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Municipal solid waste management and waste to energy strategies for a circular economy in a developing country: the case of Greater Beirut Area

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List of Acronyms and Abbreviations

AD	Anaerobic Digestion
AHP	Analytic Hierarchy Process
BML	Beirut and Mount Lebanon
CAPEX	Capital Expenditure
CDR	Council of Development and Reconstruction
CDW	Construction and Demolition Waste
CE	Circular Economy
CGC	Capacity of Garbage Container
CR	Consistency Ratio
CRF	Capital Recovery Factor
CH_4	Methane
CO_2	Carbon Dioxide
CO_2eq	Carbon dioxide equivalent
CoM	Council of Ministers
CSP	Concentrated Solar Power
EDL	Électricité Du Liban
ERA	Electricity Regulatory Authority
ETSP	Euclidean Traveling Salesman Problems
EU	European Union
E-Waste	Electronic and Electric Waste
FC	Fuel Cell
FBS	Fixed Box System
GBA	Greater Beirut Area
GDP	Growth Domestic Product
GHG	Greenhouse Gases
GIS	Geographic Information System
GNI	Gross National Income
GWh	Gigawatt hours
H_2	Hydrogen
IPP	Independent Power Producer
IRENA	International Renewable Energy Agency's
kWh	Kilowatt hour
kWp	Kilowatt peak
LCOE	Levelized Cost Of Electricity
MCDA	Multi-Criteria Decision Analysis
MEW	Ministry of Energy and Water
MoF	Ministry of Finance
MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
MW	Mega Watt
MWp	Megawatt peak
NASA	National Aeronautics and Space Administration
NDC	Nationally Determined Contribution
NEEAP	National Energy Efficiency Action Plan
NGO	Non-Governmental Organization
NPC	Net present cost
N_2O	Nitrous oxide
O&M	Operation and Maintenance
PM	Particulate Matter

PPA	Power Purchase Agreement
PPC	Production Per Capita
PV	Photovoltaic
RE	Renewable Energies
SWM	Solid Waste Management
SWOT	Strengths, Weaknesses, Opportunities, Threats
TEFC	Total Final Energy Consumption
UNDP	United National Development Program
WM	Waste Management
WtE	Waste to Energy
WtH_2	Waste to Hydrogen

Abstract

Questa attività di ricerca riguarda la gestione e il trattamento dei rifiuti solidi nei Paesi in via di sviluppo, prendendo come caso studio la Greater Beirut Area (GBA) in Libano, con l'obiettivo della transizione verso un Economia Circolare (EC). L'attività di ricerca si concentra sull'implementazione di un sistema integrato di gestione dei rifiuti solidi analizzando l'intera filiera, dal sistema di raccolta allo smaltimento finale, individuando quindi lo stato dell'arte in questo campo e focalizzando l'attenzione sui parametri che influenzano la scelta dei rifiuti solidi. GBA dovrebbe perseguire profonde strategie di decarbonizzazione, date le grandi emissioni di gas serra dovute alla produzione di energia da fonti non rinnovabili, nonostante l'esistenza di un abbondante potenziale di energie rinnovabili.

Pertanto, per obiettivi di sostenibilità a lungo termine, il modello EC proposto in questo studio collega le migliori pratiche di gestione dei rifiuti solidi alla produzione di energia verde in GBA.

Il sistema energetico del Libano dipende in gran parte dai combustibili importati, il Libano ha presentato il suo impegno ad aumentare del 30% la propria quota di energie rinnovabili entro il 2030.

La composizione dei rifiuti in GBA è composta per il 52,2% da rifiuti organici che possono essere sfruttati per la produzione di Idrogeno (H2) mediante gassificazione. Inoltre i sistemi solari fotovoltaici hanno guadagnato un enorme mercato in Libano negli ultimi anni, soprattutto per il settore residenziale.

Gli obiettivi principali di questo studio sono stati formulati come segue: (i) fornire una mappatura geografica della distribuzione dei contenitori dei rifiuti solidi in alcune aree del GBA, (ii) selezionare il miglior percorso di raccolta dei rifiuti solidi di quest'area, (iii) eseguire il calcolo dei costi della fase di raccolta per quest'area, (iv) calcolare le emissioni di gas serra derivanti dalla raccolta dei rifiuti di quest'area, (v) selezionare la tecnologia energia da rifiuti adatta per il trattamento dei rifiuti solidi urbani in GBA, (vi) implementare un modello EC per GBA che collega le migliori pratiche di gestione dei rifiuti alla produzione di energia verde.

Per raggiungere questi risultati è stato utilizzato il metodo di analisi multicriterio Analytic Hierarchy Process (AHP) che consente di analizzare e valutare diverse alternative per la produzione di energia da rifiuti, monitorandone l'impatto sui diversi attori del processo decisionale, e il Software HOMER-Pro per identificare parametri economici, elettrici e ambientali utili per la produzione di energia elettrica in GBA.

Il modello EC proposto in questo studio apporta grandi vantaggi per lo sviluppo della sostenibilità a lungo termine in GBA, con la riduzione e forse l'evitamento della generazione di rifiuti non riciclabili; con l'ottimizzazione del riciclo degli altri rifiuti; con l'ottimizzazione della fase di raccolta dei rifiuti; con lo sfruttamento dell'elevata percentuale della frazione organica per la produzione di H_2 verde; e con l'utilizzo di energia solare fotovoltaica grazie alle lunghe giornate solari in GBA.

Nell'applicare questo modello CE, si dovrebbero affrontare sfide significative, ad esempio non tutti i rifiuti possono essere riciclati o compostati, per questo è indispensabile evitare il più possibile la generazione di rifiuti; le industrie Libanesi dovrebbero essere orientate verso la produzione di prodotti ecologici; l'importazione di prodotti non ecologici in Libano dovrebbe essere ridotta al minimo; non esiste alcuna infrastruttura per la fornitura di H_2 in GBA, per questo è fondamentale l'installazione del sistema di celle a combustibile nel sito di produzione di H_2.

Abstract

This research activity concerns the management and treatment of solid waste in developing Countries, taking Greater Beirut Area (GBA) in Lebanon as a case study, with the aim of the transition towards Circular Economy (CE). The research activity focus on the implementation of an integrated solid waste management system by analyzing the entire supply chain, from the collection system to final disposal, hence identifying the state of the art in this field and focusing attention on the parameters that influence the choice of these systems, as well, GBA should pursue profound decarbonization strategies given the large greenhouse gas emissions due to energy production from non-renewable sources, despite the existence of abundant renewable energies potential.

Therefore, for long-term sustainability goals, the EC model proposed in this study links solid waste management best practices to the green energy production in GBA.

Lebanon's energy system depends largely on imported fuels, Lebanon presented its commitment to increase by 30% its share of Renewable Energies (RE) by 2030. The waste composition in Greater Beirut Area (GBA) is made by 52.2% of organic waste which it can be exploited for the production of Hydrogen (H_2) by gasification, in addition PV solar systems have gained a huge market in Lebanon in the last years, especially for residential sector.

The main objectives of this study were formulated as follow: (i) provide a geographical mapping distribution of the solid waste bins in some area of GBA; (ii) select the best solid waste collection route of this area; (iii) perform cost calculation of the collection phase for this area; (iv) calculate the GHG emissions from the waste collection of this area; (v) select the suitable Waste to Energy (WtE) technology for the treatment of the municipal solid waste in GBA; (vi) implement a CE model for GBA that links the waste management best practices to the production of green energy.

To achieve these results, the multi-criteria analysis method Analytic Hierarchy Process (AHP) was used which allows the analysis and evaluation of different alternatives for energy production from waste monitoring its impact on the different actors in the decision-making process, and HOMER-Pro software in order to identify useful economic, electrical and environmental parameters for the production of electricity in GBA.

The CE model proposed in this study brings great advantages for the development of a long term sustainability in GBA, with the reduction and perhaps the avoidance of the generation of the non-recyclable waste; with the optimization of the recycling of other waste; with the optimization of the waste collection phase; with the exploitation of the high percentage of the organic fraction for the production of green hydrogen; and with the employment of photovoltaic solar energy thanks to long solar days in GBA.

In applying this CE model, significant challenges should be faced such as not all the waste can be recycled or composted, for that it is indispensable to avoid the generation of waste as much as possible; the Lebanese industries should be shifted to produce eco-friendly product; the importation of no eco-friendly products to Lebanon should be minimized; there is no infrastructure for H_2 supply in GBA, for that it is crucial the installation of Fuel Cell system in the H_2 production site.

CHAPTER 1

1. Introduction

Solid Waste Management (SWM) is a big challenge for most of the countries throughout the world. An efficient waste management system is a pre-requisition for maintaining a safe and green environment; thus the principal goals of SWM are to reduce and eliminate the adverse impacts of waste materials on human health and on the environment, to support economic development and improve the life quality. The inappropriate management of solid waste illustrates a source of air, land, and water contamination, and demonstrates hazards to human health and the environment.

Waste management is a complex sustainability issue because of its association with many economic, technical and environmental drivers, and a multifaceted task that incorporates a diverse set of shareholders and operations; it is one of the burning issues of today with the topics of climate change, and new ways of generating energy without affecting the public health.

The functional elements of the waste management system are: waste generation, on-site handling and storage, collection, transfer and transport, material and energy recovery, and disposal.

A broad differences exist between developed and developing Countries in terms of living standards, citizen's income, consumption trends, institutional capacity and urban investment. As well, there is a considerable difference between the countries in the Municipal Solid Waste (MSW) generation rate, which highly depends on the Country's urbanization, industrialization, population growth and economic development. Waste management in the developing Countries is inadequate, and relies on waste dumping and needs efficient waste infrastructure; besides the situation will tend to degrade further more due to the steady increase of the cities, noting that the traditional solutions of the waste management in developing Countries are subjected to high costs, bureaucratic, and inefficient management systems.

An improvement of solid waste management system is a crucial factor for future sustainable development in developing Countries, but there are many challenges to overcome, such as availability of funds, appropriate technology selection and adequacy of trained people. Apart from this, some other major issues that should be taken in consideration, like the poor participation of the public in SWM, and lack of responsibilities toward waste inside society (Sharma and Jain, 2020).

Countries nowadays should shift from less-preferred waste treatment and disposal methods, towards a system where the waste reduction comes first with the 3R's rules (Reuse, Recycling and Recovery) supported by the utilization of Waste to Energy (WtE) technologies (Sharma and Jain, 2020) (Maalouf *et al*., 2019).

The economic realities are experiencing serious restrictions, caused by a shortage of natural resources and unprecedented degradation of ecosystems. In order to ensure sustainable development, which presupposes economic progress, environmental safety and improvement of the life quality of the population, new approach of the economic activity is needed. Worldwide a new development paradigm, based on the concept of a green economy, is widely adopted.

Circular Economy (CE) is considered a sustainable economic system, which it combines many approaches and concepts, such as industrial ecosystems, ecological innovations, industrial symbioses, ecological efficiency, and sustainability of socio-ecological systems.

The main task of Circular Economy is to ensure maximum efficiency of processes or services life cycle by improving resource efficiency and therefore increasing economic growth in a long-term sustainable manner.

1.1 World population

The world has experienced tremendous growth in its population from 3.1 billion in 1960 to almost 7 billion in 2010, and scientists believe that it will rise to 9.7 billion by 2050 (Worldometer, 2021). The highest population growth rates will continue to be in developing regions, accounting for 97% of the increase to 2030. The worlds developing regions will have 1.2 billion people added, a 20.7% increase, while the population of developed countries will increase a mere 3.3% adding 41 million to the current 1.3 billion people. Two-thirds of the world's people will be living in cities by 2025 (Worldometer, 2021).

1.2 Global waste generation

The increased population plays a major role in the production of a huge volume of Municipal Solid Waste (MSW). The world has generated 2010 million tons of MSW in 2016 (0.74 kg/person/day, but it ranges widely from 0.11 to 4.54 kilograms) of which 33% has been managed in a very conservative and environmentally unsafe manner. Moreover, this quantity of MSW generation is expected to increase to 2600 by 2030 and 3400 million tons by 2050 (World bank, 2021). Apart from MSW, there are other waste streams in the world, such as industrial/special, and agricultural waste. Compared to MSW, the generation rate of industrial waste and agricultural waste at the global level is 18 times and 4 times higher, respectively (World bank, 2021) (Sharma and Jain, 2020).

