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Utilizing AHP-TOPSIS as Multi-Criteria Decision Approaches to Select the Best Alternative for Waste to Energy Technology

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Abstract

The main purpose of this study is to provide the decision makers in Jordan with a methodology to choose the most competitive waste to energy technology. The study used a Multi-Criteria Decision Making (MCDM) procedure of both Analytical Hierarchy Process (AHP) alone using Expert Choice software and the combination of AHP and the technique for order of preference by similarity to ideal solution (AHP-TOPSIS). The integration between the AHP and the TOPSIS is the main contribution of this research. Four waste to energy options were evaluated using three main criteria: environmental, technical, and socioeconomic; with three sub-criteria under each main criterion. Results showed that the environmental criterion is the most important one among the three considered criteria; weight of this criterion is approximately 69.9%, followed by technical criterion, which take 20.8% as weight, and the socioeconomic criterion ranked least important with a weight of 9.3%. Additionally, landfill gas option is found as the first and most preferable waste to energy option with a global priority of 0.561 followed by anaerobic digestion with a weight of 0.296, while incineration and pyrolysis technologies ranked the least preferred options with priorities of 0.087 and 0.056, respectively.

Keywords: AHP, TOPSIS, Solid Waste, Renewable Energy.

Nomenclature

AHP: Analytic hierarchy process

TOPSIS: Technique for order of preference by similarity to ideal solution

MCDM: Multi-criteria decision-making

IN: Incineration plant

PY: Pyrolysis plant

AD: Anaerobic Digestion

LFG: Landfill Gas Recovery

D: Performance rating of alternative with respect to criteria

R: Normalized matrix

V: Weighted normalized matrix

PIS (A^*): Positive idle solution

NIS (N^{-*}): Negative idle solution

CC: Closeness coefficient

CR: Consistency ratio

RI: Random index

CI: Consistency index

1. Introduction

Jordan is a country in the MENA region, which stands for Middle East and North Africa, Jordan is a middle income country with a territory of 89,34 km^2.The country is characterized with scarcity in natural resources, mainly water and energy resources. Jordan population was 9.523 million inhabitants in 2016, distributed among 12 governorates [1].

Solid waste is managed by municipals in Jordan, which mainly depends on pipe options to transfer about 90% of solid waste to disposal locations [1]. Seventeen disposal locations are considered for operations in different cities of Jordan. In Al Ghabawil, there is the only engineered sanitary landfill that serves the capital of Jordan (Amman) and Zarqa, this location is the largest one in the country to afford the generated waste by these two large cities. The second largest landfill in the country is being rehabilitated to become a sanitary one. All the remaining disposal locations are considered as unsanitary landfills (dump sites).

Solid waste is disposed to all locations in Jordan with amount of 6,940 ton/day; as it was approximately measured in 2013, this causes an annual quantity of 2,533,100 tons/year. In 2011, due to the high number of Syrian refugees who entered Jordan, the amount of solid waste has been significantly increased which put pressure on the solid waste management [2].

Renewable energy sources, such as converting waste to energy, are clean and sustainable sources that can be used

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as a replacement of the expensive and polluting fossil fuels. Several technologies can be utilized to convert the solid waste to energy. For example, Incineration, Pyrolysis, Anaerobic Digestion, and Landfill Gas Recovery. Each method has its own attractive attributes and drawbacks. Therefore, it is very important to choose the best technology or set of technologies, so the maximum energy with minimum effort can be achieved. In this research, the above-mentioned four technologies, are considered because they are suitable for the economy of Jordan and can be utilized. Additionally, they are the most common technologies.

Selecting the best technology to convert waste to energy is especially important for a country like Jordan that lacks its own energy resources and depends mainly on the imported fossil fuel to meet the increasing demand on energy. Given the fact that energy and waste sectors are responsible for more than 80% of the total greenhouse gases emitted in the country, waste to energy option is an attractive option to Jordan. To provide the decision makers in Jordan with a methodology to choose the best method to generate energy from waste, AHP-TOPSIS are utilized.

Both AHP and TOPSIS are multi-criteria decision-making method. The concept of AHP is to construct a pairwise comparison matrix based on soliciting experts' opinion with different backgrounds from academic, governmental and nongovernmental agencies who are involved in the waste and energy sectors in Jordan. The matrices are to compare between the alternatives for each criteria, then, set of calculations are performed to select the best choice, as will be more described later. In TOPSIS, alternatives are ranked based on their distance from the best or ideal one, and then the closest alternative to the ideal is taken.

2. Literature Review

Municipal solid wastes (MSW) are an important issue in any country. Wastes are generated and accumulated because of human activities. Population growth, urbanization and changes in lifestyles have resulted in an increase in the amounts of the generated solid waste, which poses serious challenges for many cities and authorities around the world. In developing countries, this is considered true [3]. In 2011, world cities generated about 1.3 billion tons of solid waste, this amount is expected to increase to 2.2 billion tons by 2025 [4 and 5]. Unless properly managed, solid waste will cause several environmental and public health problems and will significantly affect the economic development [4].

2.1. AHP and TOPSIS in Renewable Energy Problems

Researchers in many engineering fields, as in [6], have utilized AHP. In the energy sector, AHP and TOPSIS have been utilized to make decisions regarding the energy management because the sources of renewable energy are considered more important in these days compared to traditional resources such as fossil fuel or nuclear power plants. This is because of cleanness and availabilities of renewable sources in wide range of areas. The most important advantages of many renewable energy sources are their low greenhouse effect and other emissions in comparison with fossil fuel sources [7], they are less complex [8], and cost effective. As such, increased number of countries around the world consider renewable energy alternatives to decrease their dependency on the polluting imported fossil fuel [9]. However, none of the alternatives meets all advantages of the renewable energy resources [10]. Furthermore, due to the variations in economic, technical and environmental conditions, different countries have considered different options of renewable energy technologies [11].

In Jordan, a lot of research has been performed to manage the renewable energy and to benefit from it. For example, [12, 13, 14, 15, and 16]. In energy planning, selection of renewable energy technology is not an easy task that can be made based on a single criterion of decision-making. It is rather a multivariable complex problem where there is a need to prioritize certain renewable energy alternatives from various alternatives by considering consistency and multi interests and perspectives, using multi-criteria decision making (MCDM) [9]. Analytical hierarchy process (AHP) can be adopted as MCDM tool in many cases such determining the best energy source for a specific country, [17 and 18].

Several researchers used AHP in many fields evaluating and selecting various renewable energy technologies for different countries. An AHP model was developed in [19] to select and prioritize different renewable energy technologies to be used for Electricity production in Pakistan. Based on solicitation of experts' opinion, the researchers concluded that biomass and wind energy are the most preferable renewable energy sources. AHP and data envelopment analysis (DEA) have been used in [11] to evaluate and select renewable energy technologies in China. In this research, the results showed that solar and wind energies are the best alternatives for China based on environmental, economic, technical, and social criteria.

