure 10, an increased weight was assigned to the economic criterion, i.e., 40%, while the rest of the criteria were adjusted to 20% each. In this example, anaerobic digestion becomes the most preferable technology with quite some difference compared to the other methods, while pyrolysis is ranked as the least preferable. This is expected when emphasis is put on the economic criterion since anaerobic digestion is far less costly, based on the CAPEX data presented in Table 2.

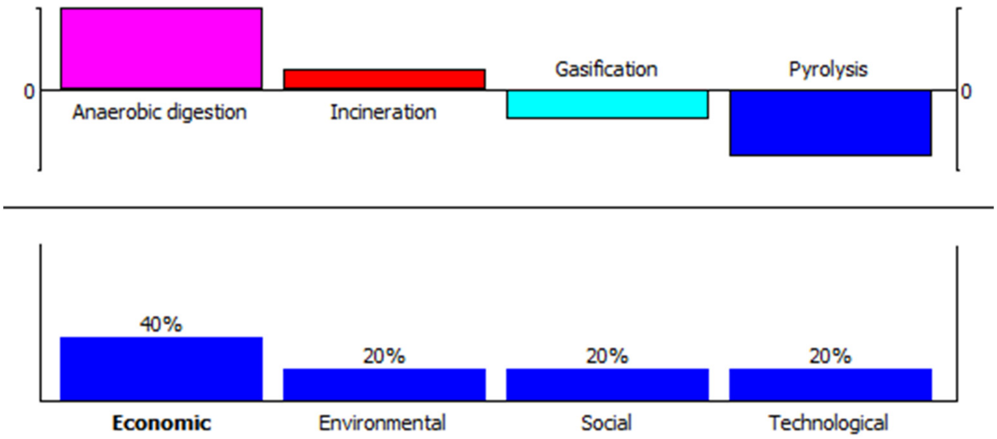

Figure 10. Sensitivity analysis of Scenario 1 by adjusting the weight of the economic criterion to 40%.

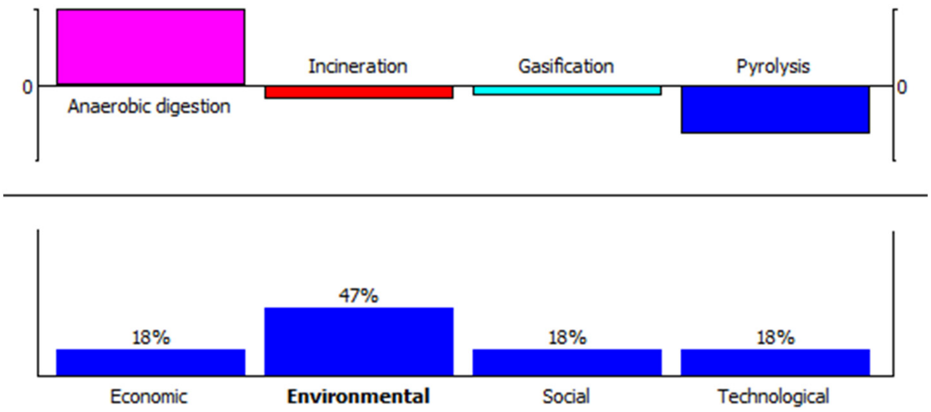

Figure 11. Sensitivity analysis of Scenario 1 by adjusting the weight of the environmental criterion to 47%.

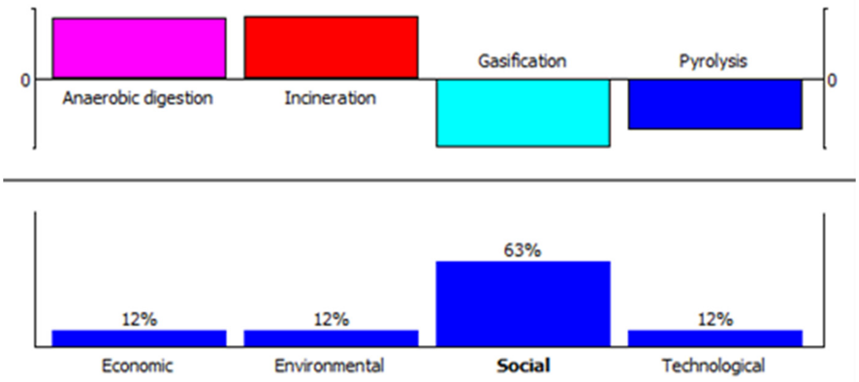

Figure 12. Sensitivity analysis of Scenario 1 by adjusting the weight of the social criterion to 63%.