The income level of any country affects the country's waste composition; daily per capita waste generation in high-income countries is projected to increase 19% by 2050, compared to low and middle-income countries where it is expected to increase by approximately 40% or more (World bank, 2021).

Figure 1 shows the relative incidence of the methods used at global level for the disposal and treatment of solid wastes.

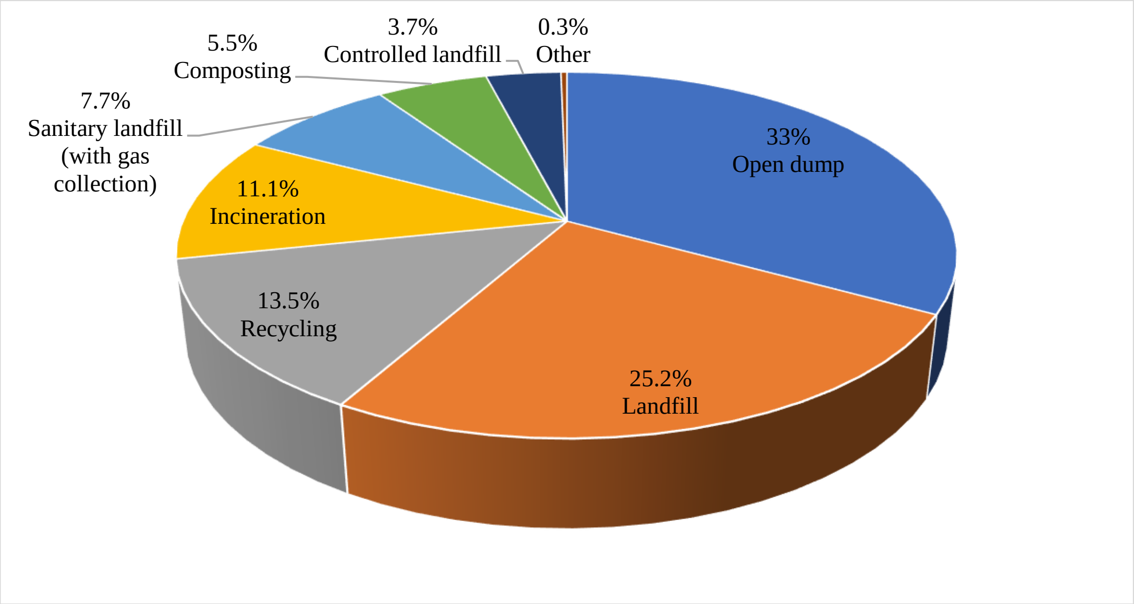

Fig. 1. Global treatment and disposal of waste (World bank, 2021)

Globally, it is estimated that 1.6 billion tons of carbon dioxide (CO_2) equivalent Greenhouse Gas (GHG) emissions were generated from solid waste treatment and disposal in 2016, or 5% of global emissions (Silpa K. *et al.*, 2018). This is driven primarily by disposing of waste in open dumps and landfills without gas collection systems. Solid waste related emissions 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 (World bank, 2021).

Organic waste is the highest percentage of world's MSW, from 2015 to 2050, the global share of organic waste is estimated to decline from 47% to 39%, while all other waste type shares increase, especially paper (Sharma and Jain, 2020).

1.3 Worldwide energy status

The existing energy stream is less than the definite energy needed for growth in numerous developing countries. Regardless of the source of energy, it is estimated that by 2040 electricity generation is expected to increase by 49%; as well, by 2040 renewable energy sources are expected to supply 8% of total global energy demand (International energy agency, 2020).

1.4 Market growth rate of Waste to Energy technologies

Over the past few years, the Waste to Energy (WtE) global market has grown significantly, and its steady growth is expected to continue; the market value of WtE technologies is expected to increase over 26.6 Billion Dollars by 2025 (Figure 2) (Sharma and Jain, 2020).

Currently, more than 2450 WtE plants are active throughout the world with a disposal capacity of around 330 Mt of waste per year, it is estimated that around 2700 plants with a combined treatment capacity of over 480 Mt per year to be operational by 2026 (Sharma and Jain, 2020).

In terms of proportion per ton of waste, the impending energy recovery as expected to surge from 0.87 GJ/ton in 2012 to 1.25 GJ/ton in 2021. In the meantime, GHG removal by WtE was estimated to surge from 16,061 in 2012 to 33,477 tons of CO_2 equivalent per year in 2021 (Awasthi *et al.*, 2019).

A WtE plant processing 1 million tons of waste per year has a regular working life of 20-30 years and involves less than 100,000 m^2 of land area, whereas a landfill for 30 million tons of MSW requires a land area of 300,000 m^2 (Awasthi *et al.*, 2019).

Bio-chemical treatments of waste are expected to significantly contribute to the development of the SWM market, especially in developing countries.

One of the biggest obstructions to the market development of WtE is the high technology cost in comparison with landfilling. The growth of the WtE market, the increasing in the global investment and the future technological improvements will most likely drive the costs down for WtE technologies, making them economically feasible in developing countries as well (Figure 3).

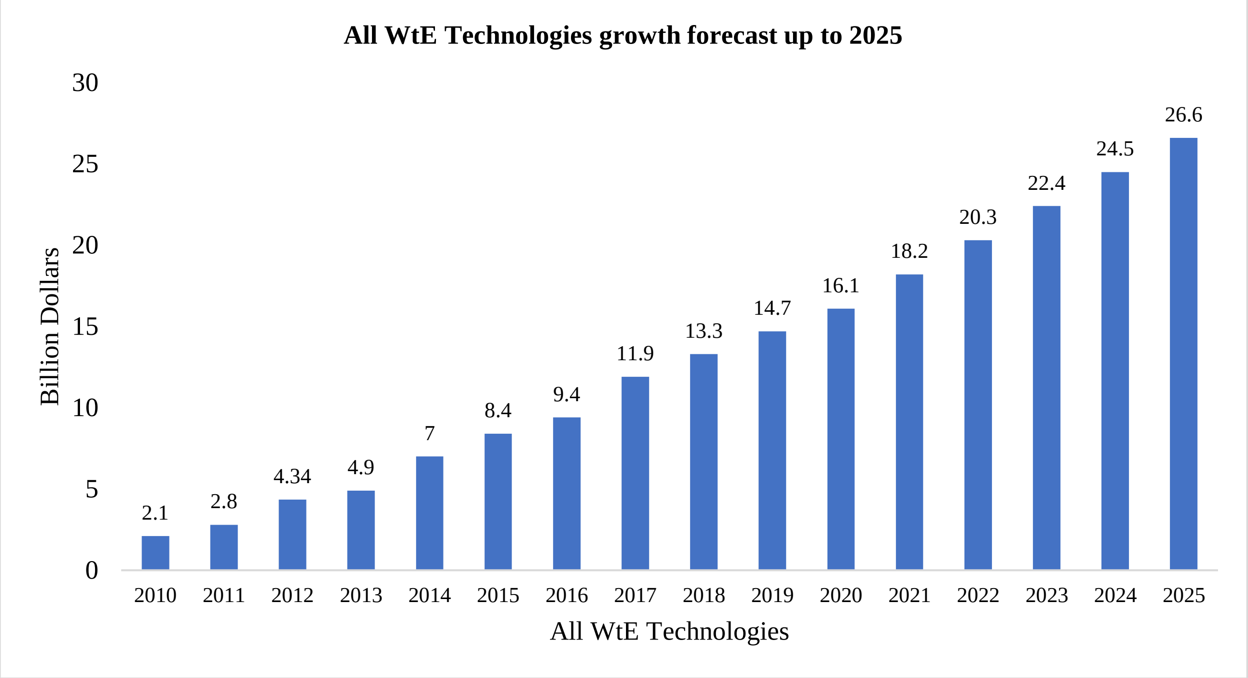

Fig. 2. WtE growth forecast (Sharma and Jain, 2020)

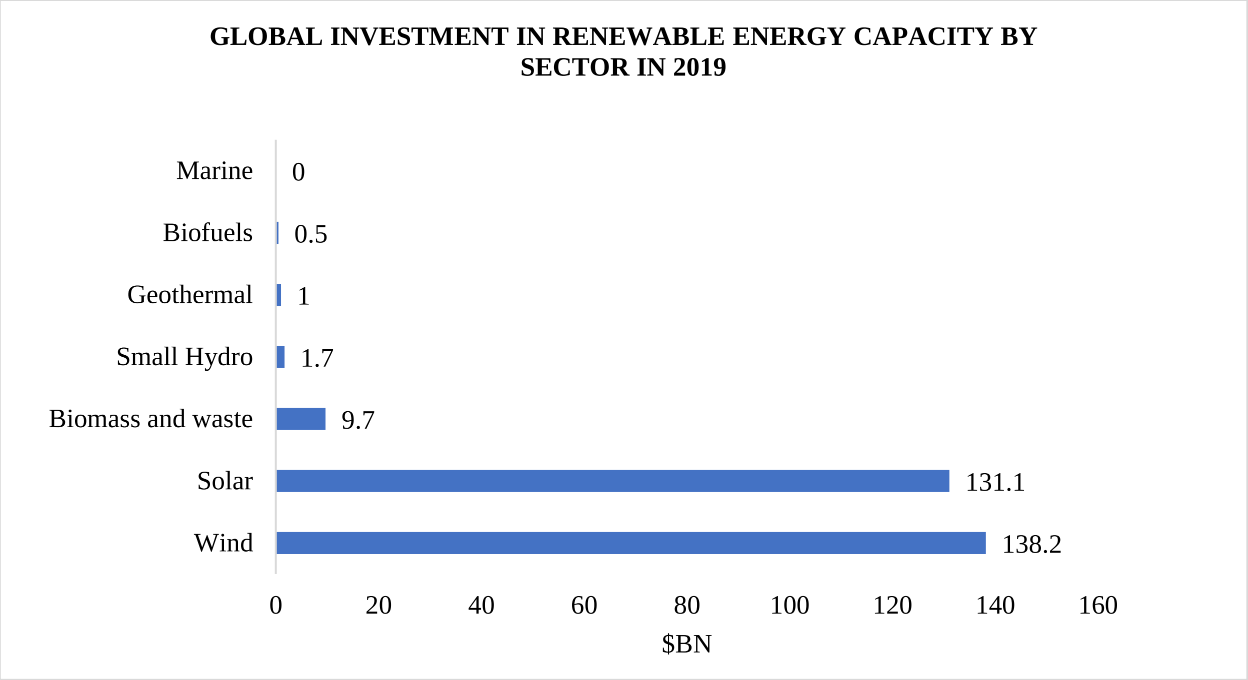

Figure 3: Global investment in renewable energy (McCrone *et al.*, 2020)

1.5 Lebanon overview

Lebanon suffers from both a serious solid waste dilemma, and a deficiency in electrical energy production. Several factors have led to the increase in the solid waste burden 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 enforcement of the law; contradiction in environmental policies; social habits that do not encourage waste minimization; social keenness to use new materials rather than used ones, and increasing number of refugees; therefore, new strategies are needed to deal with the current waste issue in Lebanon, taking into consideration the economic, environmental, social and health factors (Abbas *et al.*, 2017) (Rizkallah and Sabbagh, 2014).

Lebanon's energy system depends largely on imported fuels; therefore investing in transitioning to renewable and sustainable energy sources is the biggest improvements can be made. Lebanon is one of the first Arab countries that developed an action plan to endorse Renewable Energy (RE) deployment in 2010; this is due to the country's possession of abundant RE potential, such as wind, solar, and hydropower.

In 2015, Lebanon presented its commitment to increase by 30 percent its share of renewables by 2030 as a target across four major sectors: electricity, transport, deforestation, and waste (Kai *et al.*, 2019). Lebanon's Nationally Determined Contribution (NDC) includes both unconditional and conditional renewable energy targets, unconditional targets include meeting 15% of power and heating demand using renewable energy sources, while conditional targets include satisfying an additional 5% of power and heating requirements from renewable energy sources by 2030.

The internal sectoral targets include improving waste management efficiencies through energy recovery equivalent to avoiding emissions from landfilling, it includes a recycling rate target of 30% by 2030 (Kai *et al.*, 2019).

Lebanon should pursue deep decarbonization strategies, Hydrogen (H_2) is one solution amongst others and should be tackled in parallel with PV solar power. The costs of production of green H_2 is a major barrier, but these costs are greatly falling due to the evolution in the renewable energy technologies.