In [20], AHP have been used to rank and prioritize renewable energy options for sustainable electricity production in Malaysia. Solar energy is ranked first, and biomass is ranked second, these results were found according to the main criteria and their sub-criteria. Hydropower is set in the third rank, and finally the wind energy ranked the fourth as a least preferable option. In [18], opinions were solicited to rank the various renewable energy options in Colombia based on 5 criteria and 20 sub-criteria. In the results, technical criterion is found to be in the top of rank followed by environmental criteria, then the social, the risk and the economic criteria, which are ranked the lowest. The study concluded that the solar energy is ranked as the best alternative for Colombia.

To select the optimal waste to energy option in Sultanate of Oman, AHP model has been adopted in [21] that consisted of five criteria, six sub-criteria and eight alternatives. Among the assessed alternatives, the anaerobic digestion process was found to be the best solid waste to energy process for the country of Oman, followed by fermentation and incineration. [22] conducted another study that used AHP to select the best waste to energy technology for Dhaka city in Bangladesh. The AHP model consisted only of three criteria and three alternatives. There were no sub criteria. Among the three studied alternatives, the study concluded that the Plasma gasification ranked first followed by anaerobic digestion and pyrolysis. AHP with TOPSIS were integrated in [23] to evaluate the optimal collection strategy in reverse logistic for the Taiwan photovoltaic industry.

As noticed, utilizing MCDM in the field of generating energy from solid waste is still limited in Jordan. The purpose of the current study is to summarize and evaluate the solid waste management and energy sectors in Jordan, and to provide the policy makers in Jordan with a decision making tool to select the best Waste to Energy method of the country using two Multi-criteria decision tools, AHP and combination of AHP and TOPSIS.

3. Methodology of Multi-criteria Decision Making (MCDM)

3.1. The Analytic Hierarchy Process (AHP)

Multi-criteria decision-making (MCDM) process is utilized to select the best alternative in the presence of multiple, usually conflicting, criteria, [24]. The Analytic Hierarchy Process (AHP), which has been developed in [25], is one of the decision-making tools that serve such a purpose. AHP is performed by constructing pairwise comparison matrices based on experts' opinions. The comparisons are developed based on scaling the absolute judgments, which provides a measure of how much an alternative is important compared with others based on a specific criterion [26]. Table 1 shows the scale for measuring the opinions of experts; this scale is similar to the scale used in [25].

Table 1. Scale for pairwise comparison, [25].

Importance Scale	Definition of the Importance scale
1	Both criteria have the same importance
2	Intermediate value between the judgment in 1 and in 3
3	One criterion (row) has slightly weak importance over the other (column)
4	Intermediate value between the judgment in 3 and in 5
5	One criterion (row) is strongly important that the other criterion (column)
6	Intermediate value between the judgment in 5 and in 7
7	One criterion (row) importance is extremely stronger than the other criterion (column)
8	Intermediate value between the judgment in 7 and in 9
9	One criterion (row) importance is absolute stronger than the other criterion (column)

In this research, Experts who have long years of experience in solid waste management were interviewed to conduct the pairwise comparisons which were structured with four criteria, namely environmental, economic, social and technical aspects. These criteria were then expanded into a few more sub-criteria. Then, criteria and sub-criteria are compared based on different attributes and the pairwise comparison matrices are developed. This is done by soliciting experts' opinions and recording their judgments. Experts selected to perform, were from academics and researchers, energy business sector, regulators and nongovernment organizations (NGOs) that are dealing with energy issues. The solicitation of opinions was achieved via interviewing the experts and discussing with them the objectives of the study and asking them to fill the pairwise comparison matrices.

Judgments matrices were used to generate the priority vector to check the consistency of judgements by evaluating the consistency ratio (CR). The randomness in judgment can be measured by the consistency ratio, as in Equation 1:

$$CR = CI/RI \tag{1}$$

Where CI is the consistency index and RI is the random index, which expresses the expected value of the CI corresponding to the order of matrices. Table 2: represents the values of the RI versus the number of criteria (n).

Table 2. Random index (RI) values for different matrix sizes

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

If the CR value is acceptable (Usually less than 10%), the experts' opinions and judgments are considered consistent, alternatively, the subjective experts' judgement should be repeated until the CR values lie within the expected range. The combined priorities of each waste to energy alternative can be determined by aggregating the weights in the hierarchy, this is called judgments synthetization, which leads to select the best technology.

To analyze the sensitivity of the decisions on the proper waste to energy alternatives, dynamic sensitivity analysis was carried out to construct the sensitivity figures; Expert Choice Software was used for this purpose. Finally, the AHP model outcome regarding the ranking of waste were presented and discussed. Comparisons with the findings of researchers on appropriate waste to energy technologies were conducted. Finally, based on the findings of sensitivity analysis, conclusions will be made and recommendations for future studies will be suggested.

The procedure of applying AHP in this research is shown in Figure 1. The methodology of applying the hierarchy is shown in Figure 2, which shows 3 criteria, 9 sub criteria and 4 alternatives that should be subjected to pairwise comparison.

