Selection of a Suitable Waste to Energy Technology for Greater Beirut Area Using the Analytic Hierarchy Process

Abbas El Toufaili*, Dario Pozzetto, Elio Padoano, Luca Toneatti, and Ghassan Fakhoury

***Abstract*—Waste to Energy (WtE) is becoming an interesting option for many countries as an effective waste management solution. The goal of this study is the selection of a suitable WtE technology for the treatment of municipal solid waste in Greater Beirut Area (GBA). In adopting a potential WtE technology for solid waste treatment in GBA, the protection of the environment and citizens health is mandatory, but it is also evident the pressing need for economically feasible new electrical energy sources. For a well and an efficient functioning of a WtE plant, an appropriate supply chain system of municipal solid waste should be guaranteed. The selection of a suitable WtE technology is a complex decision and to achieve the stated objective the Analytic Hierarchy Process (AHP) method was employed and experts in the waste management sector were consulted to formulate the model. AHP analysis was performed using SpiceLogic software. Results indicate that Composting is the best choice with a global score of 0.33, followed by Anaerobic Digestion which acquired 0.21 and Incineration ranked as the third preferred technology obtaining 0.14. A sensitivity analysis was conducted to ensure the results consistency, assessing the reliability of the experts' judgments.**

***Index Terms*—Developing countries, Lebanon, multi criteria decision analysis, municipal solid waste, sensitivity analysis**

I. Introduction

The increasing world population, estimated to reach 9.7 billion by 2050 [1], is playing a major role in Municipal Solid Waste (MSW) production. The world generated 2010 Mt of MSW in 2016 of which 33% has been managed in a conventional and environmentally unsafe manner. Moreover, the MSW generation is expected to increase to 2,600 Mt by 2,030 and 3,400 Mt by 2050 [2]. Compared to MSW, the generation rate of industrial waste and agricultural waste at global level is 18 times and 4 times higher, respectively [2, 3]. Waste generation in high-income countries is expected to increase by 19% by 2050, while in low- and middle-income countries by approximately 40% [2]. Fig. 1 shows the relative incidence of the methods used at global level for solid waste disposal and treatment.

Approximately 1.6 billion tons of carbon dioxide (CO_2) equivalent greenhouse gas emissions were generated from solid waste treatment and disposal in 2016 (5% of global emissions). This is due primarily to disposing of waste in open dumps and landfills, without any gas collection systems. The emissions related to solid waste management are anticipated to increase to 2.38 billion tons of CO_2 equivalent per year by 2050 if no improvements are made in the sector [2].

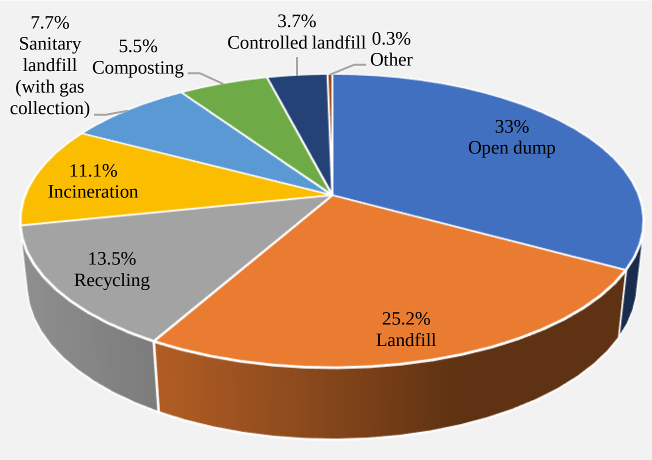

Fig. 1. Global treatment and disposal of waste (World bank, 2021) [2].

The energy production is currently insufficient to allow growth for numerous developing countries. Regardless of the energy source, it is estimated that by 2040 electricity generation will increase globally by 49%. By 2040, renewable energy sources are expected to cover an 8% of the total demand for global energy [4]. The market value of WtE technologies is expected to increase over 26.6 Billion Dollars by 2025 [3], and it is estimated that around 2,700 plants with a combined treatment capacity of over 480 Mt per year will be operational by 2026 [3]. GHG removal by WtE is estimated to surge from 16,061 tons CO_2 eq/year in 2012 to 33,477 tons of CO_2 eq/year in 2021 [5]. One of the biggest barriers to the market development of WtE is the high cost of the technology in comparison to landfilling. The growth of the WtE market, the investment increase in the WtE's research and development at global level and the future technological improvements will most likely drive the costs down for WtE technologies, making them economically feasible in developing countries as well [3].