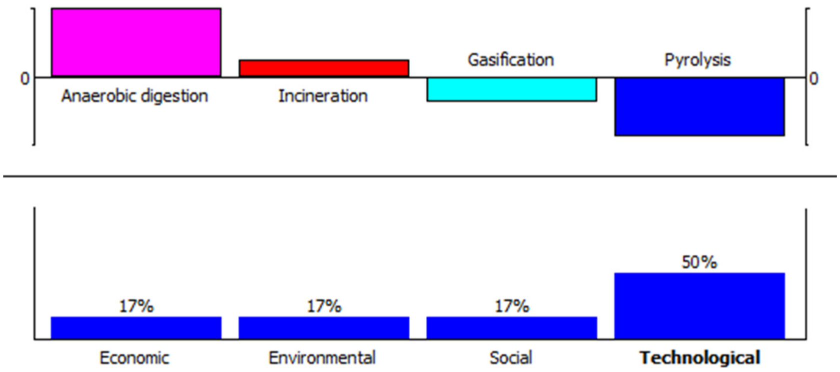

Figure 13. Sensitivity analysis of Scenario 1 by adjusting the weight of the technological criterion to 50%.

In Figure 11, increased weight in the environmental criterion was assigned to 47%, while the rest of the criteria were adjusted to 18% each. In this example, anaerobic digestion remains the most preferrable technology, while gasification barely surpasses incineration, and pyrolysis ranks last. This is expected when emphasis is put on the environmental criterion, since gasification is the most environmentally friendly technology compared to incineration.

Public opinion, as reflected in the public survey, favored incineration as a WtE technology. This can be highlighted when increasing the weight of the social criterion. In fact, if the social criterion is increased substantially, e.g., at 63%, then incineration becomes the most preferable technology, outperforming anaerobic digestion, as depicted in Figure 12. It is notable that in this case, gasification was the least preferred, despite outperforming pyrolysis in the collected data for the economic, environmental, and technological criteria, due to the fact that it was less preferred by the public.

Considering the social criterion, it was shown that the public was generally positively inclined towards the energy valorization of waste in Greece, with minimal differences among the selected technologies. From the data analysis on the responses, about 57% of the responders considered WtE implementation as necessary and 39% held a positive stance. As far as the knowledgeability of the technologies, most of the responders had a clear understanding of incineration and anaerobic digestion (34% and 44%, respectively) compared to gasification and pyrolysis (26% and 30%, respectively). Among the benefits of WtE technologies, a reduction in waste volume, environmental pollution, and decarbonization ranked to the top of the responses (57%, 54%, and 45%, respectively). Considering the disadvantages, 33% replied that there would be none, 30% would argue that they pose a threat to public health due to harmful emissions, and 28% would emphasize the aesthetic degradation of landscape. Finally, 38.3% of the responders showed no, little, or very little trust in anti-pollution control and auditing procedures, while 40.7% remained neutral and 38.3% were generally positively inclined.

Finally, in the last case of Scenario 1 (Figure 13), the weight of the technological criterion was set to 50% while the rest were adjusted to 17%. As it is shown, anaerobic digestion remains the most preferable option with quite some difference from the rest, as in the first case of Scenario 1. This is expected since the mostly costly technologies are usually less applicable at a large scale.

3.2. Scenario 2

The positive, negative, and net flows for Scenario 2 are depicted in Table 4, with all weights being equal (25%). Based on the results, anaerobic digestion and incineration ranked first and second, respectively, as in Scenario 1 (Table 3), while gasification and pyrolysis shared the last place in the ranking, with equal positive, negative, and net flows.

Table 4. Positive, negative, and net flows for Scenario 2.