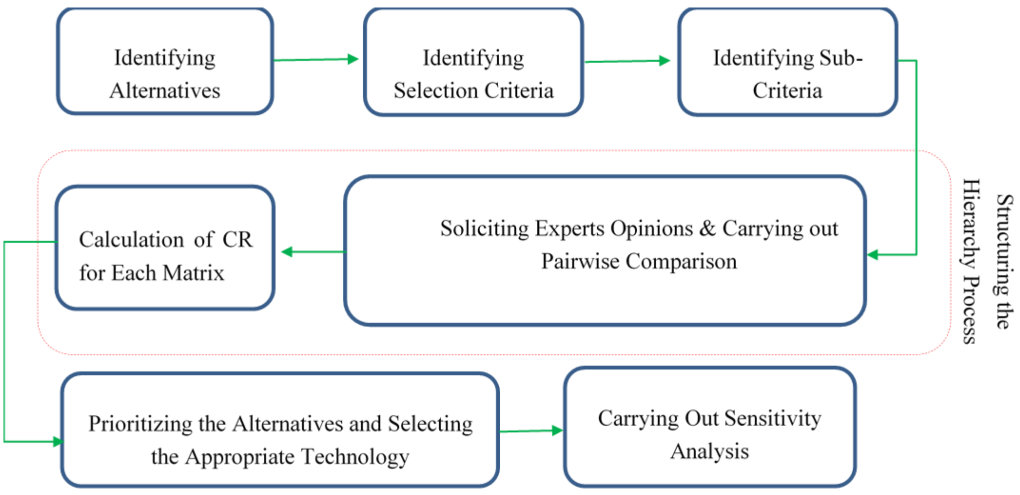


Figure 1. The methodology of AHP

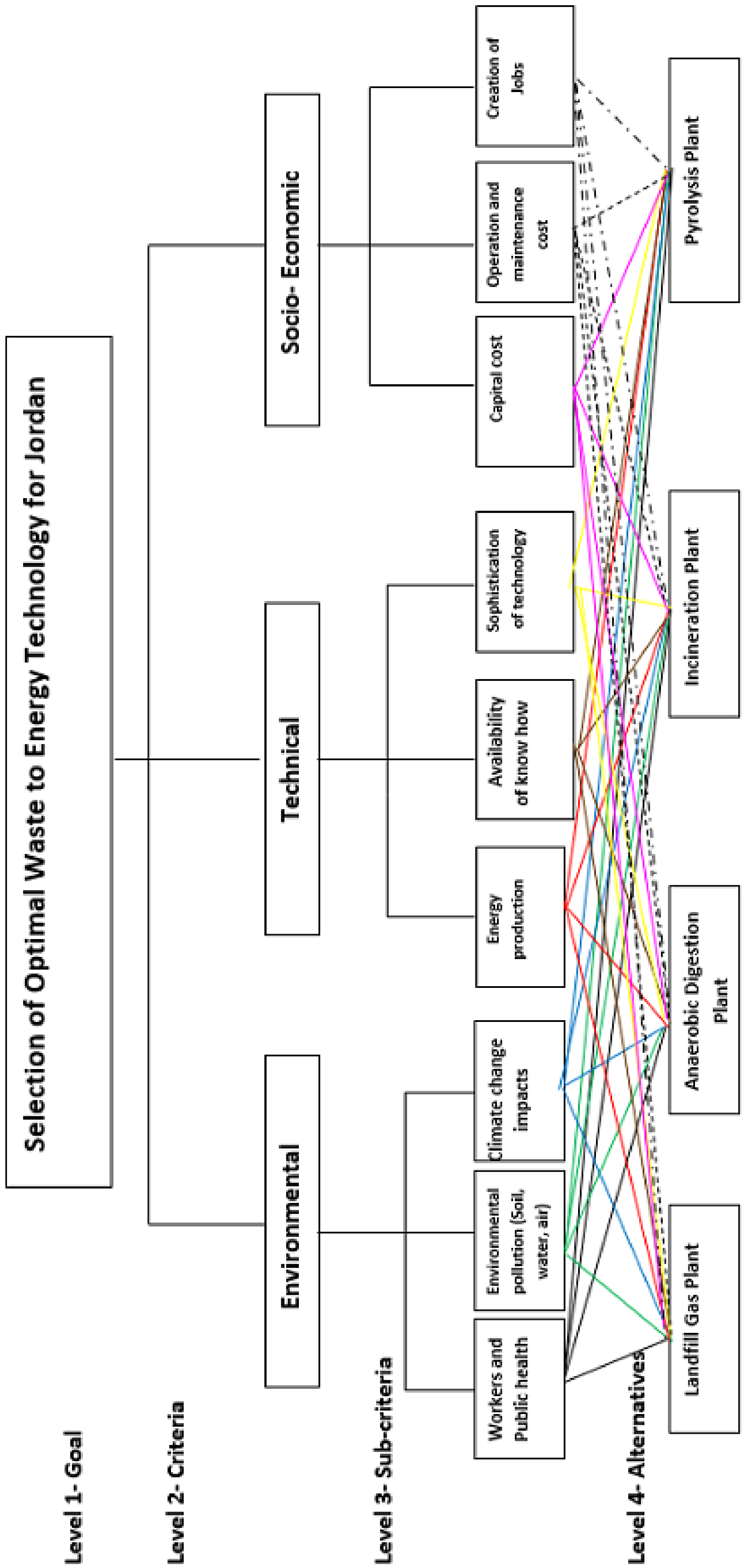


Figure 2. Analytical hierarchy model for the selection of Waste to Energy Technology

3.2. Technique of Order Preference Similarity to the Ideal Solution (TOPSIS)

TOPSIS is another known MCDM method, as proposed in [27], to find the best alternative. TOPSIS procedure starts with defining the ideal and least-ideal solutions. Then, the best solution is selected which is the one that has the minimum distance to ideal solution and maximum distance to the least-ideal solution [28]. Ideal solution is the solution that maximizes the benefits and minimizes the cost, whereas the least-ideal solution has the opposite definition. In TOPSIS, alternatives are arranged according to their "relative similarity to the ideal solution" [23]. The TOPSIS procedures are performed as in the next steps:

Step 1: Defining the matrix $D = [xij]$ which represents the performance rating of alternatives with respect to criteria, where the number of criteria is n and the number of alternatives is m.

$$D=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$$

Step 2: Determination of the normalized decision matrix, $R = [rij]$, as follows:

$$R=\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}$$

Where $rij = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{m} x_{kj}^2}}$ $\forall$ i=1, 2,…, m , j=1,2,…,n (2)

Step 3: Calculation of the weighted normalized decision matrix $V = [vij]$, which is developed as in the next, where wi is the weight of the ith criterion.

$vij = rij \times wi$ $\forall$ i=1, 2,…, m , j=1,2,…,n (3)

$$V=\begin{bmatrix} w_1.r_{11} & w_2.r_{12} & \cdots & w_n.r_{1n} \\ w_1.r_{21} & w_2.r_{22} & \cdots & w_n.r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ w_1.r_{m1} & w_2.r_{m2} & \cdots & w_n.r_{mn} \end{bmatrix}$$

Step 4: Positive ideal solution (PIS, A*) and negative ideal solution (NIS, A−) can be calculated as:

$$A^* = \{(\overset{MAX}{i} v_{ij} | \overset{MIN}{i} v_{ij} | j\epsilon c)\} \quad (4)$$

$$A^- = \{(\overset{MAX}{i} vij | \overset{MIN}{i} vij | j\epsilon c)\} \quad (5)$$

Step 5: Calculation the distances between each option and the NIS and PIS by using the Vertex method.

$$di^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j)^2} \quad , i=1,2,…,m ; j=1,2,...,3 \quad (6)$$

$$di^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j)^2} \quad , i=1,2,…,m ; j=1,2,...,3 \quad (7)$$

Step 6: The closeness coefficient of each alternative is calculated as in Equation 9. Finally, the alternatives are ranked in descending order of the CCi index.

$$CC_i = \frac{d^-}{d_i^- + d_i^*} \quad (8)$$

3.3. Integration of AHP and TOPSIS

To select the optimal waste to energy alternative in Jordan, AHP and TOPSIS decision-making processes were combined together. This has been achieved by using the weightings of the criteria and sub-criteria obtained from AHP analysis and fed into TOPSIS to rank the optimal waste to energy alternative. Figure 3 shows how the two decision-making tools were combined.