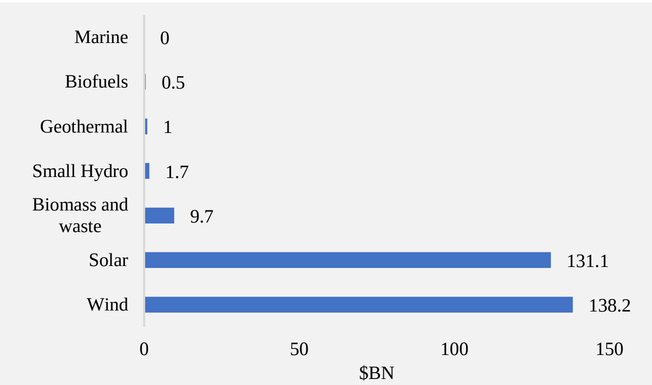

Fig. 2. Global investment in renewable energy capacity by sector in 2019 [6].

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The mismanagement of solid waste in developing countries is associated with the excessive fragmentation of the process of solid waste management, also characterized by a limited cooperation among stakeholders, the weak governance, the institutional structures, and the management capabilities. Key common challenges facing developing countries include the use of primitive treatment technologies and disposal methods, low collection coverage and irregular collection services, lack of political commitment and human resources, limited public awareness on proper waste management practices, absence of formal recycling programs at the household level, lack of organizational capacities , expertise and financial resources. Other important issues include the lack of integration of the informal systems, inadequate public-private partnerships and public participation. Solid Waste Management SWM is an ongoing challenge in developing countries due to the lack of effective material flow tracking data [7, 8].

Lebanon suffers from both a serious solid waste dilemma and a deficiency in electrical energy production. It is to be noted that several factors have led to the increase of the burden of solid waste in Lebanon: population growth, rapid growth of the urban areas and the big cities, increase in the income per capita, absence of legal framework and poor law enforcement, contradiction in environmental policies, social habits that do not encourage waste minimization, social keenness to use new materials rather than used ones, and the increasing number of refugees [7, 8].

The Republic of Lebanon is a small developing country with low-medium income population. Lebanon's GNI per capita was estimated at USD 5,510 in 2020 [2]. In 2020, about 6,800,000 citizens and 900,000 refugees were living in Lebanon, with an average density of 560 inhabitants/km^2 [9]. Approximately, 49% are located in the areas of Beirut and Mount Lebanon (BML), which account for only 20% of the territory.

The total generation of MSW in Lebanon is 2.7 million tons/year, each person generates 1.05 kg/day in average. By 2035, Lebanon will produce 2.9 million tons/year with a growth of 1.65% per year [7, 10]. The municipal collection services coverage is 98-100% in urban areas and 90–100% in rural areas. Waste disposal in Lebanon is problematic because of its limited surface area. The scavenging activities are illegal in Lebanon; nevertheless, there are between 1,000 and 4,000 waste pickers that collect trash to sell [7].

Waste generation across the country has substantially decreased in year 2020 because of: the economic crisis leading to a nation-wide decline in purchasing capacity, and the COVID 19 pandemic. Yet an improvement was observed in the proportion of the recycled waste sold to the industry as secondary raw material from 74% in the 2014–2015 period (before the 2015–2016 waste crisis) to 95% in the 2017–2019 period [10].

Fig. 3 shows the MSW generated per governorate and Fig. 4 shows the waste composition.

Only 6% and 15% of solid waste are respectively recycled and composted (Fig. 5). The most common materials that are recovered include: organic material, various types of paper products, some plastics, and metallic containers.

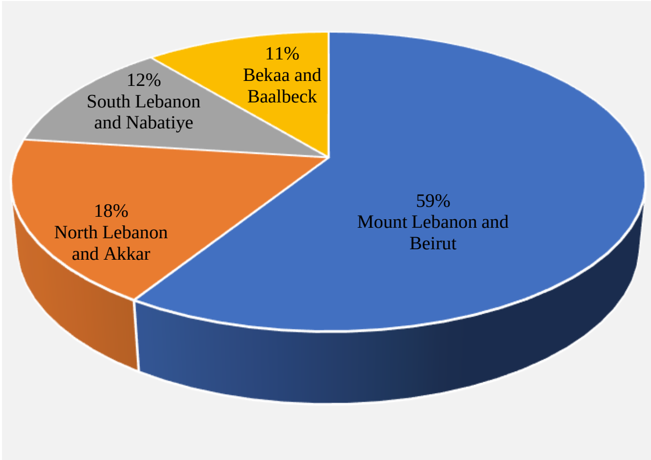


Fig. 3. MSW generated per governorate [11].

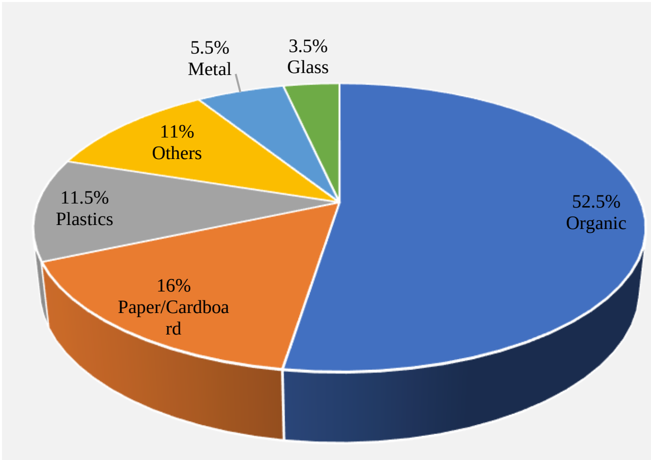


Fig. 4. Waste composition in Lebanon [10, 11].