Technology	Phi	Phi$^+$	Phi$^-$	Ranking
Anaerobic digestion	0.8333	0.9167	0.0833	1
Incineration	0.1667	0.5833	0.4167	2
Gasification	−0.5	0.25	0.75	3
Pyrolysis	−0.5	0.25	0.75	4

In Figures 14–17, emphasis was given to the economic, environmental, social, and technological criterion, modifying the weights to 40%, 64%, 64%, and 50%, while the remaining were weighted equally for each case.

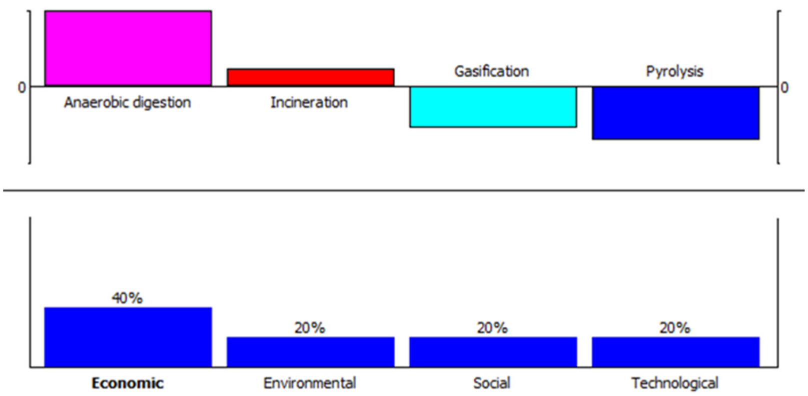

Figure 14. Sensitivity analysis of Scenario 2 by adjusting the weight of the economic criterion to 40%.

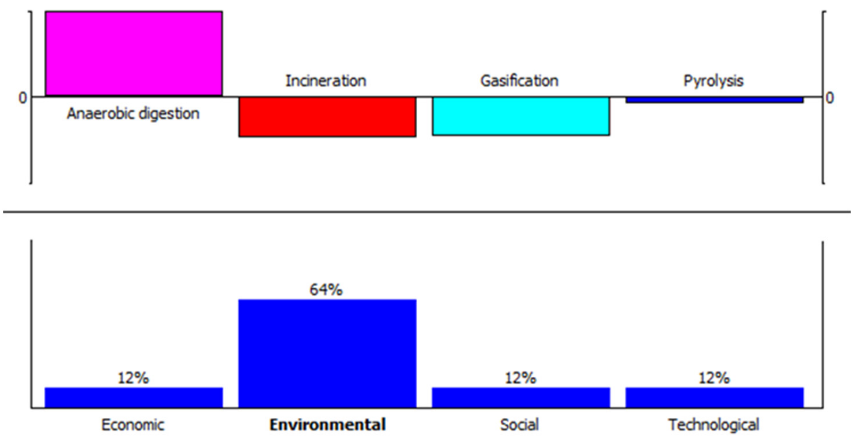

Figure 15. Sensitivity analysis of Scenario 2 by adjusting the weight of the environmental criterion to 64%.

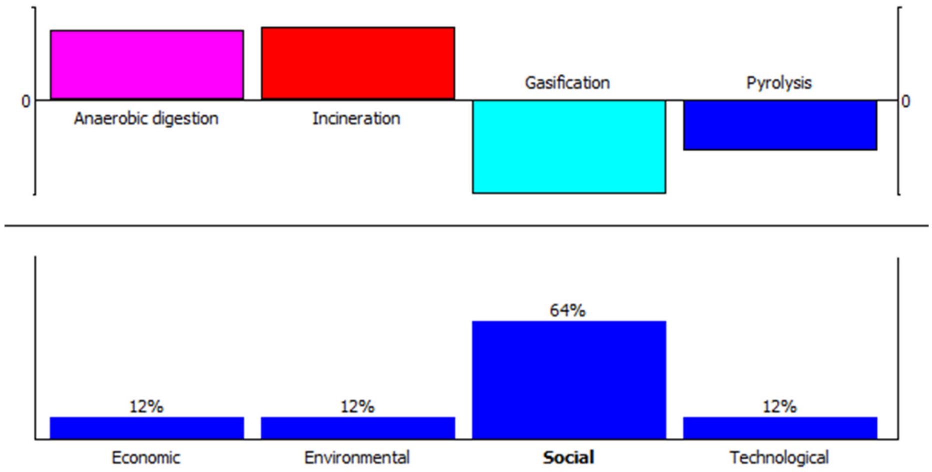

Figure 16. Sensitivity analysis of Scenario 2 by adjusting the weight of the social criterion to 64%.