4. Results and Discussion

4.1. Screening of Alternatives and Criteria

Now, there are numerous waste to energy technologies and options that are available worldwide [29]. Furthermore, too many criteria and sub-criteria can be used in evaluating the waste to energy alternatives. However, there is no universal technology or group of technology that suits all countries [30]. Therefore, selection of alternatives and definition of criteria with their weights are central in AHP to assess the alternatives. To achieve that, a screening process should be carried out at the beginning of decision-making process to identify the alternatives that are feasible for the problem and the criteria and sub-criteria that will be used in the judgement [31].

Jordan is a developing country that is lacking indigenous energy resources. The World Bank classifies countries based on their economies into four categories, namely, high, upper middle, lower middle and low. In 2017, the Bank classified Jordan as a lower middle-income country. Therefore, alternatives and criteria of waste to energy are essential to adopt and select appropriate solutions in Jordan. As such, the following alternatives of waste to energy technologies were selected for this purpose, such as Landfill biogas, Anaerobic digestion, Incineration, and Pyrolysis.

Table 3 shows three evaluation criteria and sub-criteria used in the AHP process to select the best alternative of waste to energy in Jordan. As observed, three main criteria were selected, mainly the Environmental, Technical and Socio-Economic. Under each criterion, there are three relevant sub-criteria.

Table 3. Criteria and sub-criteria used in the AHP analysis

Criteria	Sub-criteria	Description
Environmental	Public and workers' health Water, air and soil pollution Climate change	Minimum adverse impacts of the selected technologies on the public as well as on the labor health Minimum potential release of pollutants into the ecosystem Minimum Greenhouse gas emissions by technology
Technical	Energy production Know how Sophistication of Technology	Maximum possible energy production from waste Availability of expertise and staff to run the technology. Complexity of the technology and requirements of spare parts
Socio-Economic	Capital cost Operation and maintenance Job creation	Minimum Initial investment cost needed Minimum operation & maintenance cost is established Maximum number of employment opportunities created by Y technology

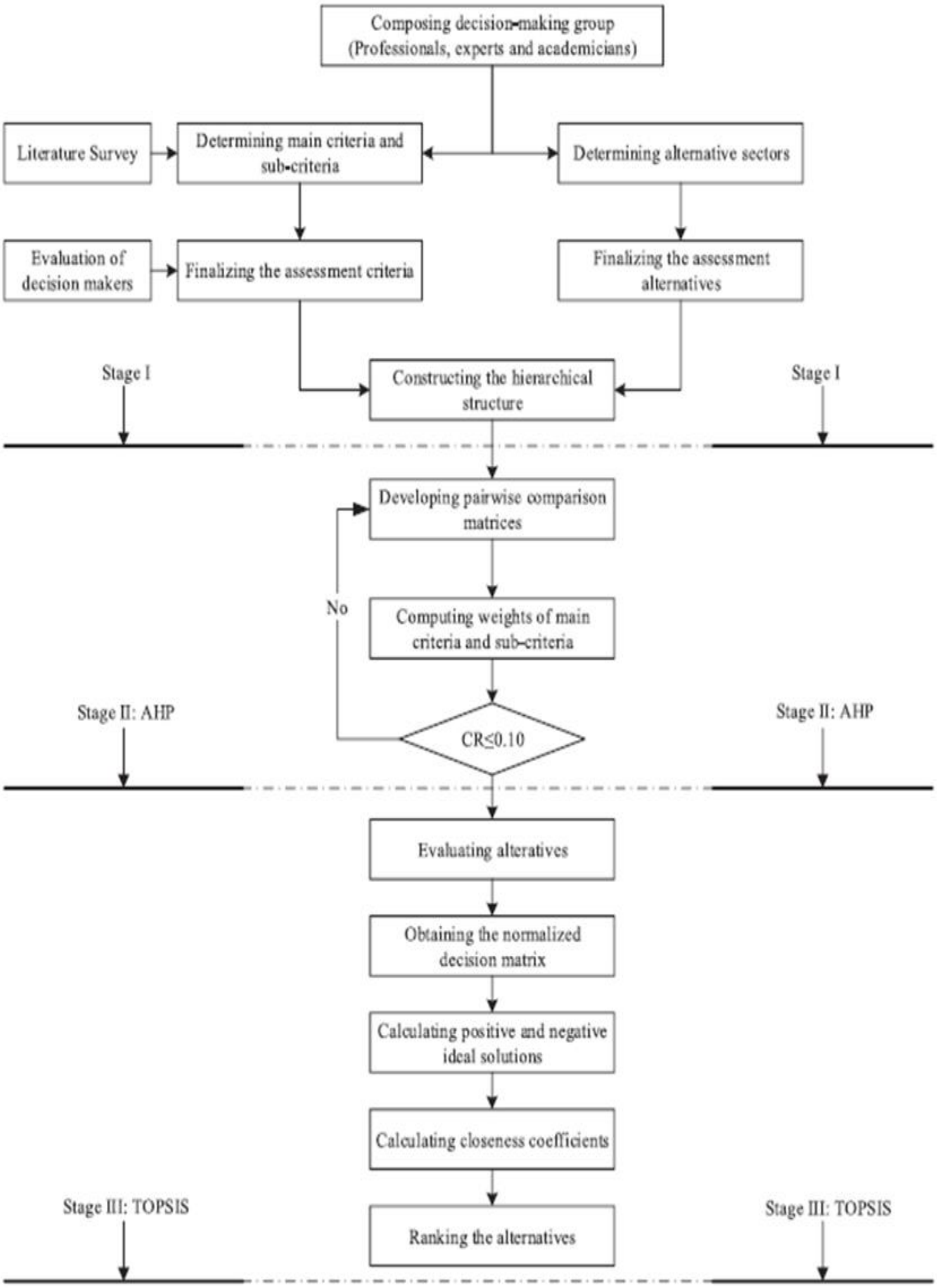


Figure 3. Flow diagram shows the procedure followed in integrating AHP with TOPSIS.

4.2. Soliciting of Expert Opinion

In AHP, expert opinion is a major step towards making judgement on the alternatives as well as the criteria importance by constructing pairwise matrices. In this study, judgments in the pairwise matrices are developed based on soliciting experts' opinions. Stakeholders, waste and energy experts, researchers, plants operators, public figures and policy makers who are familiar with the situation of the Jordanian waste and energy sectors, were consulted. In this study, opinions of 10 experts were solicited using a questionnaire. In AHP, number of experts is usually limited because the experts in the field with long experience are not easily found. Additionally, if the experts have an outstanding knowledge in the field, they are expected to provide consistent judgments that lead to the conclusions based on the low number of feedbacks; which is the case in this study, as we notice in the consistency results. Table 4 shows the categories of stakeholders whose opinions were solicited and their categories and number from each category.

The values of scores expressed through experts' opinions in each pairwise comparison matrices were aggregated using additive AHP procedure (by calculating the arithmetic mean for matrices developed by the experts) [31].