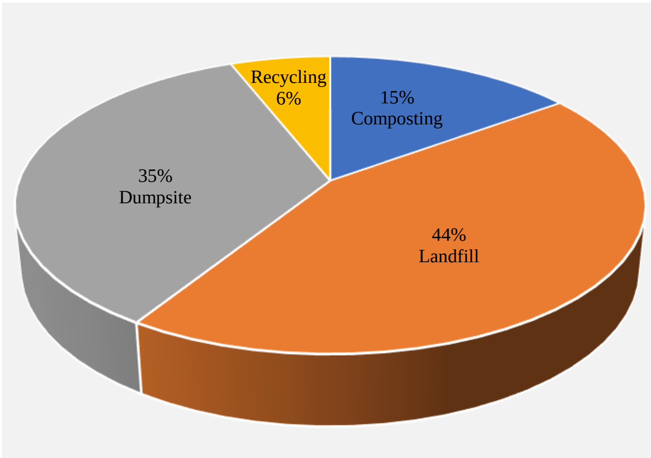


Fig. 5. Waste disposal and recovery in Lebanon [10, 11].

Beside the MSW, the waste generated from industries, construction, agriculture, and different kinds of sludge is approximately 16% of the total, amounting to approximately 188,000 tons annually [12].

Environmentally sound treatment of hazardous solid waste and other waste is also non-existent: most of it is disposed in a haphazard manner, with the exception of a portion of healthcare hazardous or infectious waste, that is treated as per the provisions of Decree 13389/2004. Other types of hazardous waste are exported in accordance with the provisions of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (Law 389/1994) [13]. The total estimated quantity of hazardous waste generated in 2019 is about 71,800 tons [14].

Energy generation in Lebanon is based on oil products importation, while the renewable energy sector in Lebanon is still in the infancy stage. Power generation costs weigh heavily on the Lebanese economy. The electricity sector of Lebanon is actually a big financial burden for the country. Over the last years the generation of electricity from “Electricity of Lebanon” has not increased, but the demand has increased approximately by 7% each year [15, 16]. Hence, “Electricity of Lebanon” has not been able to satisfy the national demand for electricity alone; this has led to the spread of smaller private diesel generators, which operate in an unofficial capacity in a parallel electricity market. Fig. 6 and 7 show the total primary energy supply and the total final energy consumption by sector.

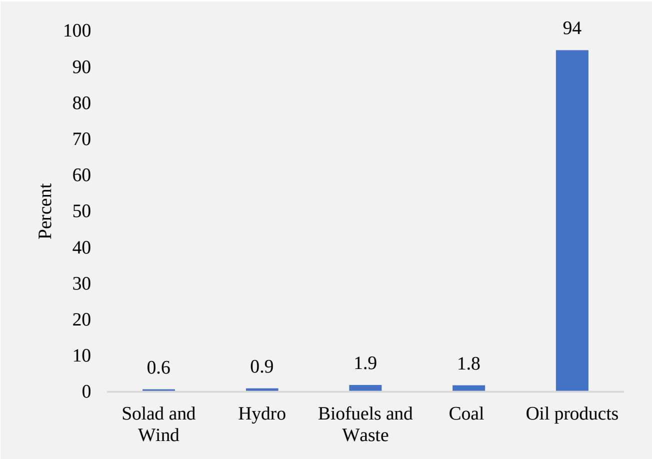


Fig. 6. Total primary energy supply by source [17].

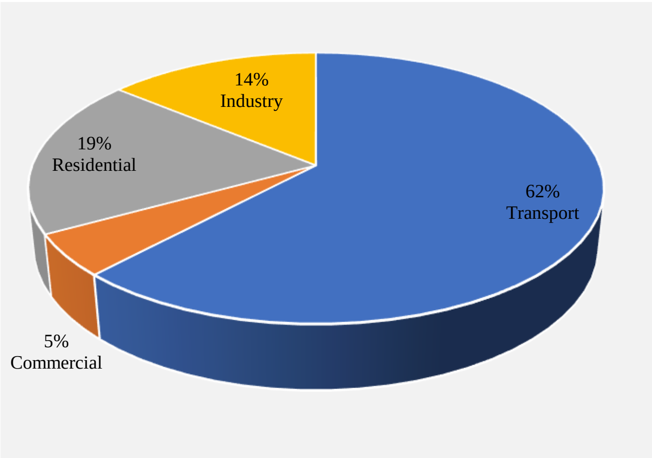


Fig. 7. Total Final Energy Consumption (TFEC) by sector (2019) [17].