Due to electricity blackouts, PV solar systems have gained a huge market in Lebanon in the last years, especially for residential sector. As well, these solar systems can be incorporate in processes for the generation of green energy, but the waste generation of these solar systems might be an environmental concern in the long term.

Public, private and international entities are actively involved in discussing the issues of the attractiveness for the transition to a closed-cycle economy in Lebanon to find harmony between the economy, society and the environment.

1.6 Objectives

Taking Greater Beirut Area (GBA) in Lebanon as a case study, with the aim of the transition towards CE in GBA, the research activity concerns the implementing of an integrated solid waste management system by analyzing the entire supply chain, from the collection system to final disposal, hence identifying the state of the art in this field and focusing attention on the parameters that influence the choice of these systems.

GBA should pursue deep decarbonization strategies given the large greenhouse gas emissions due to energy production from non-renewable sources, despite the existence of abundant renewable energy potential; therefore for long-term sustainability goals, the CE model proposed in this study links the best solid waste management practices to green energy generation in GBA. More precisely, the main objectives were formulated as follow: (i) provide a geographical mapping distribution of the solid waste bins in some area of GBA, (ii) select the best solid waste collection route of this area, (iii) perform cost calculation of the collection phase for this area, (iv) calculate the GHG emissions from the waste collection of this area, (v) select the suitable WtE technology for the treatment of the MSW in GBA, (vi) implement a CE model for GBA that links the waste management best practices to the production of green energy.

CHAPTER 2

2. Materials and Methods

The aim of the below methodology is to gather all the information needed for understanding the status in Lebanon and GBA regarding waste and energy management, the necessary data were gathered from national and international entities. Then the creation of the CE model for GBA is accomplished by optimizing the collection and transport of the MSW which it is done by applying Traveling Salesman Problems after adopting waste management calculation methodology; by employing AHP method for better recognizing of the factors that govern the selection of the WtE technology; thereafter by using HOMER-Pro software for the simulation of a potential Green Energy generation systems in base of the AHP method's context result and the current energy trends in GBA.

2.1 Lebanon

The Republic of Lebanon is a small Mediterranean developing lower-middle income Country with a total area of 10,452 km^2; the capital and largest city is Beirut. Lebanon's Gross National Income (GNI) per capita was estimated at USD 5510 in 2020 (World bank, 2020). In 2020, about 6,800,000 citizens and 900,000 refugees were living in Lebanon, with an average density of 560 inhabitants/km^2. Approximately 80% of the population live in urban areas, 49% are located in the areas of Beirut and Mount Lebanon (BML) which account for only 20% of the territory (United Nations Population Fund, 2020).

Fig. 4. Lebanon map

2.2 Waste management in Lebanon

Waste generation in Lebanon has increased significantly due to the rise in population living standards, urbanization, immigration of Syrian refugees, and increasing in the population growth rate of 0.16% (world population review, 2021). The total generation of MSW in Lebanon is about 2.6-2.7 million tons/year, each person generates 1.05 kg/day in average around the Country, this quantity changes depending of the rural area where is 0.85 kg/day, and the urban area where is 0.95–1.2 kg/day. By

2035, Lebanon will generate 2.9 million tons/year with a growth of 1.65% per year, due to the increase of the population (Rizkallah and Sabbagh, 2014).

The municipal collection services coverage is 98-100% in urban areas and 90-100% in rural areas. The public cleanness responsibility was given to the municipalities, and the supervision of open dumping was given to the Ministry of Public Health.

Lebanon pays an average of 154 USD per ton of waste, while the other worldwide countries have an average between 7.22 to 22.8 USD per ton. The waste dumping charging in Lebanon is around 45 USD in comparison with the global average which is 11.15 USD (Boswall, 2019).

Even if the scavenging activities are actually illegal in Lebanon, there are around 1000 to 4000 scavengers, they collect between 100 to 500 tons per day mainly in the GBA (Rizkallah and Sabbagh, 2014).

Many government institutions are involved in the planning and management of solid waste as it is evident in Table 1. In 2019 the Lebanese Ministry of Environment submitted a national waste management strategy, but hasn't been adopted a roadmap of the future landfills and incinerators (Azzi, 2016) (Boswall, 2019).

Duties of different stakeholders	**Main Responsibilities**
Waste Management Board	Developing waste strategy and authorizing waste management plans.
Ministry of Environment	Initiating waste management standards and guidelines and implementing waste management programs.
Ministry of Interior and Municipalities	Participation in the National Strategy and implementation of local waste management plans. Establishing/implementing waste management programs.
Municipalities	Participation in the National strategy and plan through the Waste Management Board. Proposing and implementing local waste management plans for non-hazardous municipal waste. Establishing/implementing waste Management programs. Management of waste collection.
Council of Development and Reconstruction (CDR)	Assistance in procurement of Waste Management (WM) projects upon request. Assistance in the development of WM plans upon request.
Private Sector, Non-Governmental Organization (NGO's), World Bank, Italian Development Cooperation Agency, European Union	Abiding by laws, regulations and guidelines on waste management. Prohibition of littering, illegal bumping and burning. Participation in the National strategy and plan through the Waste Management Board. Participation in the development and implementation of local waste management plans. Participation of facility and generator management plans.

Table 1: Responsibilities of solid waste management stakeholders in Lebanon (Abbas *et al.*, 2017)

There is also the private sector that plays an important role in the design and provision of SWM services in Lebanon; some industries are trying to implement the Zero Waste concept, other companies are dealing with the waste recycling business. Apart from the institutions and the private sectors, there are as well the NGO's that are trying to draw attention to pressing environmental problems, and to increase environmental awareness to the society.
Lebanon suffers from deep-rooted problems, there is still absence of long-term SWM strategies and inaccurate representation of the costs. There is a lack of financial deterrence, an unequal access and distribution of resources and services, continued rural-urban migration, and a potential exposure to the residents to health hazards and deterioration of the environmental health (Ghanimeh *et al*., 2020).

The MSW generated per governorate is shown in Figure 5.

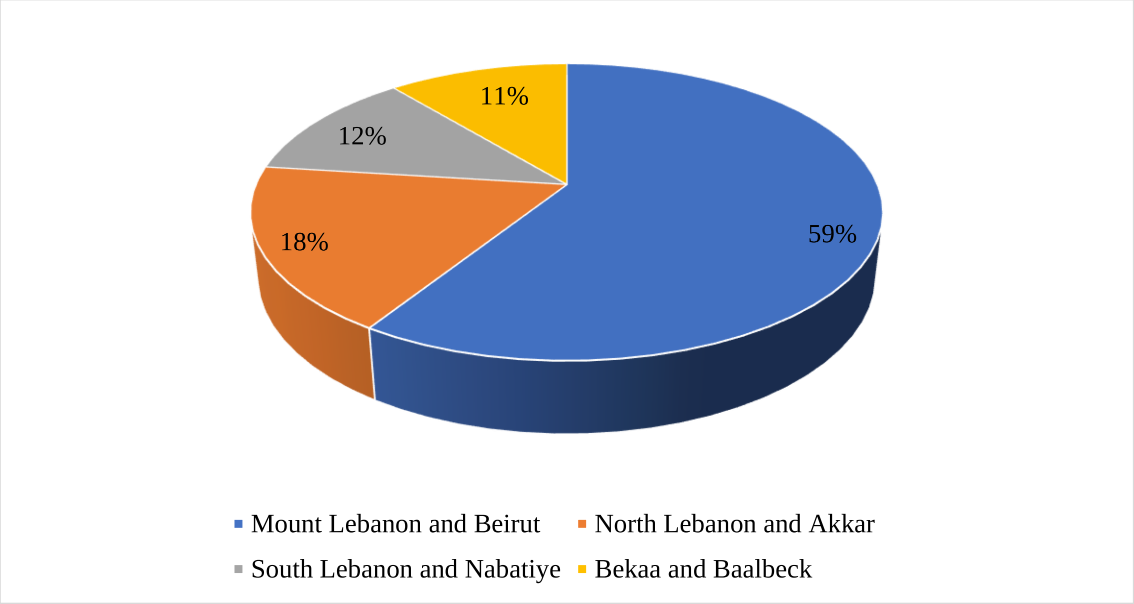

Fig. 5. MSW generated per governorate (Karaki, 2016)

As it is evident in Figure 6, the highest waste fraction in Lebanon is the organic with a composition of 52.5%, Lebanon produces organic waste with high moisture content, often exceeding 60%.

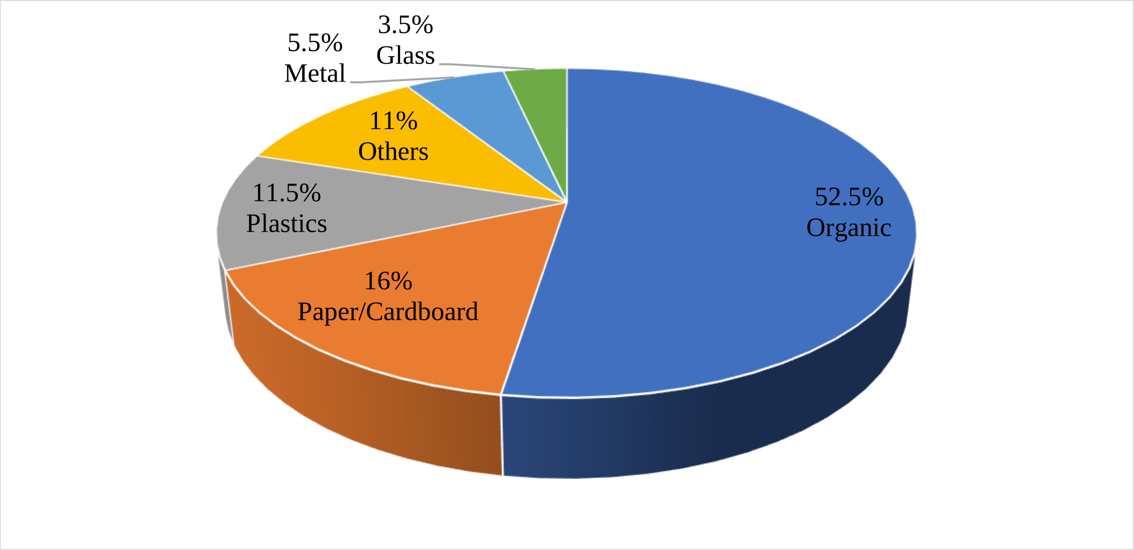

Fig. 6. Waste composition in Lebanon (Rizkallah and Sabbagh, 2014) (Karaki, 2016)

Waste disposal in Lebanon is problematic because of its rough terrain, and limited surface area, however, the Lebanese waste sector is heavily dependent on landfilling. Despite the high content of organic and recyclable materials in waste stream, only 8% and 15% of solid waste are recycled and composted respectively. The most common materials that are recovered include: organics, various types of paper products, and some plastics and metallic containers.

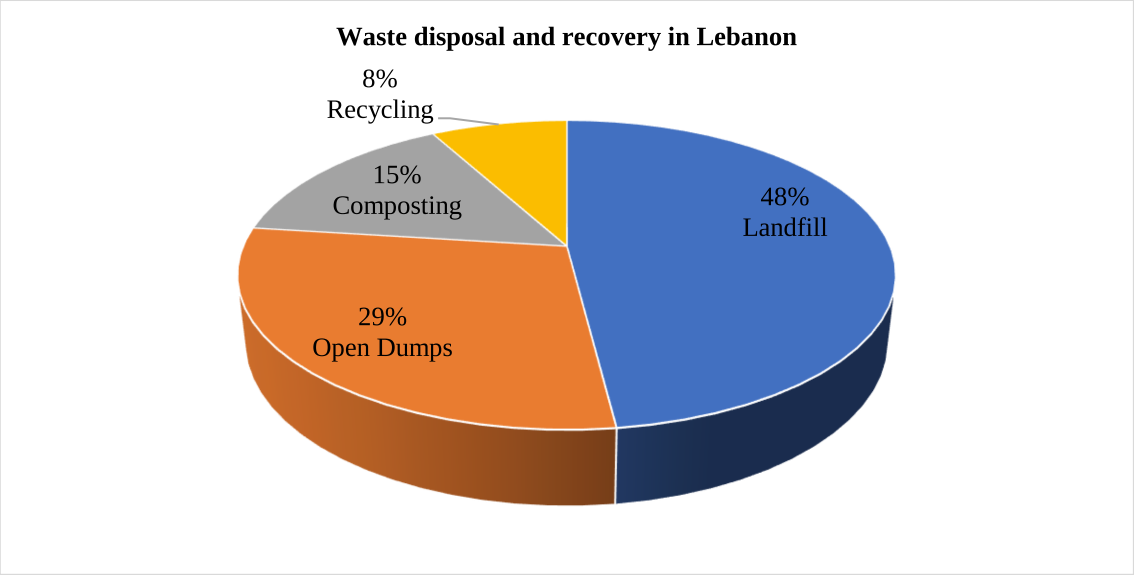

Fig. 7. Waste disposal and recovery in Lebanon (Karaki, 2016) (Sweep net, 2018)

In Lebanon there are the following plants where the solid waste is taken to: Coral facility located in Karantina (300 tons/day), which is the main composting plant in Lebanon; anaerobic digester located in Saida (300 tons/day), which produces bio-methane to generate electrical energy and fertilizer; 7 sanitary landfills and 49 sorting plants; 33 composting plants; 1000 open dumps, of which 617 are MSW dumps (Boswall, 2019).