Table 4. List of stakeholder categories and their numbers whose opinions were solicited

No.	Stakeholders category	Profession	Number
1.	Waste and Environmental Academicians	Lecturers and Researchers	3
2.	Energy Academicians	Lecturers and Researchers	2
2.	Waste and municipal Professionals	Policy and Decision makers	2
3.	Community members	Business and NGOs members	3
	Total		10

4.3. Results of Pairwise Comparison

After the screening and constructing of the hierarchy structure, pairwise comparison was conducted to generate judgement matrices. This has covered the comparison between alternatives with respect to each sub-criterion, between sub-criteria with respect to main criterion, and between criteria with respect to the goal.

Initially, pairwise comparison of the selected criteria to achieve the goal was performed. Table 5 demonstrates a matrix with the derived priorities of the main criteria with respect to goal based on the pairwise comparison obtained from the experts. The value of the consistency ratio (CR) is 0.08, which is less than 0.1, consequently, the judgements in the matrix are consistent and logically satisfactory. Equation 1 is used here and in the next results to calculate the CR. In all of the next tables, the star symbol (*) represents the comparison value (x_{ij}) which can be found directly from the table and equals to ($1/x_{ji}$).

Table 5. Pairwise comparison matrix of main criteria with respect to goal

Criteria	Environmental	Technical	Socio-Economic	Priority vector
Environmental	1	4.5	5.6	0.699
Technical	*	1	3.0	0.208
Socio-Economic	*	*	1	0.093

The highest weight was given to the environmental criterion with value of 0.69. Then, the technical criterion that has a weight of 0.21, in addition to the criterion of socio economic that has the least weight of 0.09. This means that the environmental issues should take the maximum care and attention when the solid wastes are used to generate energy in Jordan. This is can be justified by the fact that Jordan is located in a semi-arid region where the environmental issues are of high concern for the decision makers of the country. For example, Jordan ranks the second poorest country worldwide in terms of renewable water resources [32]. Therefore, it is important to conserve and save every drop of water from pollution.

To choose the most suitable alternative of the waste to energy method for Jordan, three pairwise comparison matrices were developed. Each matrix represents the relative weights, resulted from the experts' feedback, of three sub-criteria with respect to one main criterion.

Tables 6, 7 and 8, show the pairwise comparisons, and Figures 4 a-c shows the weights for the environmental, technical, and socio-economic sub-criteria with respect to main criteria, respectively.

Table 6 presents pairwise comparison of environmental sub-criteria with respect to the main criteria. The consistency ratio of the pairwise matrix was calculated and found to be 0.09 of less than 0.1, which means that the judgments were consistent.

Table 6. Environmental criterion pairwise comparison matrix

Sub-Criteria	Workers & Public health	Environmental Pollution	Climate Change	Priority Vector
Workers & Public health	1	4.6	5.6	0.7
Environmental pollution	*	1	3.1	0.20
Climate change	*	*	1	0.1

Figure 4 (a) shows the weights of the environmental sub-criteria, where the workers and public health sub-criteria ranked first with 70% of the total weight, followed by environmental pollution criteria with 20% of the total weight and finally the climate change criteria which has the least weight of 10%. The high weight of the workers and public health sub-criteria may be justified as that the soliciting of the experts' opinion took place during the corona virus lockdown in Jordan, when the public health issues were priority for everybody in the country, which has been reflected on the solicited opinions and gave the public health the highest priority.

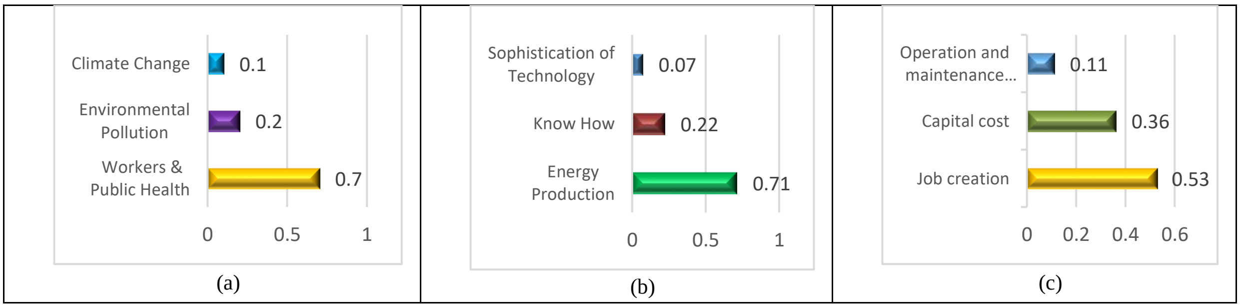


Figure 4. Relative weights of Environmental (a), Technical (b), and socio-economic (c) sub-criteria with respect to main criterion

The pairwise comparison results of technical sub-criteria with respect to the main criterion are presented in table 7. The CR was found to be 0.08 which is a satisfactory value as it is less than 0.1.

Table 7. Technical criterion pairwise comparison matrix

Sub-Criteria	Energy Production	Availability of know how	Sophistication of technology	Priority Vector
Energy Production	1	4.3	7.4	0.71
Availability of know how	*	1	4.2	0.22
Sophistication of technology	*	*	1	0.07

Figure 4(b) depicts the relative weights of Technical sub-criteria with respect to main criterion. It can be observed that energy production sub-criteria has the highest weight of 71%, followed by know how sub-criteria of 22% and technology sophistication with 7%. This can be understood from the energetic situation of Jordan, where more than 95% of the energy is imported, and therefore finding national resources of energy that can contribute to energy security of the country is a priority. As such, the experts gave the highest priority for energy production generated by each of the waste to energy alternative.

Table 8 presents the pairwise comparison matrix of sub-criteria with respect to socio-economic criterion. The calculated consistency ratio found was 0.08, which implies the acceptance of the experts' judgements.

Table 8. Pairwise comparison matrix of sub-criteria with respect to Socio-economic criterion

Sub-Criteria	Capital Cost	Operation & Maintenance Cost	Job Creation	Priority Vector
Capital Cost	1	4.2	2.0	0.53
Operation & Maintenance Cost	*	1	3.5	0.36
Job Creation	*	*	1	0.11

Figure 4(c) shows the results of the ranking of the socio-economic sub-criteria. Job creation has the highest priority with a weight of 53%, followed by capital cost of 36% and finally the operation and maintenance cost of 11%. Considering the fact that the unemployment rate in Jordan reached 19% in the year of 2019 (DOS, 2019), it is not surprising that job creation has the highest priority according to the experts' opinion, especially during the corona virus pandemic lockdown when many people lost their jobs which increased the percentage of the unemployment above the announced figure of 19%.

Taking into account that the waste to energy projects in Jordan are mainly financed through grants or soft loans, and the payback period of most renewable energy projects are short, the financial issues like capital and operation and maintenance costs have received less weight as compared to job creation sub-criteria.