Lebanon is one of the largest emitters of CO_2 in the Middle East and it is estimated that 53% of the Greenhouse Gases (GHG) emissions in Lebanon are produced by the electricity sector. The renewable energy sector in Lebanon plays a marginal role in the energy balance, attesting itself only at 5% of Total Primary Energy Supply (TPES), and less than 10% of the production of electricity. Lebanon’s Nationally Determined Contribution (NDC) includes 15% as unconditional renewable energy target meeting power and heating demand using renewable energy sources by 2030, while conditional targets include satisfying an additional 5% of power and heating requirements from renewable energy sources [17]. In 2022, a big leap in using solar panels for electrical energy generation was observed.

Lebanon is facing difficulties in the implementation of an efficient waste management supply chain system due to lack of regulatory and economic instruments, absence of a cost recovery system, weak citizen’s awareness and involvement, political indecision attributed to the volatile decisions which is aggravated by the lack of scarcity governance elements that make the Ministry of Environment (MoE) often incapable of moving forward. The budget of the MoE is low, this limits the capacity of MoE to play the role of the leader in imposing environmental governance, the limited budget affects as well the waste data availability. Citizen’s lack of trust because of the past substandard experience with the public sector. The absence of networking between the different stakeholders which obstacles the continuance of the project implementation.

The main goal of this study is to analyze the aspects that affect the SWM system in Lebanon, taking Greater Beirut Area (GBA) as a case study. The study aims at implementing an integrated solid waste management system for a long term sustainability plan, taking into consideration the opportunity to produce energy from waste applying some WtE technologies. This paper analyzes in depth the challenges that must be coped with to manage in a proper manner the MSW by adopting WtE technology in high-density population cities of developing countries.

II. Material and Methods

A. *Multi-criteria Decision Analysis*

There is a great potential for producing energy from waste, but the challenges are many: policy uncertainties, budget limitations and competition with non-renewable energy sources, to name a few [18]. The selection of a suitable WtE technology is a complex decision and it involves many factors, such as waste quality and quantity, and social, environmental, technological, and economic aspects. As the number and complexity of technological alternatives for conversion of waste into energy grows, so are the strategic decisions required for the effective evaluation and management of these sustainable energy plans. This has led to the popularity of Multi-Criteria Decision Analysis (MCDA) methods. They have been widely used throughout the energy industry and the applications in the field of waste management are steadily growing [19, 20]. Several MCDA methods have been used in these fields [21], and the Analytic Hierarchy Process (AHP) has been widely applied to support decision making processes in waste management [22].

1) AHP model building

The AHP, first introduced by Saaty in the late seventies, is a multi-criteria decision making method quite often used to solve complex decision making problems in a variety of disciplines [23]. The AHP hierarchical structure allows decision makers to easily comprehend problems in terms of relevant criteria and sub-criteria. The decision support procedure of the AHP consists of the following steps [24]:

1) the decision problem is clearly defined and the main goal determined;
2) the criteria, sub-criteria, and alternatives related to the

problem are defined, which become the nodes of the AHP hierarchical model;

3) the relative importance of criteria with respect to the main goal and sub-criteria with respect to criteria (weights), and the relative priorities of the alternatives against the criteria or sub-criteria are assessed. The author of the method suggested to perform each assessment by pairwise comparing the child nodes in a level of the hierarchy with respect to a parent node at an upper level, thus producing a pairwise comparison matrix;
4) the consistency of each pairwise comparison matrix is checked;
5) the final ranking of the alternatives is obtained by means of a weighted sum;
6) a sensitivity analysis is eventually performed to verify the stability of the ranking.

B. Greater Beirut Area Case Study

1) Greater Beirut Area (GBA)

It is complicated to consider the whole Lebanon as a single case study, since the selection of the suitable WtE is based on many factors such as geographic location, social conditions, and commercial activities. This study is focused on GBA, because it represents the more critical case of Municipal Solid Waste Management (MSWM) in Lebanon.

GBA consists of Beirut, the capital, and 5 other districts which are Matn, Baabda, Alley, Chouf, and Keserwan with an area of 200 km^2. It has a population of approximately 2,668,000 million, 268,000 of which are refugees [25]. The waste generation is of 1.1 kg/capita/day, which is in total 2,640 tons of waste per day, with a population density of about 11,000 inhabitants per km^2 [7]. We assume that the MSW composition in GBA matches the same percentages of the MSW composition in Lebanon.

2) Application of the AHP to the case-study

Since the goal of this study is to select the most suitable WtE technology for the treatment of the MSW in GBA, the AHP main goal has been formulated to reflect such an objective. To choose the criteria/sub-criteria that are used in the evaluation of the alternatives, a comprehensive literature review was conducted on the WtE technologies and on solid waste and energy sectors. The criteria/sub-criteria considered encompass a range of environmental/health, technological, economic, and social factors. The data collected during the review were used to help the participants in the pairwise comparisons.