Beside the MSW, there are the waste generated from industries, construction, agriculture, and different kind of sludge which are approximately 16% of the total waste stream amounting to approximately 188,000 tons annually. As well as, it was estimated a quantity of about 7000 tons of end-of-life vehicles and approximately 1,875,000 used car tires (Abbas *et al.*, 2017).

Hazardous waste generation is about 3338 tons per year including industrial waste containing heavy metals, industrial oily wastes, paints, resins, and adhesives residues.

There is also the medical waste that is around 25,040 tons per year of which 5000 tons are infectious. According to the Ministry of Environment there is only 6 of 30 public hospitals and 42 of 129 private hospitals in Lebanon with licenses to be able to treat their infectious wastes through microwaving or autoclaving either on-site or off-site; these facilities treat about 7383 kg of medical waste daily (Abbas *et al.*, 2017).

Environmentally sound treatment of hazardous solid waste and other waste is also non-existent, as most are disposed in a haphazard manner, with the exception of a portion of healthcare hazardous infectious waste that is treated in accordance with the provisions of Decree 13389/2004, and some types of hazardous waste that 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) (Policy Summary on Integrated Solid Waste Management, 2018).

A substantial waste generation rates decreasing across the country in the period 2020-2023, this is attributed to 2 reasons: the economic crisis leading to a nation-wide decline in the purchasing capacity, and the COVID 19 pandemic resulting in repetitive lockdowns leading to slowdown/interruption of activities in most sectors. Yet an improvement was observed in the proportion sold to the industry as secondary raw material from 74% in the 2014-2015 period to 95% in the 2017-2019 period (Ghanimeh *et al.*, 2020).

2.2.1 Waste streams in Lebanon

Considering the economics of waste recovery, it is difficult to estimate the waste prices in the Lebanese market, because there is no national systems for tracking the full supply chain of the waste. A cost of 120-169 USD per ton of waste collected was estimated by the Lebanese municipalities, this is almost five times the global average of 35 USD per ton (ACTED, 2020). An average 488 tons/month of waste is collected by municipalities. An improvement was observed in the waste proportion sold to the industry as secondary raw material from 74% in the 2014-2015 to 95% in the 2017-2019 period (Reduction of UPOPs, 2022), this may be attributed to the considerable effort put by NGOs and local communities to reduce the accumulated waste during the crisis by sorting and recovering recyclable materials, this has led to sorting initiatives and small businesses that gave a boost to the recycling industry (Ghanimeh *et al.*, 2020).

Waste recycling in GBA is still scant, only 6-8% of the waste is being recycled. A target of 30% of recycling has been set by the Lebanon’s NDC. Noting that 10 to 12% of GBA’s solid waste cannot be composted or recycled. The cost of waste recovering and recycling in Lebanon is high, making waste recycling an unprofitable business, considering that most sorting facilities are not run with profitability, most cost recovery seems to be achieved through subsidizing waste collection and sorting. The cost recovery for municipal facilities in Lebanon is only realistic if they achieve economy of scale (ACTED, 2020).

- **Plastic**

Lebanon has a vigorous plastic manufacturing industry, with a high potential to absorb recycled plastics, even so, the cost recovery for municipal sorting facilities or private recycling companies is scarce.

The main constraint of the Lebanese plastic manufacturing and recycling is the energy cost, since these processes are energy-intensive, therefore a reduction in energy costs it is critical to encourage plastic recycling. The prices for virgin plastic in Lebanon are much lower than prices in Europe, which lead to an increase of plastic manufacturing industries profitability. In order for recycled plastic to be absorbed effectively into local industries, measures should be taken by improving the efficiency of the waste collection and sorting logistics, and by increasing the prices of virgin plastics through taxes and customs (ACTED, 2020).

- **Paper and Cardboard**

The paper and cardboard industry are the most promising opportunities for the CE in Lebanon. There are an estimated 338 firms engaged in the paper product industries in Lebanon, therefore this industry has the capacity to absorb recycled paper locally (ACTED, 2020). The EU funded Environmental Governance report estimated Lebanon's paper imports to total 90,000 tons. The cost of pulp is considerably higher than recyclates, which makes paper recycling cost-viable. Recycled paper has the potential to replace imported virgin paper pulp and form a closed-loop system locally (ACTED, 2020). The recycling paper process is water-intensive, therefore it needs to be managed properly to ensure high efficiency.

Paper-based products are replacing the single-use plastic product, but in order to be competitive, small and large-scale producers need to reach economy of scale and bring down prices, and so stimulate demand (ACTED, 2020).

- **Electronic waste**

The total generation of Electronic and Electric Waste (e-waste), has been estimated in 2016 at 51,000 tons by the Global E-waste Monitor (National e-waste monitor, 2022). The total value of imports of electronic and material goods into Lebanon was estimated at 1,878,855.89 USD in 2016 (Balde *et al.*, 2017). E-waste is not only contains hazardous substances that should be prevented from entering the environment, but also highly valuable materials.

However, in order to be recycled, e-waste must be managed using complex integrated facility, such facilities does not exist in Lebanon, as a result, used electric and electronic devices are dumped with municipal waste in landfills or directly into the natural environment, or are handled by mostly unskilled people in the informal waste market where they burn the e-waste to collect copper and other metals, generating toxic pollution. Considering an average cost of 1350 USD per ton of e-waste, this represents an economic potential of over 64 million USD per year in cost-recovery (ACTED, 2020).

- **Glass**

Lebanon consumes around 71 million colored bottles a year, most of these bottles are used once only, and then sent to landfills. Imports of glass to Lebanon declined by 57.44% in March 2020 compared to previous years, this has driven up the cost of glass containers, particularly for the agro-food sector; as a result, an emerging market for re-used glass offers strong potential for integrating circular logistics within local markets and promoting absorption of this infinitely recyclable material (ACTED, 2020). Globally, glass reuse has been held up as an exemplary recycling practice, due to its strong economic results, glass is 100% infinitely recyclable and offers the unique potential to ensure circular material flows with no leakages, it is an ideal product for the CE concept (ACTED, 2020). Moreover, remelting crushed glass consumes significantly less energy than the process of producing new glass, it is estimated that for every 10% of recycled glass added to the mixture, an energy saving of 2-3% can be achieved, as well, glass can also be crushed and used as an aggregate in concrete (ACTED, 2020).

- **Construction and Demolition Waste**

Unit generation rates of construction waste are 38-43 kg/m^2 for new development projects in Beirut city and 76 kg/m^2 for low-rise buildings in the outskirts of Beirut respectively. The majority of the generated Construction and Demolition Waste (CDW) is being openly dumped.

Roadside dumping and burying of CDW as backfill material is a prevailing practice. Major gaps in the management of CDW include absence of a recycling/disposal infrastructure; lack of means to control open dumping; and insufficiency national investigation regarding the suitability of CDW for recycling as various contaminants may be present depending on the source of the waste (ACTED, 2020).

- **Industrial/Hazardous waste**

The exact amounts of industrial waste generated in Lebanon is not available, nine industries have been identified as major sources of hazardous waste: packaging, paints, fertilizers, printing, metal, textile, tanning, cleaning products and used oil. The country lacks from adequate infrastructure for the management of industrial hazardous waste. Industrial hazardous waste is rarely sorted, it usually ends up in the MSW stream or directly discharged into the environment (Reduction of UPOPs, 2022) (Policy Summary on Integrated Solid Waste Management, 2018).

- **Organic waste**

A large fraction of organic waste in Lebanon is sent to landfills, where very little bioenergy is recovered from it. In this context, it is interesting to consider best management practices of bio-waste, perhaps by recovering useful energy.

The management of bio-waste systems is:

- **Composting**

The compost products in Lebanon suffer from low quality because of the lack of the standard Nitrogen Phosphorous Potassium ratios, which causes chemical imbalance in soil; as well as, the compost products made locally is often contaminated with non-biological debris, due to inadequate household sorting of organic waste. Thirdly, the relatively small Lebanese agricultural market is saturated with imported compost from the European Union (EU). Another major challenge of the composting business in GBA is the lack of the needed area for the composting plants (Azzi, 2017).

- **Biogas**

Anaerobic bio-digesters, have enormous market potential in Lebanon, they are cost-effective and would yield substantial revenue for business. Bio-digesters installed by Lebanese companies mainly produce liquid fertilizer, which is given away for free, the methane gas produced is generally burnt off in summer, but is used in winter to heat the water that is fed into the digester. Such schemes are highly dependent on adequate household-level sorting (Huber, 2019).

Other types of waste such as metals, textiles, wood, used tires, used batteries, and used oil are recovered directly by scavengers and private companies. The major fraction of the medical waste is managed by hospitals and the rest is sent with the municipal waste stream (Sabbagh *et al*, 2014).

Following wastewater treatment, a fraction of the organic component is removed from wastewater, in the form of sludge. In Lebanon, based on default parameters, an average of 12.43 kg BOD/cap of organic sludge is being removed per year, this quantity of sludge can be used for energy recovery (CEDRO, 2013).

2.3 Energy status in Lebanon

Energy generation in Lebanon is based on the importation of oil products as it can be seen in Figures 8, 9 and 10, while the renewable energy sector in Lebanon is still in the infancy stage. The electricity sector of Lebanon is actually a big financial burden for the country finances, and it is monopolized by Électricité Du Liban (EDL) which controls over 90% of the Lebanese electricity sector; in 2017 EDL had an operating loss of 1.4 billion USD (IRENA, 2020).

Over the last years the generation of electricity from EDL hasn't increased, but the demand has increased approximately 7% each year that passes, the influx of refugees to Lebanon has contributed to the increasing gap between electricity generation and demand (Ibrahim *et al.*, 2013) (Wehbe, 2020).

The Lebanese electricity sector is suffering from 1990s, essentially because of the lack of investment with the result of significant deterioration of the sector's infrastructure. Hence, EDL has not been able to satisfy national electricity demand alone, a situation that has led to the development of smaller private diesel generators who operate in an unofficial capacity in a parallel electricity market (IRENA, 2020).

According to the updated 2019 policy paper by the Ministry of Energy and Water (MEW) of Lebanon, the country's consumer peak was estimated at 3669 megawatts (MW) in 2019. The total installed production capacity in Lebanon was around 2600 MW. However, as the effective generation capacity ranges between 1800–2000 MW over the year, an additional 1500 MW would be needed to meet the overall demand. For instance, in 2018 EDL's power plants' contribution to electricity demand amounted to 1884 MW (Ahmad *et al*., 2020).

In terms of the energy consumption by sector, the transport sector is dominating, followed by the residential one (Figure 11).

Despite its recent economic challenges, Lebanon is expected to have a 75% increase in final energy consumption in buildings by 2030. In 2018, cooling energy represented approximately 32% of total Lebanese electricity consumption (Cooling Sector Status Report Lebanon, 2022).