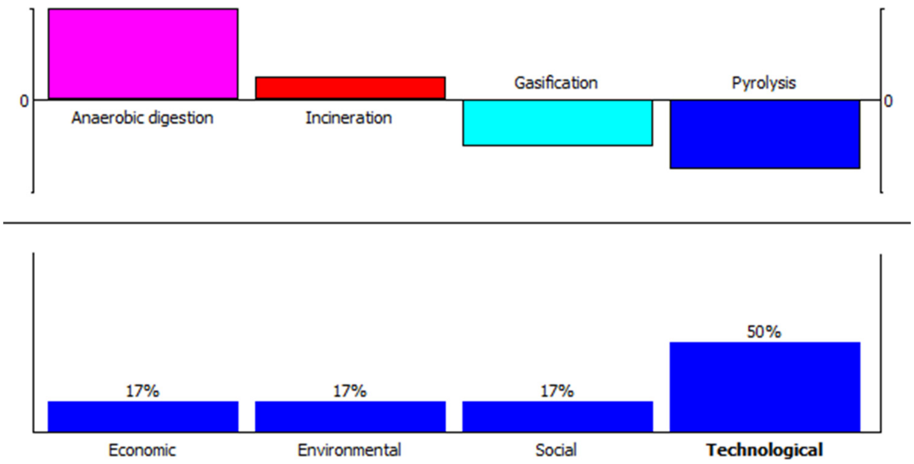

Figure 17. Sensitivity analysis of Scenario 2 by adjusting the weight of the technological criterion to 50%.

The results in this scenario differed slightly from Scenario 1. The experts' ratings on the technologies' economic performance were generally in accordance with the collected data in Scenario 1. A sensitivity analysis produced the following results. Whether emphasis was given to the economic, environmental, or technological criterion, anaerobic digestion ranked first, as in Scenario 1. However, public preference, as it is shown in Figure 11, favored incineration as the optimum choice over anaerobic digestion. Among thermochemical processes, pyrolysis was preferred in comparison to incineration and gasification, as the weight of the environmental criterion increased. As in Scenario 1, the increase in the weight of the social criterion to 63% favored incineration over anaerobic digestion. Finally, an increase in the weight of the technological criterion to 50%, as shown in Figure 17, ranked incineration as second, gasification as third, and pyrolysis last.

4. Discussion

Anaerobic digestion appeared to be the cheapest and most realistic option compared to the thermochemical processes, while gasification and pyrolysis are more expensive and early in their large-scale implementation for Greece, according to the experts' opinion. Incineration represents a middle choice in terms of cost and realistic large-scale application, with a significant portion of the cost attributed to anti-pollution technology. Additionally, a strong correlation was noted between the investment cost and the capacity of anaerobic digestion and incineration units, as shown in Figures 3 and 4. Anaerobic digestion and incineration are more widespread, with the former developing in recent years, even in

Greece. Furthermore, in these two technologies, social consensus seems to be achieved. Public predisposition towards incineration and anaerobic digestion was generally positive compared to the other two. An important preference criterion and a key factor in the NIMBY syndrome is the level of trust in pollution control procedures, while at the same time, the general attitude towards energy production from waste is positive. In conclusion, the public perception of the technologies under consideration is characterized as positive [71].

Matters of technological hysteresis in Greece should be addressed in order to implement these technologies in large-scale applications. Most cases of the large-scale application of gasification, pyrolysis, and a combination (Thermoselect method) come from Japan [28] in widely known commercial plants. Italy also utilizes pyrolysis, although not at a large scale, but many plants involve the mass-burning of MSW. With the exception of Finland (Metso Lahti), gasification is not widely used in Europe [28].

Additionally, there is a notable gap in LCA studies related to energy production from MSW on a large scale, as revealed by the literature review carried out by the authors [41,42]. This fact poses a future challenge in the research field. However, the expert responses generally aligned with the ranking derived from the processing of data in PROMETHEE in Scenario 1, indicating incineration with energy recovery as the most polluting process, anaerobic digestion as the most environmentally friendly, and gasification and pyrolysis in the middle.