4.4. Pairwise comparison of the alternatives under sub-criteria

The local priorities of alternatives under each sub-criterion are obtained from the pairwise comparison based on the experts' opinions. The results of comparison are presented in Figure 5. As it can be observed, the analysis revealed that all the alternatives have the same order of ranking under all the considered sub-criteria but with different priority values. The landfill biogas ranked first, followed by anaerobic digestion. On the other hand, the incineration and pyrolysis technologies, ranked third and fourth, respectively with relatively low weights. Considering the high tech nature of thermal process, and because the highest fraction of municipal solid waste in Jordan is food waste that comprises more than 50% of the total weight of the generated waste, the experts ranked biological processes like landfill biogas and anaerobic digestion of being the most preferable under all the sub-criteria as shown in Figure 5.

In order to have similar system boundaries for all alternatives, it is worth mentioning that all stages of solid waste storage, generation, storage, collection transfer and transport are the same for all alternatives. Consistency ratios for all pairwise comparison of the sub-criteria were calculated with values less than 0.1, except for the knowhow and operation and maintenance sub-criteria which both have a consistency ratio of 0.11, which is acceptable as it is slightly higher than 0.1.

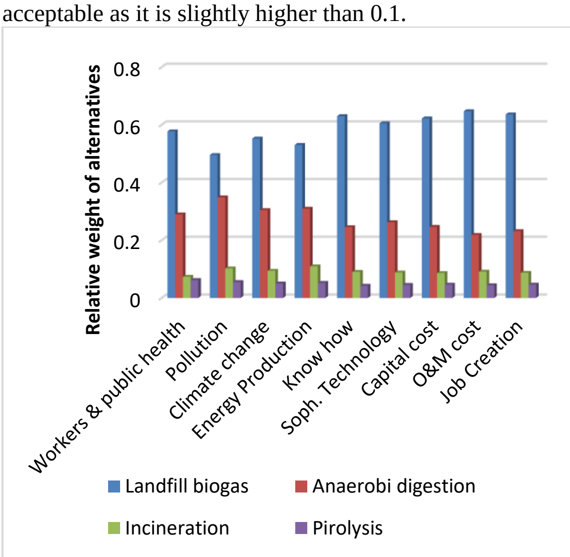


Figure 5. Ranking of waste to energy options based on each sub-criteria

4.5. Global Priorities of Alternatives

Relative (local) priorities of the criteria with respect to the main goal, as well as the relative priorities of the alternatives with respect to all sub-criteria were determined. Global priorities can be determined for waste to energy alternatives by multiplying the local priority vector of each criterion by local priority vector of alternatives, then the results are summed to get the global weight vector, as follows, [33 and 34]:

$$P_{Gi} = \sum P_{cj} P_{ij} \qquad (9)$$

Where:

P_{Gi} is the global priority of the ith alternative with respect to the main goal

P_{cj} is the relative priority of the jth criteria with respect to the main goal

P_{ij} is the relative priorities of the ith alternative with respect to jth criteria

The landfill biogas plant option ranked first with a global priority of 0.561, followed by anaerobic digestion plant that was ranked second alternative with a weight of 0.296. The incineration plant and pyrolysis plants are the least preferred alternatives as judged by the low weight of 0.087 and 0.056 respectively.

As previously mentioned, both landfill biogas and anaerobic digestion are biological processes that depend on the biodegradation of organic fraction of the waste in the absence of oxygen which produce methane as a source of energy. On the other hand, the incineration and pyrolysis are thermal processes that depend on combustion of certain fraction of solid waste that has a relatively high heating value like plastics and wood. In terms of technology, thermal processes are sophisticated technologies as compared to biological processes that required qualified experienced personnel. Considering the high tech nature of thermal process, in addition to the fact that the highest fraction of municipal solid waste in Jordan is food waste comprising more than 50% of the total weight of the generated waste, the experts ranked biological processes, such as landfill biogas and anaerobic digestion, of being the most preferable under all the sub-criteria

5. Results of AHP and TOPSIS Integration

The second decision-making tool adopted in this study is the combination of AHP with TOPSIS. The criteria and weights obtained from AHP pairwise comparison were taken and fed into TOPSIS model to find their sub-criteria global weights, by using Equation 9, so as to prioritize waste to Energy options for Jordan. The sub-criteria were given letter symbols as in Table 9. Results in the global weight column are explained next.

Table 9. Criteria and Sub-criteria symbols

Criteria	Weight	Sub-criteria name	Sub-criteria Symbol	Global Weight	Type (Should be …….)
Environmental	0.699	Workers and Public Health	C11	0.488	Maximized
		Environmental Pollution	C12	0.146	Minimized
		Climate Change	C13	0.065	Minimized
Technical	0.208	Energy Production	C21	0.147	Maximized
		Availability of Know How	C22	0.046	Maximized
		Sophistication of Technology	C23	0.015	Maximized
Socio-Economic	0.093	Capital Cost	C31	0.033	Minimized
		Operation and Maintenance Cost	C32	0.011	Minimized
		Job Creation	C33	0.049	NA

First step is to find the global weights of the sub-criteria based on experts' opinion. Table 9 shows the global weights of the sub-criteria under each main criteria based on the expert's opinion. As can be seen from table, sub-criteria C11, C21and C33 has the highest weights under each criterion. After the weights of sub-criteria were calculated a decision matrix under TOPSIS has been developed. Table 10 shows the decision evaluation matrix that relates different alternatives to the nine sub-criteria.

Table 10. Decision evaluation matrix

	C11	C12	C13	C21	C22	C23	C13	C32	C33
Landfill Gas (LFG)	3.2	3	4.2	2	5.2	3.2	1.8	1.6	5.4
Anaerobic Digestion Plant (AD)	8.4	5.2	6.4	3.2	7.8	2	3.6	5.8	9.4
Incineration Plant (IN)	6.8	6.2	6.8	4.8	1.8	8.2	7	9.4	2.2
Pyrolysis Plant (PY)	3.8	8.8	9.2	7.4	2.6	5	9.2	7	2.8
Weights	0.488	0.146	0.065	0.147	0.046	0.015	0.033	0.011	0.049

After developing the decision matrix, the normalized matrix and the weighted normalized matrices are determined which are presented in tables 11 and 12, respectively. Equations 2 and 3 are used for this purpose.

Table 11. Normalized decision matrix.

	C11	C12	C13	C21	C22	C23	C13	C32	C33
LFG	0.269	0.243	0.305	0.208	0.525	0.310	0.147	0.121	0.473
AD	0.706	0.422	0.465	0.334	0.788	0.194	0.294	0.440	0.824
IN	0.572	0.503	0.494	0.500	0.182	0.795	0.572	0.714	0.193
PY	0.319	0.714	0.668	0.771	0.236	0.485	0.752	0.531	0.245
Weights	0.488	0.146	0.065	0.147	0.046	0.015	0.033	0.011	0.049

Table 12. Weighted normalized decision matrix.