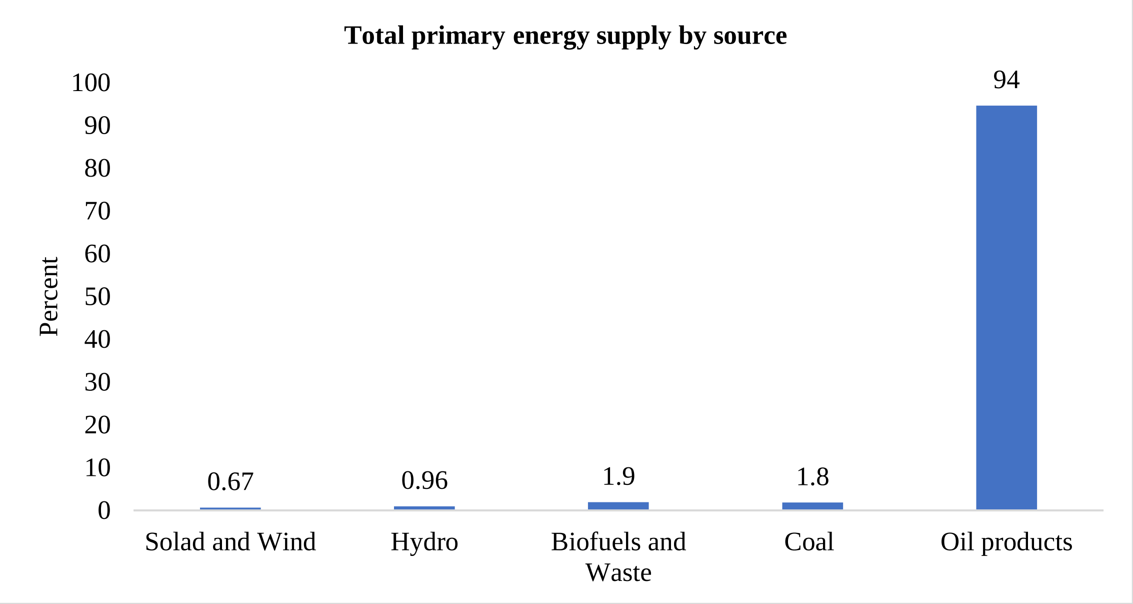

Fig. 8: Total primary energy by source (IRENA, 2020)

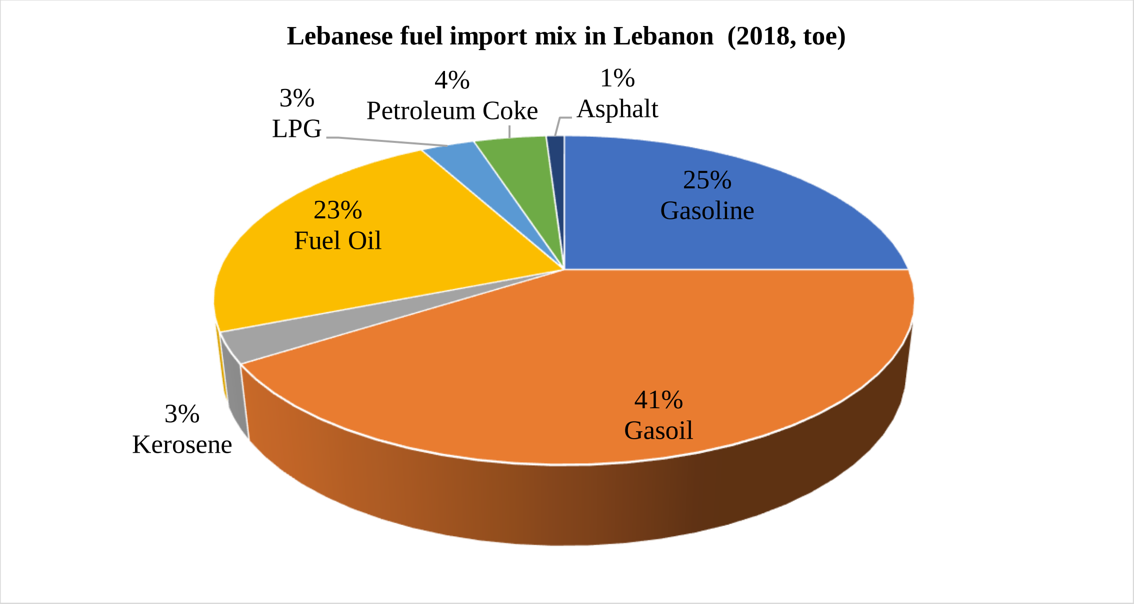

Fig. 9: Lebanese fuel import (IRENA, 2020)

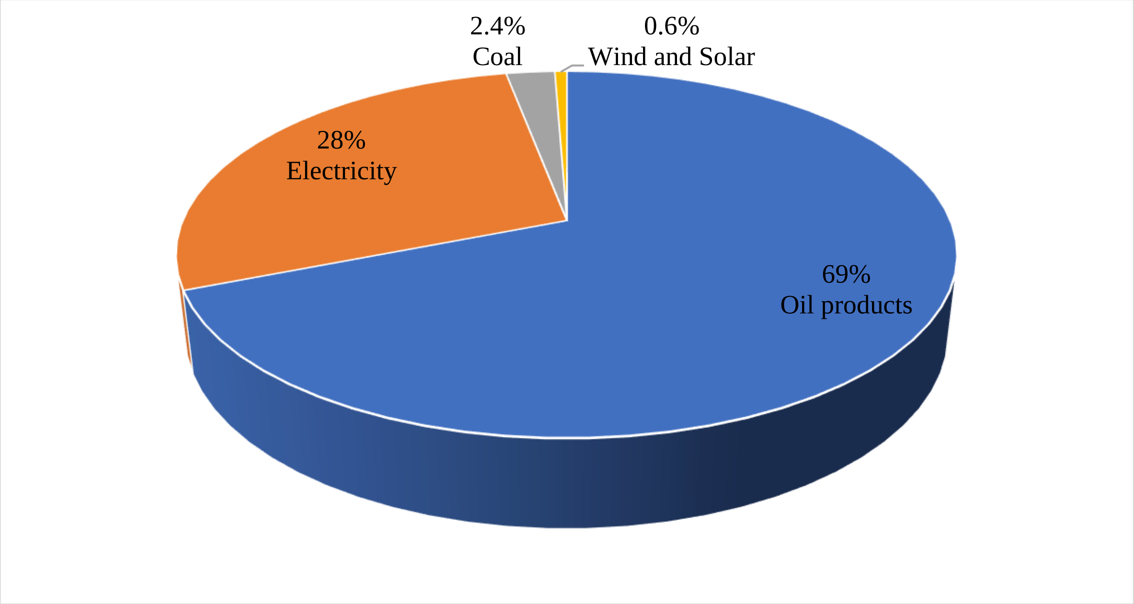

Fig. 10: Total Final Energy Consumption (TEFC) by source (2019) (IRENA, 2020)

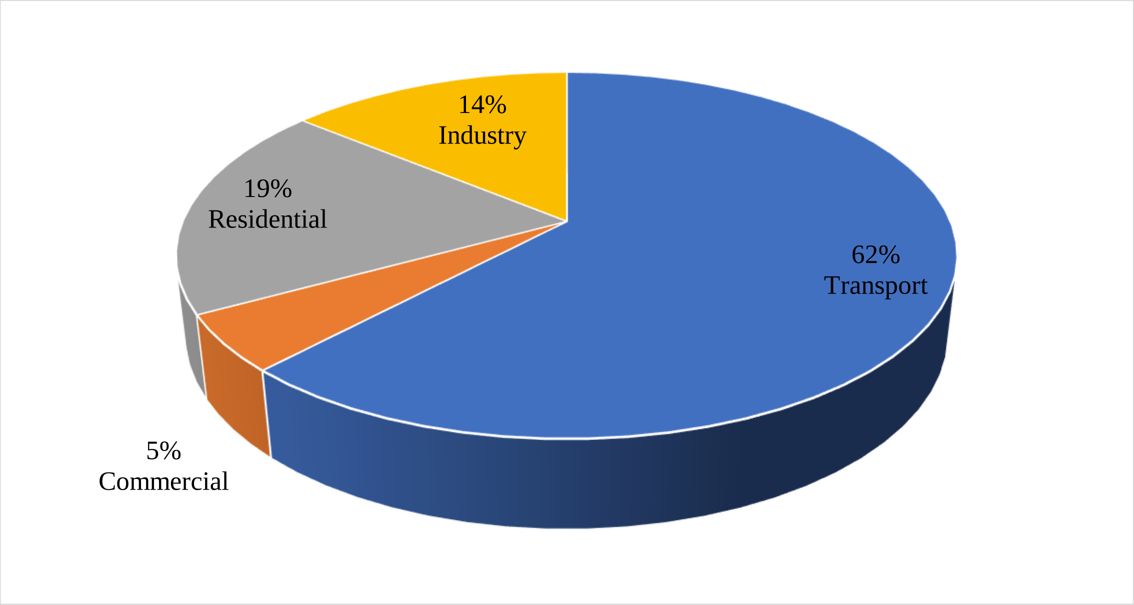

Fig. 11: TEFC by sector (2019) (IRENA, 2020)

2.3.1 Energy costs

An on-site generator costs around 175 USD per month if privately owned, while on the other hand, if neighborhood diesel-generator electricity is rented, the monthly subscription fee exceeds 100 USD for a standard 10-15 Amperes. An EDL's tariff level of approximately 9 US cents per kWh, compared with the tariff of private generator at around 30 US cents/kWh, the Lebanese public can achieve savings of around 800 million USD per year if the diesel generators were phased out, even if the EDL's tariff were doubled, savings would be around 400 million USD (Ahmad, 2020).

A typical 2 kWp PV solar system, if properly designed and if energy efficiency measures are carried out first at residences, then the diesel generator rent will be removed, equal to at least 100 USD per month, and EDL bills can be cut in half, therefore, a saving of around 120–150 USD per month is achievable (Ahmad, 2020).

In Table 2, an installation cost estimation for some RE technologies (EL Helou, 2022).

Technology	**Cost of installation ($/kW)**
Concentrated Solar Power (CSP)	11000
PV	1400
Offshore Wind shallow	8000
Waste to Energy	15300

Table 2. Cost estimation for RE technologies installation (EL Helou, 2022)

2.3.2 Renewable Energy context

Despite having a great RE potentials, the total installed renewable energy power capacity by the end of 2022 amounts to 286 MW from hydropower sources, 9 MW from bioenergy, wind capacity of 3 MW and around 250 MW of solar power. Between 2020 and 2022, the installed capacity of solar power across the country multiplied more than eight-fold, largely from rooftop solar, over 650 MW were installed in 2022 alone, bringing Lebanon's total solar capacity to 870 MW. Installed capacity should reach 1000MW in June 2023 (Abou Moussa *et al*, 2022).

According to the United National Development Program (UNDP) report, it is estimated that around 863,000 tons of biodegradable waste is generated in Lebanon per year. This equals a total energy potential of 743 GWh steam and 278 GWh of methane (CEDRO, 2012).

In 2018, the Prime Minister announced a renewable target of 30% of electricity consumed by 2030, as reflected in the latest electricity reform paper adopted by the Lebanese government in 2019, furthermore, Lebanon approved the Paris Agreement in Parliament under the law 115 in March 2019 (IRENA, 2020).

Additional measures are required to scale-up renewables to the level of 30% by 2030, as per Table 3.

Renewable Energy Target-Lebanon 2030	
Renewable Energy Sector	MW
Wind	1000
Hydro	601
Centralized Solar PV	2500
Decentralized Solar PV	500
Biogas	13

Table 3. Renewable energy target, Lebanon 2030 (IRENA, 2020).

2.3.3 Energy Legal framework

In 2002, Law 462 was presented with the objective of reforming the structure of the Lebanese energy sector. The law provided for the establishment of the Electricity Regulatory Authority (ERA) and allocated it the authority to grant electricity generation licenses to Independent Power Producer (IPPs) in order to feed the national grid. Although Law 462 has been in force since 2002, it has never been implemented. Following an initial emphasis on privatization in the period 1999–2002, the focus shifted towards public-private partnerships and corporatization, leaving Law 462 somewhat outdated. Law 288, adopted in 2014, further side-lined Law 462 by indicating that the Council of Ministers (CoM)-upon joint recommendations from the Ministry of Energy and Water (MEW) and the Ministry of Finance (MoF)-could license IPPs. Law 288 was applicable for a period of two years (from April 2014 to April 2016), but was then extended in 2016 for another two years until 2018 under Law 54, despite the CoM not having issued any licenses (IRENA, 2020).

Law 288 provided the opportunity to conclude a wind Power Purchase Agreement (PPA) contract, allowing for private sector entry to the Lebanese electricity generation market. In 2019, the updated electricity policy paper adopted by the Lebanese government proposed to parliament an amendment of Law 288/2014 (under Law 129/2019) to extend its application period for three additional years to allow the establishment of an independent electricity regulatory authority. This amendment is yet to be addressed by the Lebanese parliament (IRENA, 2020).