In this study, the AHP structure consists of four levels. The first level presents the goal, which is the selection of a suitable WtE technology for the treatment of MSW in GBA. The second level consists of 4 main criteria, while the third level includes the sub-criteria, which detail the meaning of the main criteria to which they are connected, thus making the assessment more accurate. Finally, the alternatives that are submitted to the evaluation are presented in the fourth level of the AHP model. Fig. 8 shows the structure of the AHP model and Table I summarizes the characteristics of the WtE technologies.

To apply the AHP method and obtain credible preferences, 5 experts in the waste management sector in Lebanon were engaged, and their opinions were gathered using a questionnaire. The questionnaire includes guidelines for the experts on how to carry out the comparison, as well as the matrices to conduct the pairwise comparison using Saaty's recommended 1–9 point scale, where 1, 3, 5, 7, and 9 respectively indicates equal preference, moderate preference, strong preference, very strong preference, and extreme preference, and 2, 4, 6, and 8 are compromise values.

As previously mentioned, the elements of each matrix are the scores obtained from the comparisons between pairs of child nodes in a level 'i' of the hierarchy connected to the same parent node in a level 'i-1'. The comparisons concern the importance of the criteria with respect to the main goal, the importance of the sub-criteria connected to a criterion, and the priorities of the alternatives connected to a sub-criterion. Each of the N experts performed the pairwise comparisons: therefore, for each of the abovementioned comparisons, a set of N pairwise comparison matrices was produced. The aggregate scores of a comparison were finally obtained using the geometric mean [26].

To ensure the consistency of the experts' judgments, a proper check was performed for each matrix by calculating the consistency ratio (CR). If the CR value is lower than the threshold level (usually 10%), the consistency of the judgments is considered acceptable. As a final step, to take into account the potential variations in the experts' opinions, a sensitivity analysis was conducted. The AHP analysis was performed in SpiceLogic, which is a well-established software package for carrying out AHP studies based on mathematical decision-making theories [27, 28].

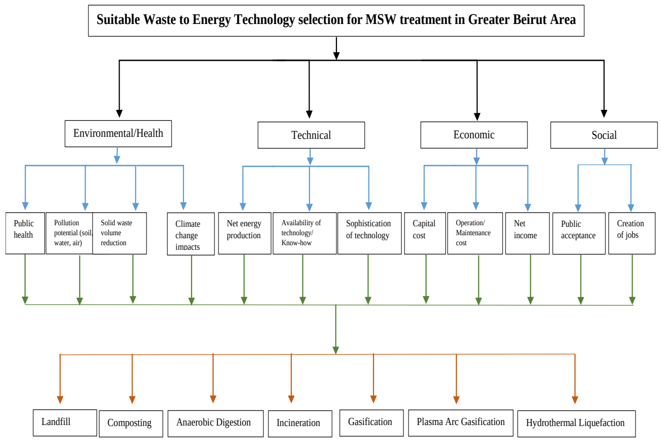


Fig. 8. AHP hierarchical model.

TABLE I: CHARACTERISTICS OF THE WTE TECHNOLOGIES [29–32]

	Incineration	Gasification	Plasma arc gasification	Landfill	Anaerobic Digestion	Composting	Hydrothermal Liquefaction
Suitable waste	General waste Stream	RDF, mixed residual MSW, agricultural wastes, energy crops	Organic and Inorganic wastes	MSW	Organic waste	Organic waste	Organic waste

Waste Sorting required	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Volume reduction of waste	Up to 75%	82%	90%	60%	60%	50%	N/D
Benefits	Suitable for high calorific value. Fast treatment.	High efficiency.	Easily expandable technology.	Low cost	Higher composition of methane (CH_4) and lower composition of carbon dioxide (CO_2) than landfill.	Reduces the need for chemical fertilizers.	It only consumes 10%–15% of the energy content of the feedstock. Energy efficiency of 85-90%. It can process wet biomass.
Limitation	High capital, maintenance, and operation costs.	Immature. Inflexible. Less competitive technologies. High risk of failure.	High energy input. High capital and operational cost.	Soil and groundwater pollution. Air pollution Large land area required.	Unsuitable for wastes containing less organic matter. Require extra space.	Require large area. Odor problem.	Elevated pressure needed.
Technology readiness level	High	Medium	Low	High	High	High	Medium
Automation level	Medium	Medium	High	Low	Low	Low	Medium
Society readiness level	Low	Low	Low	Medium	Medium	Medium	Medium
Primary products	Heat	Syngas	Syngas	Landfill gas	Biogas and digestate	Fertilizer	Bio-oil
Subsidiary/Toxic products	Ash, Dioxins, Heavy metals.	Vitreous slag, Polyhalogenated, organic compounds. Char, ashes, tar	Slag, vitrified glassy rock.	Residue Leachate	Sludge, NH_3.	N/D	Char
Ton CO_2 emissions per ton of MSW	1.67	1.3–1.5	1.3–1.5	1.97	1.19	1.61	N/D
Application	Generation of electricity and steam/heat.	Electricity generation and chemicals production.	Electricity generation	Electricity generation	Electricity generation. Nitrogen rich fertilizer production.	Land fertilizer	Production of chemicals to be used as fuel
Plant life (years)	30	30	20	30	15–20	10–15	20
Average capital costs (US$M) (plant capacity: 1000 tons MSW/day)	116	80	100	70	50	10	More expensive treatment than pyrolysis and gasification
Average operational cost (US$M)	8.2	6.8	8.5	2	2	1	N/D
Average net income (US$M)	0.5	3.1	3.2	0.5	0.5	N/D	N/D
Net energy production (kgoe/ ton of MSW)	36-45	30-63	63-81	4.5–9	9–13.5	3.2	N/D