	C11	C12	C13	C21	C22	C23	C13	C32	C33
LFG	0.131	0.035	0.019	0.031	0.024	0.004	0.004	0.001	0.023
AD	0.345	0.062	0.030	0.049	0.036	0.002	0.009	0.005	0.040
IN	0.279	0.073	0.032	0.074	0.008	0.012	0.019	0.008	0.009
PY	0.156	0.104	0.043	0.104	0.012	0.007	0.025	0.006	0.012
A_i^*	0.131	0.035	0.019	0.104	0.036	0.012	0.004	0.001	0.04
A_i^-	0.345	0.104	0.043	0.031	0.008	0.002	0.025	0.008	0.009

Finally, the closeness coefficient to the ideal solution for each waste to energy was calculated, by using equations 4-8, as presented in Table 13. As it can be seen from the table, the Landfill biogas alternative has the least distance to the ideal solution and consequently the highest closeness coefficient of 0.75, which implies that landfill biogas is the most preferable alternative under AHP-TOPSIS. This is in agreement with the findings under AHP model. However, the second ranked alternative under

TOPSIS was found to be pyrolysis, which ranked the least preferable under AHP.

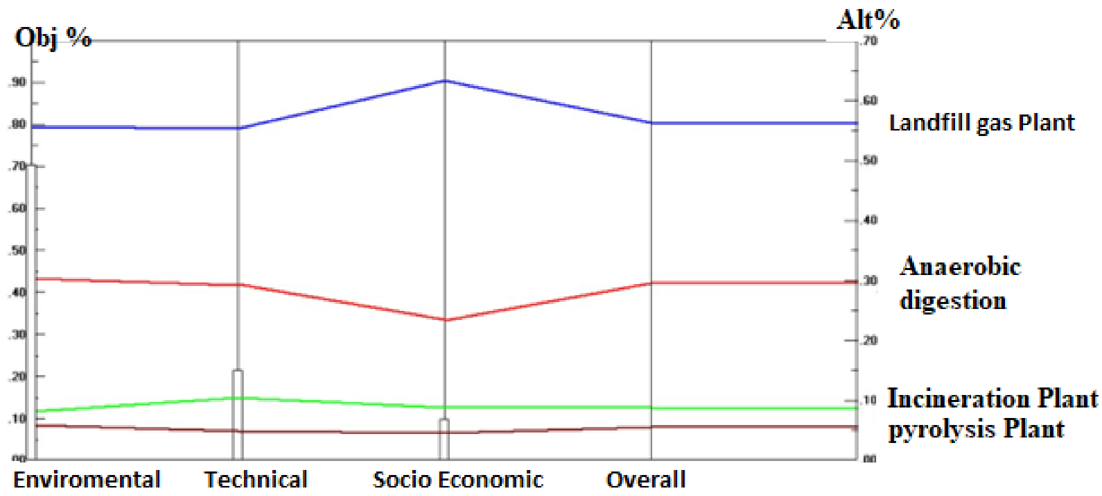
Table 13. Distance and closeness to the ideal solution of the waste to energy alternatives

Alternative	d_i^*	d_i^-	CC_i	Ranking
LFG	0.076	0.228	0.75	1
AD	0.233	0.065	0.21812	4
IN	0.163	0.086	0.34538	3
PY	0.088	0.203	0.69759	2

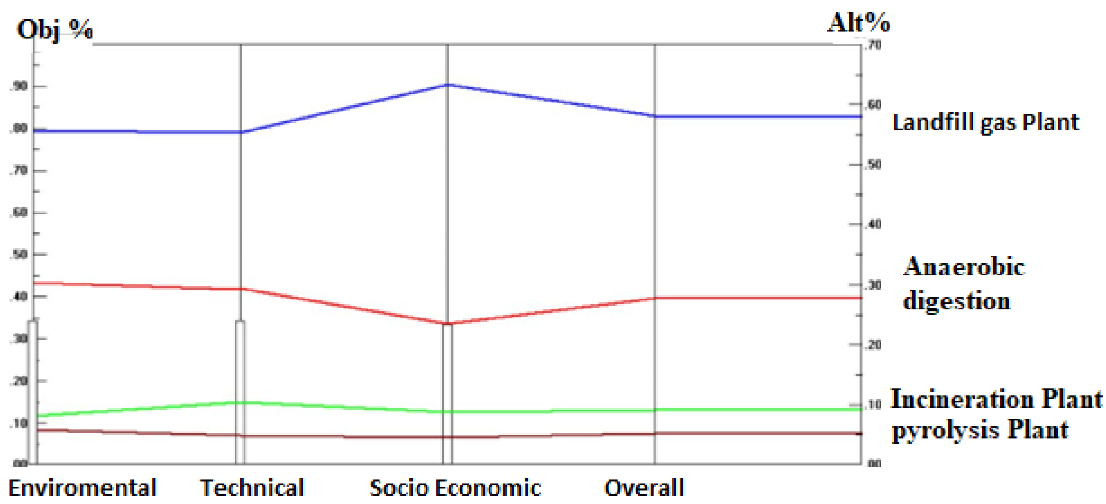
6. Sensitivity Analysis

The results of analytical hierarchy process analysis are highly dependent on the preferences of experts where any changes in the relative importance of the various criteria and alternatives assigned by the experts may influence the results of AHP analysis in terms of ranking the alternatives or changes in the value of the global priorities of the alternatives [34]. As such, carrying out sensitivity analysis is an important step to check the consistency of the results as well as the robustness of the ranking. To analyze the sensitivity of the selected alternatives, performance sensitivity graphs were obtained according to different scenarios using Expert Choice software. In this study, sensitivity analysis was performed based on different scenarios.

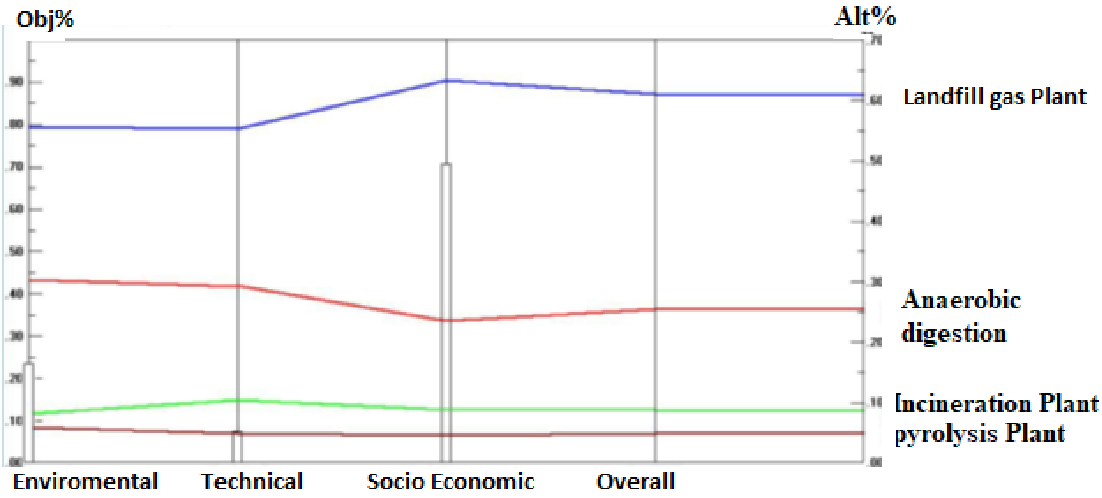
The first scenario is called Baseline. Under this scenario, there is no change in criteria weights, which are exactly as assessed based on the experts' opinion as shown in the graph presented in Figure 6 (a). It is worth mentioning that this is a dynamic graph with two main vertical axes. The purpose of the axis on the left of the graph is to show the relative importance of each main criterion, while the second axis on the right is the alternative axis which is used to measure the total weight of each alternative.