2.4 Environment Concerns in Lebanon

Lebanon is one of the largest emitters of CO_2 in the Middle East; in 2021 Lebanon emitted 24,96 million tons CO_2eq., which is diminishing from 2019 mainly due to a significant decrease in energy-related emissions. The main contributor to greenhouse gas emissions in Lebanon remains the electricity production (60%) followed by the transportation (32%), industry and residential sectors (each 4%) (Kai *et al.*, 2019). Almost 40% of the overall electricity GHG emissions can be attributed to private diesel generators, as these generators are mostly located in dense residential areas, environmental impacts endanger the public health, diesel generators were also shown to be contributing to the high levels of fine Particulate Matter (PM), which has also been linked to serious impacts on human health (Ahmad, 2020). For each MWp added to the distributed renewables generation in Lebanon, approximately 1000 tCO_2eq is removed.

Another major polluter is EDL's thermal power fleet, since the power facilities are usually located close to very densely populated areas. EDL power plants emit 0.65 kg of for each kWh produced, thus 2 kWp PV solar system would be contributing to a daily saving of approximately 5 kg of CO_2, reaching up to 47,000 kg of CO_2 over the lifetime of the PV solar system (CEDRO, 2021). The cost of environmental degradation in Lebanon is approximately estimated to be 485 million USD per year or 2.9% of the Growth Domestic Product (GDP). That is why the country is trying to shift towards renewable energies and trying to reduce its GHG emissions to at least 15% by 2030.

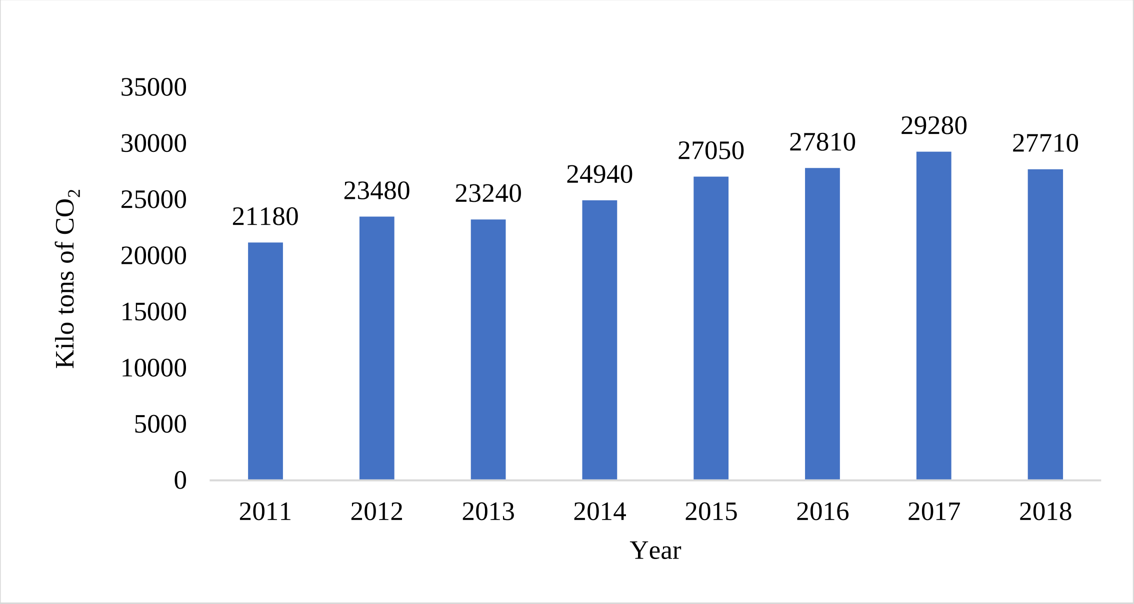

Figure 12: CO_2 emissions in Lebanon (International Renewable Energy Agency, 2020)

2.5 Greater Beirut Area

GBA consists of Beirut, the capital, and 5 other districts which are Matn, Baabda, Alley, Chouf, and Keserwan with an area of more than 200 km^2. It has a population of approximately 2,668,000 million people of which 268,000 are refugees, with a population density of about 11,000 inhabitants per km^2 (Lebanese Arabic Institute, 2021) (Rizkallah and Sabbagh, 2014).

The waste generation in GBA is around 2077 tons of waste per day (Lebanese Ministry of Environment, 2023). The composition of municipal solid waste is similar to the national one specified in Figure 5.

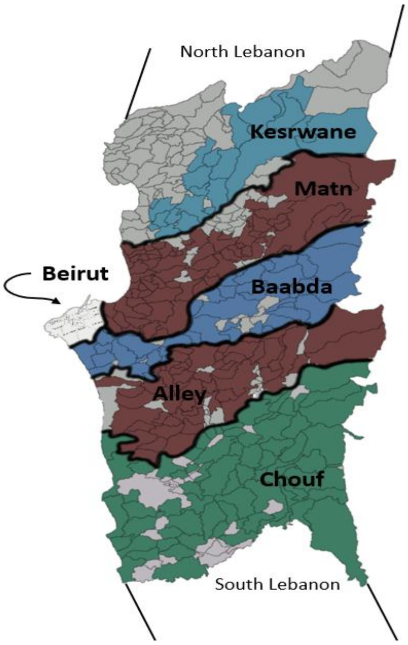

Figure 13: Location of the study area (Beirut-Lebanon) (World Atlas, 2021) (Lebanese Arabic Institute, 2021)

GBA is an urban area with diverse types of buildings, but mostly there are attached multiunit residential buildings that per average have 10 floors with 30 apartments each, more or less, where in each apartment there is a family of approximately 4 to 5 people living per apartment. Outside of Beirut, especially in the Mount Lebanon there are more detached and semidetached one or two-family building houses.

Our study is focused on GBA, because it represents the more critical case of Municipal Solid Waste Management (MSWM) in Lebanon.

2.6 SWOT Analysis of the SWM in Greater Beirut Area

Once reading the information about the waste in Lebanon and mostly in GBA, it is clear that they have a major problem in the management of MSW. There is no information about the collection routes, the collection days, the location of the trash bins, if there actually segregating the trash into different bins, or if everything ends up in the landfill.

It was indispensable relying on SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis, since it is a perfect tool to discover the possibilities and ways for successfully implementing the MSWM. SWOT analysis is, specifically, a basic model that assesses what in a project can and cannot be done, as well as its potential opportunities and threats. From the information found in various scientific articles, a qualitative survey was applied using SWOT analysis in order to formulate strategic action plans, to recognize factors that are liable for ineffective waste management and to improve MSWM in GBA (Aydin Temel *et al.*, 2018) (Ommani, 2011).

2.7 New SWM system in GBA

GBA needs a new SWM system, as there is no information on collection routes, and the location of the garbage bins, if the citizens actually segregate the garbage in different bins, or if everything ends up in landfills. There is a difference of around 4% to 15% from the waste collected and the waste generated in the city, the difference is made because the waste sometimes is burned in illegal dumps, thrown into the sewers, or recovered for recycling.

After analyzing several case studies at global level in the aim of implementing a plan for the SWM in GBA, a suitable methodology called Fixed Box System (FBS) could be useful in this case.

FBS methodology might be helpful in implementing a plan for the SWM in GBA, since it helps in determining the correct number and distribution of bins needed inside the GBA; selecting the best collection and transportation system in terms of equipment and materials; and optimizing the collection and transportation routes (Gallardo *et al.*, 2015) (Mejía, 2009).

2.7.1 MSW management process

To start with the pre-collection phase, the methodology was applied to the city of Beirut, which is divided in 12 quarters and a total of 60 sectors (Lebanese Arabic Institute, 2021) (World Atlas, 2021).

The pre-collection phase starts by segregating the waste from houses, to be able to deposit it into the suitable bins. The attitude of the citizens in participating and collaborating, is the most important factor for having an efficient pre-collection process, for that it is indispensable to take into consideration the following perspectives that could affect the citizens behavior: distance of the collection bins from the buildings (far or not); capacity of the bins (already overflowing and no more trash fits); level of knowledge in separating from houses the waste by fraction in the suitable bins; incentives for the citizens in applying the 3R's.

It is necessary to calculate how much waste bins will be needed, to deposit the organic and non-organic waste, knowing the number of inhabitants, the Production Per Capita (PPC) which usually reflects the amount of waste collected, but not the waste generated, the minimum and maximum days' number of accumulation, the density of solid waste in the bin, the peak production per day, the capacity of the bins and the safety factor.

After the pre-collection phase with the bins located at a fixed location, the next step is the collection phase that begins when the compactor truck passes to collect the waste from the bins, and to transfer it to the treatment plant.

For the organic waste the compactor truck will collect the waste from the bins every day (to avoid smell, especially in the summer).

In a week the collection truck will be working a total of 6 days (from Monday to Saturday) dividing Beirut in 3 zones.

The number of the compactor trucks that the city will need for the collection of its waste will be calculated, as well, the number of bins one truck will collect until it reaches full Capacity of Garbage Container (CGC). These calculations will enable the selection of the best route for the collection of the solid waste, taking in consideration the economic and environmental factors.

For the collection a mechanized compactor collection truck of back rear with a volume of 15 m^3 and a compaction density of 800 kg/m^3 will be used.

CGC for each waste fraction is defined by Eq. 1:

$$\mathrm{CGC} = \frac{\text{Volume truck container} \cdot \text{Density truck container}}{\text{Volume type waste bin} \cdot \text{Density type waste bin}} \qquad (1)$$

The average estimated time required for the bins emptying by the compactor truck is 40 seconds, the time for moving the truck between one bin and another is 80 seconds, the transportation time of the load from the last bin to the treatment plant is 25 minutes, the waste discharging time is 25 minutes,

and the dead time equal to 10% of the total. This information was estimated by interviewing workers who are dealing with waste collection at the municipality of Beirut.
The calculation of the time per trip until a full truck loading is defined by Eq. 2:

Time per trip = [CGC * Time truck dumping + (CGC -1) * Time transport between bins + Time to plant + Time to unload] * (1 + Dead time) (2)

Organic waste is collected every day of the week, non-organic waste at most every 4 days, therefore the number of trips is (Gallardo *et al.*, 2015), Eq. 3:

$$\text{Itinerary} = \frac{\text{Max volume accumulation of waste}}{\text{Volume truck container} * \text{Density truck container}} \tag{3}$$

Beirut suffers from traffic and transport congestion during the day, sometimes it is difficult for the garbage truck to access the roads, in order to solve part of the problem, garbage collection must be done during the night shift as there is less traffic (Saroufim and Otayek, 2019). The trips per shift (workers have an 8-hour work cycle) (Gallardo *et al.*, 2015), Eq. 4:

$$\text{Trips per shift} = \frac{\text{Job cylce}}{\text{Time per treep}} \tag{4}$$

Number of compacting trucks (Gallardo *et al.*, 2015), Eq. 5:

$$\text{Trucks number} = \frac{\text{Number Intinerary}}{\text{Trips per shift}} \tag{5}$$

2.7.2 Costs estimation

It was needful to estimate the cost for the solid waste pre-collection and collection phases, for that, it should be calculated the Capital Recovery Factor (CRF) of a compactor truck (Boskovic *et al.*, 2020), Eq. 6:

$$\text{CRF} = \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \tag{6}$$

The annual cost of the compactor truck TC, Eq. 7:

$$TC = P * CRF + M * V \tag{7}$$

where P = Compactor truck price, M = Maintenance cost of compacter truck, V = Truck volume capacity.
The total labor cost for 3 workers (1 driver and 2 assistants, the latter 2 have to handle up the bins, because the bins usually are not in the right place, and they also have to clean up the waste left near the bins by the inhabitants) using 1 compactor truck: Eq. 8 and 9:

$$LC_{organic} = O * C * h * D_{organic} \tag{8}$$

$$LC_{non\text{-}organic} = O * C * h * D_{non\text{-}organic} \qquad (9)$$

where: O = *Workers per truck*, C = *Labor cost per hour*, h = *Hours worked per day*, $D_{organic}$ = *Days worked per week for organic waste*, $D_{non\text{-}organic}$ = *Days worked per week for non-organic waste.*