*Composting and Landfill are not WtE technology, but they are mentioned in the table for comparison reason.

III. Results and Discussion

A. Importance of the Criteria and Sub-criteria

The following results are based on qualitative analysis as per the experiences of the engaged experts.

The priorities of the main criteria with respect to the goal are shown in Table II. It can be noticed that the environmental-health criterion has the highest weight, followed by the social criterion, then the technical criterion, while the economic one has the lowest weight. This clearly indicates that the main concern of the experts is environmental pollution and its impacts on the citizens' health.

TABLE II: MAIN CRITERIA PRIORITIES WITH RESPECT TO THE GOAL

Criteria	Relative weight
Environmental-Health	0.54
Social	0.16
Technical	0.15
Economic	0.13

Table III presents the priorities of the sub-criteria. Regarding the Environmental-Health criterion, public health is the top concern of the experts followed by the pollution potential. The availability of technology has the highest priority under the technical criterion, since many WtE technologies are sophisticated and need considerable expertise and skilled technical teams. Net income and capital cost are of particular interest when the economic factor is considered, as some technologies need high investment; however, the role of the operational and maintenance cost is not negligible. The operational cost for pollution prevention is significant as well. Those costs vary depend on the WtE locations, the market prices of the end-products, and on the adopted pollution control system. A higher conversion efficiency from waste to end-products is a possible solution for capital cost reduction, noting that WtE plants have good profitability, the revenue from selling electrical energy is notable, in addition, they have strong capability to combat external conditions fluctuations risk As for the social criterion, 'public acceptance' results far more important than 'creation of jobs'; this confirms the findings of other studies, which reported that public acceptance is one of the main impediments to many WtE projects in different countries.

TABLE III: SUB-CRITERIA PRIORITIES WITH RESPECT TO THE MAIN CRITERIA

Sub-criteria	Relative weight
Environmental-Health	
Public Health	0.57
Pollution Potential	0.23
Solid Waste Volume Reduction	0.04
Climate Change Impacts	0.14
Technical	
Availability of Technology/Know How	0.71
Net Energy Production	0.22
Sophistication of Technology	0.06
Economic	
Net Income	0.58
Capital Cost	0.24
Operation/Maintenance cost	0.17
Social	
Public Acceptance	0.81
Creation of Jobs	0.23

B. Priorities of the Alternatives

Fig. 9 highlights that composting ranked as the best alternative with a global priority of 0.33. It should be known that the greatest part of the GBA dwellings is constituted by high buildings with no or very small green areas; thus, performing the composting process could be problematic. Anaerobic digestion (AD) of solid waste ranked as the second preferred technology with a priority of 0.21, but the problem with AD technology is that it treats only some types of solid waste. Although it has significant potential in producing energy (more than the other technologies), incineration was the third preferred technology with a priority of 0.14. The reason behind this ranking is that solid waste incineration is still facing strong public opposition in Lebanon due to concerns related to human health risks. It is worth noting that the main problem in GBA is the unavailability of the needed area for the installation of new WtE technology.

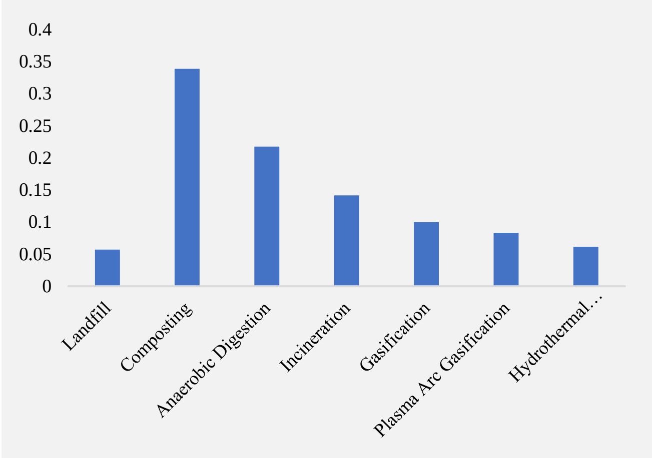


Fig. 9. Global priorities of the WtE alternatives for GBA.