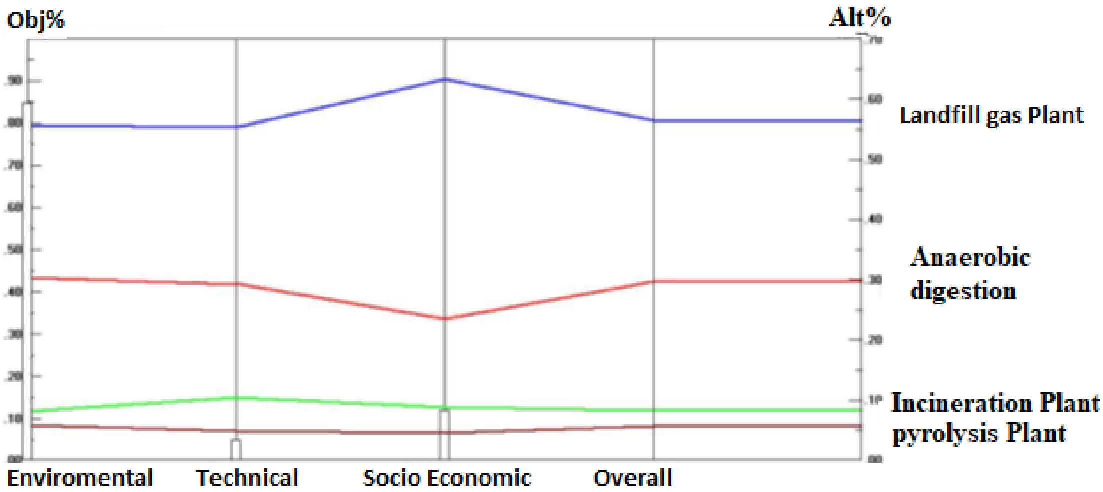
(a) Sensitivity analysis according to baseline scenario



(b) Sensitivity analysis according to second scenario under which criteria have equal weights



(c) Sensitivity analysis according to third scenario under which socio-economic criterion weight increased to 75%



(d) Sensitivity analysis according to third scenario under which the technical criterion weight decreased to 5%

Figure 6. Sensitivity graphs

The second scenario is based on the assumption that all the three criteria used in evaluation of waste to energy alternatives have the same weight of 33.3%. Figure 6 (b) shows the sensitivity analysis of this scenario. It seems that the alternatives are not that sensitive under this scenario. The ranking remains the same, where landfill gas plant has the first priority; however, there are slight changes in the weight of alternatives.

The third scenario is used to change the criteria weights. According to this scenario, the criteria weights are randomly changing and the alternative weights are detected. Figures 6 (c-d) depict these changes. It can be observed that by changing the weight of the socio economic criterion from 9% to 70%, the weights of environmental criteria decreased to 24% and technical criterion to 5%. Moreover, the weight of the landfill gas alternative increases from 56% to 61%, while the weight of the anaerobic digestion alternative decreases to 25%. On the other hand, the weights of the incineration and pyrolysis alternatives did not witness significant changes.

7. Conclusions and Recommendations

In Jordan, energy and waste sectors are responsible for more than 80% of the total greenhouse gases emitted in the country from all sectors. Therefore, adopting waste to energy options is a win-win approach that will lead to the reduction in the amount of fossil fuel combustion and the polluting emissions associated with this use. In addition, it will reduce the amount of improper disposal of solid waste and the amounts of the greenhouse gases by utilizing the methane in energy production.

This study has focused on the selection of appropriate waste to energy option for Jordan using two decision making tools, namely analytical hierarchy process (AHP) and combination of analytical hierarchy process and technique for ordering preference by similarity to the ideal solution (TOPSIS). Four levels AHP model was constructed that consists of 3 criteria, 9 sub-criteria and 4 alternatives. Opinions of ten experts from various academics, researchers, governmental and nongovernmental agencies were solicited to carry out pairwise comparison of the criteria and alternatives using a specially designed questionnaire. Thirteen pairwise comparison matrices were generated. The analysis of priorities for criteria, sub-criteria and alternatives was conducted using Expert Choice software. Consistency analysis of the pairwise comparison matrices was conducted where in most cases the consistency ratio was less than 0.1.

Pairwise comparison of the criteria with respect to the goal of selecting appropriate waste to energy alternative revealed that the environmental criterion has the highest priority followed by technical criterion and the least priority was assigned to the socioeconomic criterion. As for the pairwise comparison of the sub-criteria under the main criteria, workers and public health sub-criteria had the highest priority under the environmental criteria, while the energy production had the first priority under technical criteria, and finally the job creation sub-criteria had the first priority under the socioeconomic criteria.

Under AHP, the global priority of alternatives revealed that landfill gas plant is the most preferred option with a weight of 56%, followed by anaerobic digestion with a weight of 29%, while the incineration and pyrolysis alternatives are the least preferred alternatives with 9% and 6%, respectively. This indicates that alternatives based on biological processes, as landfill gas and anaerobic digestion, are more preferable than alternatives based on thermal technologies, such as incinerator and pyrolysis. This maybe because that biological processes are less complicated and cheaper than thermal ones, which suit developing countries like Jordan.

Under AHP-TOPSIS analysis, the landfill gas alternative is also ranked the most preferred alternative, while the pyrolysis alternative is ranked the second, the incinerator is ranked third (same rank as under AHP), and finally the anaerobic digestion was the least preferred option.

Based on the findings of the current study, the following recommendations are made:

1. Jordan should consider waste to energy technologies more seriously and start adopting technologies like landfill gas and anaerobic digestion. Some recent research shows the economical advantages of utilizing such technology, as in [35].
2. In case the decision makers will follow the recommendations of the current study by adopting landfill biogas technology as an option of waste to energy in Jordan, the landfills should be designed and constructed as an engineered facility with proper lining, capping and containment systems, so as to maximize the amount of biogas generated and collected.
3. Further studies are recommended to cover other alternatives of waste to energy, such as refuse derived fuel, gasification by considering more criteria and sub-criteria and using other decision making tools rather than AHP and TOPSIS.

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