The total annual cost of a compactor truck TAC, Eq. 10 and 11:

$$TAC_{organic} = TC + LC_{organic} \qquad (10)$$

$$TAC_{non\text{-}organic} = TC + LC_{non\text{-}organic} \qquad (11)$$

These calculations are based on the following information: $P = 20{,}000$ *euros* (Ali Baba, 2021); $M = 4{,}000$ *euros/year* (estimated by interviewing mechanical technicians in Lebanon); $V = 15$ *tons; Discount factor:* $i = 10\%$ (Downing and Matthews, 2010); *Amortization period:* $n = 10$ *years* (Boskovic *et al.*, 2020); $O = 3$ *people;* $C = 1.83$ *euros;* $h = 8$ *hours,* $D_{organic} = 7$ *days/week,* $D_{non\text{-}organic} = 6$ *days/week; Weeks worked per year:* $w = 52$ *weeks.*

As for the fuel cost, the following information are noted (Nguyen and Wilson, 2010): *Fuel Price in Lebanon/liter:* $FP = 0.44$ *euros/l; Fuel consumption while travelling:* $FC_{Tra} = 0.250$ *l/km, while idling:* $FC_{Idl} = 2.3$ *l/hour; Number of stops:* $N = 44$*.*

It could therefore calculate Eq. 12, 13, 14, 15 and 16:

$$\text{Total liters while travelling} = Tl_{Tra} = FC_{Tra} * T_{Dis} \qquad (12)$$

$$\text{Total time while idling} = Tt_{Idl} = N * TD \qquad (13)$$

$$\text{Liters while idling} = l_{Idl} = FC_{Idl} * Tt_{I}dl \qquad (14)$$

$$\text{Total liters while idling} = Tl_{Idl} = (l_{Idl} * T_{Dis})/Tl_{Tra} \qquad (15)$$

$$\text{Total fuel cost per trip of Saifi} = FC_{coll} = (Tl_{Tra} + Tl_{Idl}) * FP \qquad (16)$$

It is also necessary to know the annual cost of the bins Using Eq. 17 and 18 (D'Onza *et al.*, 2016), basing on the subsequent information: Q*: quantity of the bins; Purchase price:* $P = 70$ *euros/bin* (price in the Lebanese market asking more than 1 company that produce this kind of bins)*; Depreciation rate:* $D = 10\%$ (D'Onza *et al.*, 2016)*; Cleaning of the bin* $C = 25$ *euros; Maintenance cost/year* $M = 18$ *euros* (estimated by interviewing workers at the municipality of Beirut).

$$\text{Annual cost for 1 bin} = ACC = P * D * M * C \qquad (17)$$

$$\text{Annual cost for all bins} = Q * ACC \qquad (18)$$

After waste pre-collection and collection phases, the waste is sent to the city of Qortadah (selected using QGIS) which is located in the Baabda district with a distance of about 24 km, an altitude of 600 meters and an area of 242 hectares (Localiban, 2007).

Regarding GHG emission, the major component of waste handling and transportation is considered to be CO_2 since CH_4 and N_2O emissions are negligible (Menikpura, 2013).

To be able to calculate these emissions, the following information must be known:

Energy (MJ/unit) = energy content of the fossil fuel = 36.42 MJ/l diesel; Emission Factor of CO_2 *of the fuel = EF = 0.074 kg* CO_2*/MJ diesel; Waste per route = 1322.1 tons per day/110 trips per day = 12.01 tons*

The total GHG emissions, Eq. 19:

$$\text{Emissions} = \frac{\text{Fuel}}{\text{Waste}} \times \text{energy} \times \text{EF}$$

2.7.3 Best municipal solid waste collection route

To be able to find the best route collection, Euclidean Traveling Salesman Problems (ETSP) was applied. The Traveling Salesman Problems (TSP) is historically known, and related mathematical problems were treated in the 1800s by the Irish mathematician Sir William Rowan Hamilton and by the British mathematician Thomas Kirkman (Jiang, 2010). There are applications of the TSP in many branches of science (genome project, robotics, electronic circuits, logistics problems, etc.), which constitutes an attractive area for a diversity of researchers (Jiang, 2010).

In the ETSP, the n bins are distributed with uniform randomness in 2-dimensional hypercube and the distance is measured in the Euclidean metric. If there are n bins distributed uniformly according to the system of drop-off points, the distance between the bins is measured in the Euclidean metric $\Delta l = \sqrt{\Delta x^2 + \Delta y^2}$. The ETSP makes a question: which order has to be followed for collecting the bins; this question can be resolved by considering a collection of yes–no decisions posed in the following form: should bin b (x_b,y_b) be visited immediately after collection bin a (x_a,y_a):

- if yes, then bin b will be collected after bin a in a route, and cost c_{ab} $c_{ab} = \sqrt{(x_a - x_b)^2 + (y_a - y_b)^2}$ will be incurred;
- if no, then bin b should be followed by some other bin that is not a.

The final route will give a feasible tour result of n yes answers in such a way that each bin is entered and exited once in a continuous route (Jiang, 2010).

ETSP was applied with the help of the Solver add-in tool available in Microsoft Excel. The first step in using Microsoft Excel is to make an origin-destination matrix from each point in the map, and using the distances taken from Geographic Information System (GIS). The solver will help finding the result by adding constraints in the matrix giving different feasible scenarios for each bin: from which points the collection route starts from, and not one bin should be repeated once it solves the problem. As a final result, ETSP should lead us to choose the shortest route for the collection of the MSW, that it will impact not only on cost saving, but also on reducing the GHG emissions, because as mentioned before it is one of the biggest concerns in the SWM (Menikpura, 2013).

The following guidelines are applied:

1. the objective is to know the total distance of the route once it passes through the bins;
2. the route must have the minimum distance summed up between the bins numbers;
3. the variables that will be changing is the route order with the variables of the Euclidean mileage matrix and the constraints applied;
4. the first constraint applied to the solver is that not one bin should be repeated once it solves the problem;

5. the second constraint applied is the starting point, from which bin the collection route starts from;
6. the evolutionary option is designed to find feasible, good, and optimal solutions.

QGIS software was used to analyze and edit spatial information on the map area of Beirut. It was exploited to locate the collection bins in the area, and it was also helpful in determining the distances between the bins.

2.8 Multi-Criteria Decision Analysis

Whilst there is a great potential for generating energy from waste, the challenges are many, such as policy uncertainties, financing, and competition with non-renewable energy sources.

The selection of a suitable WtE technology is a complex decision and it involves many factors, such as, waste quality and quantity, social, environmental, technological and economic concerns, this has led to the popularity of Multi-Criteria Decision Analysis (MCDA) methods that help in taking strategic decisions for an effective evaluation and management of sustainable energy plans. They have been widely used throughout the energy industry, and are growing in popularity within the field of waste management (Aravossis *et al*., 2021) (Achillas *et al*, 2013). Whilst one MCDA method is not necessarily better than the other, the AHP (Analytic Hierarchy Process) is widely used to support decision making processes in the field of waste management (Loken *et al*., 2007) (Soltani *et al*., 2015).

AHP model building

The AHP, first introduced by Saaty in the late seventies, is a multi-criteria decision making technique, quite often used to solve complex decision making problems in a variety of disciplines (Saaty, 1980). The AHP hierarchical structure allows decision makers to easily comprehend problems in terms of relevant criteria and sub-criteria. The decision procedure using the AHP is made up of the following steps (Hummel *et al*., 2014):

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 at a level 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.

Pairwise Comparison by Solicitation of Experts Opinions for AHP Application

Since the main goal of our study is to make a decision regarding the suitable WtE technology for the treatment of the MSW in GBA, the AHP model goal has been formulated to reflect such an objective. To choose the criteria/sub-criteria that will be used in the alternatives evaluation, a comprehensive literature review was conducted on the WtE technologies and on the solid waste and energy sectors in the aim to gather data and determine a suitable evaluation criteria for our case study. The criteria/sub-criteria considered encompass a range of environmental/health, technological, economic and social factors. The collected data is used to help the participants in the conduction of the pair-wise comparisons through the AHP decision making process.

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 is devoted to the sub-criteria which details the meaning of the criteria to which they are connected and make the assessment more accurate. Finally, the alternatives that will be considered for the evaluation to achieve the study goal are presented in the fourth level of the AHP model. Figure 14 shows the structure of the AHP model, and in table 4 a summary of the WtE technologies characteristics.

To apply the AHP technique and develop credible decision preferences, 5 experts in the waste management sector in Lebanon were engaged, and their opinions were gathered using survey questionnaire. The questionnaire includes guidelines for the experts on how to carry out the comparison, as well as 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 (Saaty, 1980).

To ensure the experts' judgments consistency, a consistency check was performed for each matrix by calculating the Consistency Ratio (CR). In the case where the CR value is within acceptable range (usually less than 10%), the judgments are considered consistent. 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 (Mogbojuri *et al*, 2021) (Sipahi *et al*., 2010).

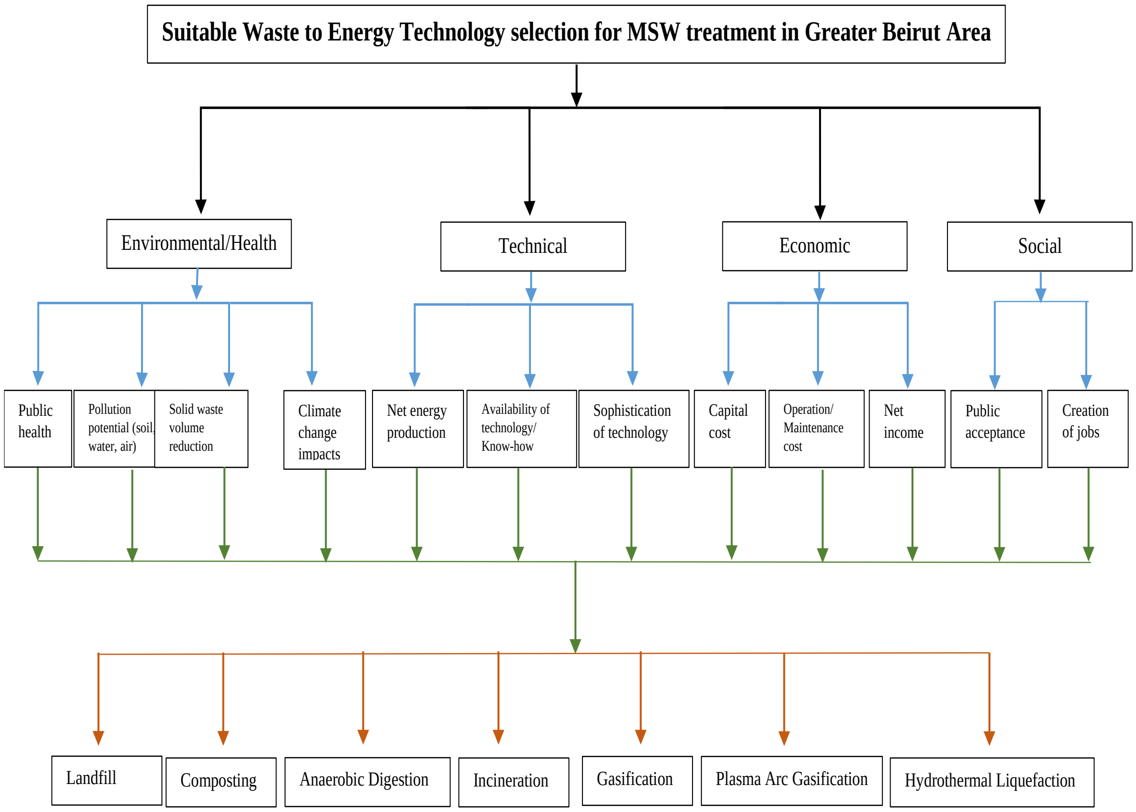

Fig. 14. Structure of the AHP model

	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 there are mentioned in the table for comparison reason.

Table 4. WtE technologies characteristics (Beyene *et al.*, 2018), (Nizami *et al.*, 2017) (Hoang *et al.*, 2022) (Wael *et al.*, 2022)

2.9 Energy production potential in GBA

It was indispensable to take into consideration 2 potential technologies for the production of energy in GBA. The Waste to Hydrogen (WtH_2) technology, since a great fraction of the MSW in GBA is made from organic waste. Another energy production technology is the solar power, given that in the last 2 years there is a high increase in decentralized solar power systems installation in GBA.