C. Sensitivity Analysis

The last step of the AHP method is sensitivity analysis, where the criteria/sub-criteria weights are modified in order to observe their impact on the overall ranking. If the ranking of the alternatives does not change, the results are said to be robust. SpiceLogic software allows to verify the influence of each criterion/sub-criterion on the final ranking of the alternatives.

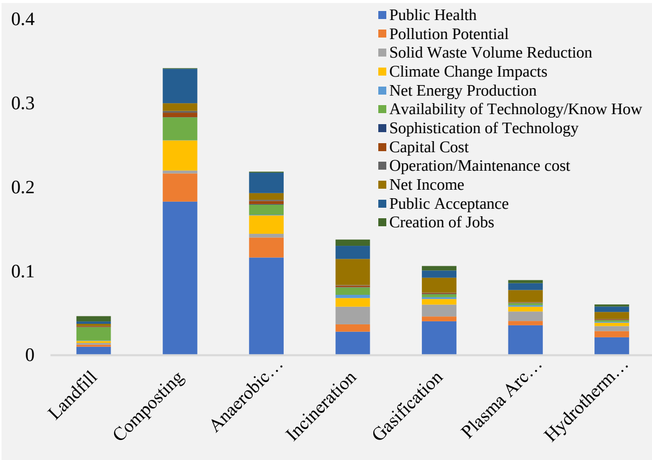


Fig. 10. Overall performance of WtE technologies with the contributions of the sub-criteria.

It has been planned to omit the sub-criteria one by one to assess their impact on the alternatives' ranking. The chart shown in Fig. 10 represents the contribution of the sub-criteria to the overall performance of each alternative. It is evident the importance of the sub-criterion 'public health', which was already mentioned before. Indeed, the citizens in GBA have concerns about possible polluting emissions that might be released by some WtE technologies, as they are aware that many Lebanese citizens suffer from lethal diseases related to environmental pollution.

If the public health sub-criterion was omitted, incineration would become the second preferred technology followed by AD (Fig. 11). Omitting the other sub-criteria has no significant impact on the ranking of the alternatives.

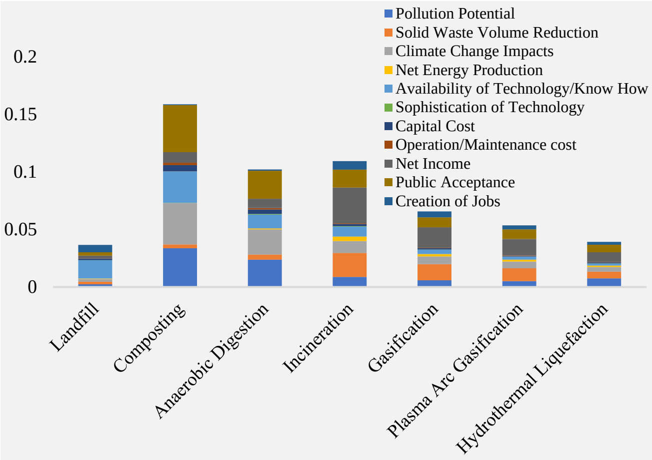
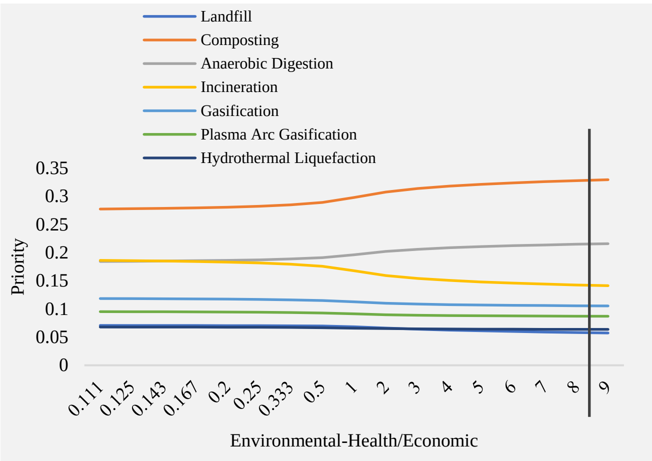


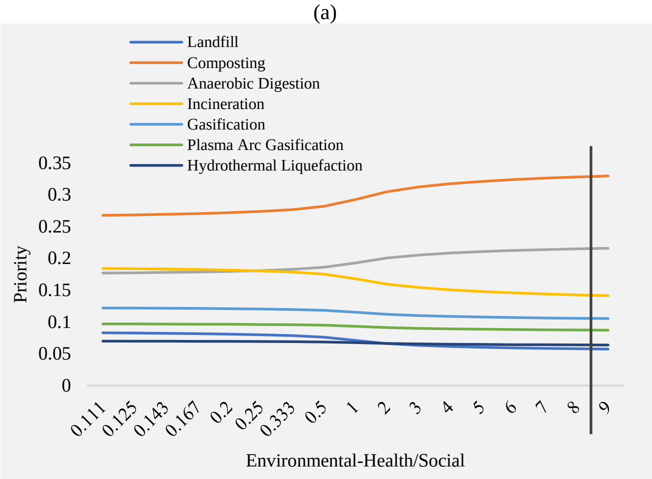
Fig. 11. Overall performance of WtE technologies with the contributions of the sub-criteria (omitting 'public health').