Multi-criteria analysis identified anaerobic digestion as the optimal choice in most cases. Incineration and gasification differed minimally in the produced rankings, with the former maintaining a slight lead over the latter, except when the weight of the social criterion increased. If greater emphasis were to be placed on environmental protection, Refuse-Derived Fuel (RDF) gasification could be combined with anaerobic digestion, provided the appropriate technology is developed, while if emphasis is placed on social consensus, the combination of incineration and anaerobic digestion becomes preferable. These conclusions are also confirmed by the scenario analysis based on expert opinions. The preference of anaerobic digestion over other alternatives, in an MCDA framework, was highlighted in previous works, as in [17], where it was ranked 1st among five WtE technologies, outranking Landfill Gas Energy (LFG), incineration, TPS Thermiska Gasification, and Columbus Battelle gasification, mainly due to its higher performance in the environmental and economic criteria. In [16], anaerobic digestion was compared with Incineration, gasification, and pyrolysis, using the "Simple Multi Attribute Rating Technique Exploiting Ranks" (SMARTER) methodology, where it was shown to be the preferred option due to greater flexibility in small- and large-scale applicability and the high calorific value of biogas.

The combination of anaerobic digestion with thermochemical processes is reinforced by the fact that biochemical processes only affect the biodegradable fraction of waste, while materials with a high calorific value, such as plastic, paper, etc., could undergo thermochemical processing if they arise as RDF from mechanical processing facilities. The co-generation of electricity and heat is also considered a sustainable practice in the field of energy production from waste, achieving greater efficiency cumulatively. Furthermore, considering special streams, such as plastic, recent technological research further enhances regeneration for this type of waste [72].

Finally, the importance of establishing a methodological framework for a multi-criteria analysis for waste-to-energy methods, with specific and clear stages, should be emphasized. This framework should serve as a useful tool in the research process, avoiding gaps where critical aspects of the subject under consideration are overlooked.

5. Conclusions

The maximization of the efficiency of waste resources is strongly related to the optimal management of energy resources in order to establish a sustainable energy system for the greatest societal benefit, a vital issue for sustainable development. Undoubtedly, there are numerous technical specifications and uncertainties in the complex problem of selecting the necessary mixture of WtE technologies for a real case under consideration. In this light, MCDA presents a strong capability to reproduce local or regional characteristics and processes and "imprint" them for the quantification of the economic, environmental, social, and technological performances of alternative WtE technological solutions and management strategies. Decision makers are advised to approach a WtE management problem considering MCDA principles in order to make better informed decisions and to put forward technological solution hierarchies tailored to local and regional characteristics, taking into account the local energy mix, treatment conditions, and efficiency. It is the author's strong belief that when WtE solutions are implemented through a multi-criteria framework, both a rational waste-treating strategy and low-carbon-footprint energy production can be accomplished simultaneously.

In this paper, a generic methodological framework to assess WtE technologies based on the PROMETHEE approach has been proposed. The method focused on large-scale applicability and social preference, adopting economic, environmental, social, and technological criteria. A combination of data sources was selected, including the scientific literature, a public survey, and an expert's opinion survey, providing alternative indices and data sources for the economic and environmental criteria and enriching the methodology with the input of location-specific data. The applicability of the methodology has been demonstrated for two different scenarios and four WtE technologies analyzed at a national level for the case of Greece. The results showed that Anaerobic Digestion is considered as the most preferable choice due to the cost effectiveness and lower environmental burden compared to gasification, pyrolysis, and incineration. More specifically, when all the criteria are evaluated with equal weights, anaerobic digestion greatly outperforms incineration (net flow 0.833 versus 0.1667), while incineration only becomes the most preferred choice if the social criterion is in high focus (i.e., over 63% weight)

The validity of the methodology was explored via sensitivity analysis for both scenarios. The application of the method for the case of Greece emphasized the need for an assessment of the large-scale applicability of WtE technologies, but also of the technology concerns, preferences, and public consensus.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en17122971/s1, Criteria and data collection. Table S1. Question format for the large-scale application of technologies.

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