To check the stability of the overall priorities, a further sensitivity analysis was performed at the main criteria level. The effect on the final ranking of a change in the pairwise comparison of importance between two main criteria was investigated.

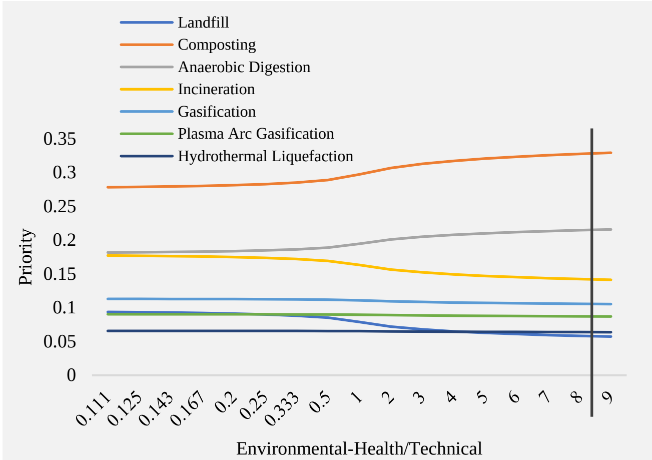
As it can be seen in Fig. 12, moving the vertical line through the scale 1 to 9 does not changes the final ranking of the alternatives. Even for the three less preferred alternatives, only a slight change in the priorities takes place. Therefore, it can be concluded that the final ranking of the alternatives is not influenced by the experts' judgments on the relative importance of the main criteria.



(a)



(b)



(c)

Fig. 12. Main criteria sensitivity analysis: (a) comparing 'Environmental-Health' and 'Economic'; (b) comparing 'Environmental-Health' and 'Social'; (c) comparing 'Environmental-Health' and 'Technical.

IV. Conclusions

The goal of this study was to analyze the aspects that affect the solid waste management system in GBA taking into consideration the opportunity to produce energy from waste. The WtE technology selection is considered a complex decision process, especially in GBA where solid waste management has become a pressing issue that should be solved in a sustainable manner.

AHP is widely used as a support tool for decisions concerning MSW management. In the specific case, a four-level hierarchy structure was developed to solicit the expert's opinions, where the considered criteria/sub-criteria encompass a wide range of environmental/health, technological, economic, and social factors.

Examining the weights assigned by the surveyed experts to the criteria and sub-criteria, the importance of 3 connected pillars clearly emerged: keeping the environment and public health protected while balancing the net income to the capital cost in adopting WtE technologies. Based on the priorities against criteria and sub-criteria, the considered WtE technologies were evaluated. Composting ranked as the best alternative with a global priority of 0.33. AD obtained a priority of 0.21, thus resulting as the second preferred technology, while Incineration ranked third with a priority of 0.14. The last step of the AHP method was the sensitivity analysis, which aimed to verify the influence of each criteria/sub-criteria on the final ranking of the alternatives. To assess the sensitivity of the final ranking of the alternatives to the sub-criteria, these were omitted one by one to see their impact on the ranking. The importance of the public health sub-criteria weight attribute is evident. Omitting that, the incineration alternative will become the second preferred technology followed by Anaerobic Digestion. From the results obtained, the adoption of a WtE technology for the solid waste treatment in GBA must be subject to a careful examination of its impacts on the environment and the citizens health, while it is also evident the pressing need to have an electrical energy source keeping a financial feasibility of this potential technology. For a suitable WtE's technology selection, a balanced correspondence among all the criteria and sub-criteria should be guaranteed.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Conceptualization and methodology were formulated by Dario Pozzetto, Elio Padoano, Luca Toneatti, Ghassan Fakhoury and Abbas EL Toufaili. Software was applicated by Abbas EL Toufaili. Validation was done by Dario Pozzetto, Elio Padoano, Luca Toneatti and Ghassan Fakhoury. The Formal analysis, investigation and data curation were executed by Abbas EL Toufaili. Writing—original draft preparation was accomplished by Dario Pozzetto, Elio Padoano, Luca Toneatti, Ghassan Fakhoury and Abbas EL Toufaili, while the Supervision was conducted by Dario Pozzetto, Elio Padoano, Luca Toneatti and Ghassan Fakhoury. All authors had approved the final version.

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