2.9.1 Waste to Hydrogen

Hydrogen has many applications such as generation of electricity, in transportation sector and in other chemical industries. As an energy carrier, Hydrogen has the advantage of being stored and transported, which is beneficial for large-scale industrial applications and long-distance transportation. The global hydrogen market in 2018 was valued at over 135.5 billion USD, with an estimated annual growth rate of 8 percent until 2023 (Green Hydrogen in developing Countries, 2020). For Hydrogen to become a sustainable alternative to fossil fuels, it is essential that it is produced using renewable energy, green Hydrogen production has the potential to use excess electricity generated by solar and wind power, making it a complementary technology for these renewable sources. Green Hydrogen could provide developing countries with a powerful technology to support national sustainable energy objectives and decarbonization strategies; as well, it could enhance national energy security by reducing the exposure to oil price volatility and supply disruptions.

Hydrogen technologies are capital intensive, and further cost reductions and efficiency gains need to be realized to scale up green Hydrogen solutions. The potential applications for green Hydrogen and fuel cells in developing countries have not been fully explored.

As per decarbonization perspective, analysis conducted by McKinsey for the Hydrogen Council in 2017 suggested that a transition toward a hydrogen economy could lead to 7.5 gigatons of annual CO_2 abatement by 2050 (McKinsey & Company, 2018).

Since the Climate regulations are much stronger, and considering that the Hydrogen can be produced and stored for long periods of time, then dispensed when needed, as well the cost of producing hydrogen from clean sources has fallen dramatically, thus, decentralized green hydrogen production could soon become cost competitive, in light of all these facts Hydrogen production is in stable increase with time.

2.9.2 Solar Power

International Renewable Energy Agency's (IRENA) Global Atlas for Renewable Energy indicates that annual average solar irradiation in Lebanon ranges between 1520 and 2148 $kWh/m^2/year$, with a significant majority of areas being above 1900 $kWh/m^2/year$. Building on this solar irradiation data, IRENA estimates that the potential for utility scale solar PV could reach 182 GW (Renewable energy outlook-Lebanon, IRENA 2020). According to the National Energy Efficiency Action Plan (NEEAP), the national solar PV targets are 150 MWp and 300 MWp in 2020 and 2030, respectively (LCEC, 2016).

Beirut City has a potential of distributed rooftop solar PV capacity between 200 and 300 MWp, the average rooftop area is estimated at 185 m^2, which translates into an average capacity of 12 to 17 kWp, depending on the rooftop occupancy factor (Ahmad, 2020).

It is interesting to simulate the best alternatives for energy production in GBA in terms of CE's modeling. To perform such simulations, HOMER-Pro software was used.

2.10 HOMER-Pro Software

HOMER-Pro is a sophisticated software application for modelling and analyzing hybrid energy systems. One of HOMER-Pro's primary features is its ability to simulate both AC (Alternating Current) and DC (Direct Current) power systems, making it especially helpful for analyzing hybrid systems that incorporate both sources of power. HOMER-Pro allows simulation of grid-connected and off-grid connected systems which generate electricity from various combinations of solar PV modules, wind turbines, biomass based power generators, micro-turbines, fuel cells, batteries, Hydrogen storage and traditional sources such as diesel generator with various fuels options and different type of loads.

In our study, HOMER-Pro software has been used for the evaluation of the optimal solution of the life-cycle cost of the proposed hybrid energy system. The HOMER-Pro software requires the location data, the electric load, the capital and maintenance costs of the different components. HOMER-Pro ranks its result based on the least cost combination (Al Badi *et al.*, 2022) (Suresh *et al.*, 2019).

2.11 Circular Economy Model

CE is a regenerative system in which resource inputs, waste, emission, and energy loss are minimized by closing, and optimizing energy and material loops. Noting that the introduction of new technologies enables the development and introduction of new CE models.

CE modeling assisted by RE technologies provides a great asset for the resolution of Lebanon's waste and energy crisis in a sustainable means bringing significant economic, social and environmental benefits to the Lebanese economy. The CE model proposed in this study links the best waste management practices for a green energy generation for GBA.

CHAPTER 3

3. RESULTS AND DISCUSSIONS

3.1 Differences between developed and developing Countries that affect SWM

The below illustrate the major differences between developing and developed Countries that pertain to the layout of Municipal Solid Waste Management (MSWM) solutions:

- An essential difference between developing and developed nations refers to the heterologous amount and specifications of waste produced. The waste produced tends to rise as revenue growths, in addition, the combination of the waste also tends to be different.
- In developing Countries, attention needs to be paid on the characteristics and properties of waste, including the quantities of waste generated, waste composition, moisture content and calorific value. Waste produced in developing nations involves a huge percentage of organic substances, generally three times more than that of developed ones. In developed Countries, the moisture content of waste is estimated to be in the range of 20–30%, whilst in developing Countries it is 50% or higher (Mmereki, Baldwin and Li, 2016), which it can be an obstacle in adopting sustainable combustion technologies as a waste treatment option.
- In developed nations waste produced contains high percentage of packaging materials.
- The availability of funds is primarily the main obstacle for developing Countries, which spend a higher percentage of their SWM budget on waste collection alone, while less than 10% on final treatment of waste, while developed countries spend a large portion of their SWM budget on waste treatment.
- Waste collection is an important element for sustainable waste management. Whilst in developed Countries the infrastructure is well developed, this is not the case in developing Countries where the roads are in bad conditions or inaccessible. In developed Countries, good financial management promotes the implementation of a well-functioning waste collection system, thus increasing the efficiency of transfer and transportation as well as the trust of service users, this is a key component in determining the economics of the whole SWM system. Another problem is the lack of financial resources to buy proper equipment and machinery; these services are expensive for municipalities in developing Countries, moreover, waste collection machinery and equipment are outdated, used without proper maintenance and suffer from breakdowns.
- Developing Countries have limited or absent solid waste segregation programs. Accordingly, developing Countries lack household segregation and rely on informal ‘waste picking’, making long-term planning difficult, and which may impact on the ability to effectively administer SWM systems.
- In contrast, developed Countries have effective programs on waste segregation, and they do have equipment and machinery to promote waste segregation at the household level. As well, they pay more attention to waste flow data, characterization and identification of the sources and types of waste (Mmereki, Baldwin and Li, 2016).
- Unlike developed Countries, which have adequate data on material recovery, this kind of data in developing Countries are rare. In developing Countries, the informal sector dominates the recovery market, and the recycling systems are driven by revenue from selling recovered materials by ‘rag pickers’ or ‘street buyers’ who continue to collect, use and sell materials, without any government financial support. The recovered materials are of high standard in developing Countries than observed in developed ones, the reason for this is the labor intensive manual sorting used compared to automated techniques in developed Countries (Mmereki, Baldwin and Li, 2016).

- Developed Countries have addressed their SWM by implementing effective and functioning policy frameworks and comprehensive solid waste plans, with clearly defined objectives in waste material flows.
- In the majority of developed Countries, there is sufficient financial investment, public-private partnerships and expertise in the field of SWM. Most importantly, for effective management of SW, developed Countries have integrated policy approaches that encompass not only the environmental and technical aspects, but also the institutional, financial, technical and educational aspects together with the implementation of appropriate technologies of SWM.
- The key concern in the municipal waste management sector in developing Countries is the lack of appropriate legislation, monitoring, and enforcement capacities accompanied by weak public institutions.
- Developed Countries' policy favor the 4R's rules (reduce, recovery, reuse and recycle), and it is focused on the adoption of sustainable waste management technologies aimed at reducing landfilling of waste, and optimizing environmental protection, incinerator bottom ash treatment, emission control devices and dioxin reduction, odor control for composting facilities and anaerobic digesters.
- In developing Countries, the disposal of waste in an uncontrolled manner or in open dumps and conventional landfills is still prevalent which may generate high volumes of leachate, and increase the risk of groundwater and air pollution due to improper design, that is, without leachate and gas collection systems.
- Politics inevitably plays an important role in improving SWM efficiency, the relationship between central and local governments affects the structure, functioning and governance of SWM systems, and the extent of citizens to participate democratically in policy-making processes. The greatest challenge in many developing Countries is to strike the right balance between policy, governance, institutional mechanisms and resource provision and allocation. In addition, petty and high-profile corruption is also rampant in many developing Countries than in developed ones.
- Lack of public awareness is one of the major problems of SWM in developing countries, only a small percentage of the public know where their own domestic waste ends up once it has been collected, or how much the waste collection and disposal service costs them. As well, municipalities don't have awareness programs for SWM staff, and for the public. The essential barriers for raising awareness about waste management activities are: deficiency in funds, and lack of interest from key stakeholders; rooted cultural practices and behavioral norms; unsupportive legal and regulatory frameworks (Mmereki, Baldwin and Li, 2016).
- Developed nations benefit a relative affluence of capital and enjoy high labor prices, while developing ones have a relative rarity of capital and affluence of inexperienced and cheap labor.
- Affordability of solid waste management by the household is another challenge in developing countries. The existence of timely, affordable and frequent collection services could facilitate a cleaner environment, and assist in ensuring a healthy and safe population (Mmereki, Baldwin and Li, 2016).
- Developing Countries employ relatively cheaper technologies (landfilling) compared to other waste management options due to the absence of alternative waste management techniques. Incinerators are often designed without emission systems, which often produce gases harmful to public health and the environment. Biological treatment processes such as composting are not sustainable approaches in developing countries due to the following reasons: (a) high operating

and maintenance costs compared to that of open landfilling; (b) higher cost of composts than commercial fertilizers and (c) incomplete separation of materials such as plastics and glass, making the compost poor for agricultural application (Mmereki, Baldwin and Li, 2016).

- Developed Countries have adopted high standards of workplace health and safety, abiding by state guidelines, compared to a very bad informal waste sector worker's situation in developing Countries.
- In developing countries, the general public is not well-sensitized and encouraged to participate in waste management programs. Developing Countries lack social advocacy or government pressures to segregate waste at source. Therefore, effective environmental awareness campaigns at the educational and community levels can eventually help in improving SWM efficiency and reducing environmental risks (Mmereki, Baldwin and Li, 2016).

3.2 SWOT analysis

After analyzing information collected about the SWM in Lebanon, the following deductions were formulated:

Strengths

- For several years the government has been taking out emergency plans to improve the waste management, but the government hasn't been able to move forward due to many reasons;
- Stabilizing a better coordination between the private contractors in charge of waste collection and transportation and the public entities, will lead to a clear and more organized SWM system;
- Organizing public awareness programs (which could start from the schools);
- Considering the inhabitants as a strength, they could help in spreading the word of environmental awareness, applying the 3R's, trying to change their lifestyle for a better SWM system;
- Incentives for the citizens in applying the 3R's rule will help in the implementation of an effective SWM;
- Increasing efforts for recycling, keeping in mind future population growth;
- Strengthening public and private partnerships;
- Making sure that the laws related to the SWM and environmental protection are applied, with strict sanctions for the violators;
- Applying new waste collection system;
- Adopt a strategy of less plans and more application.

Weaknesses

- The corruption in the country, which results in an ambiguity in the public tenders, an absence of economic measures, unfinished businesses, to cite a few;
- Missing of information due to the lack of database and record keeping;
- New initiatives for improving the SWM system are usually going with a slow pace;
- A lack of source segregation, most of the waste ends up in the landfills;
- The community's non-willingness to cooperate and participate because in many occasions the government has defrauded them;
- Financial, political, technological and community barriers are making the SWM a complex issue to be solved in Lebanon;
- High cost of sweeping and collection, and low percentage of waste recovery;

- Weak public institutions.

Opportunities

- Using software and applications, with sensors and smart devices specific for different connectivity and data management applications that help to optimize the waste collection;
- Installing reverse vending machines in the supermarkets, to give the chance for the people to recycle for example the bottles and receive discounts or money in return;
- Agreements between the recycling companies and the municipalities to help in creating jobs, to support the local community, and to raise environmental consciousness in segregation and recycling of the waste;
- Waste to Energy is another opportunity by using technologies such as incinerator, anaerobic digestion, gasification, pyrolysis, or even landfill biogas capture. GBA could benefit from these technologies for electrical energy generation;
- Enforcing laws and rules to oblige public and private sectors in respecting the environment and minimizing the pollution;
- Short term contracts with penal clauses, surveillance, audit, and financial control on the private companies are also essential;
- New jobs are expected to appear in a number of different waste management activities.

Threats

- A complete stop of the collection service due to financial lack; Lebanon has one of the most expensive SWM systems in the world;
- The way handling the waste after the collection, the waste is burned in open dumps affecting the health of the nearby community, or they are dumping it in landfills that are already almost full of capacity;
- Landfills are causing pollution to the soil and the air, causing health problems to the population living in the surroundings, and loss of land that is very hard to regenerate again;
- The citizen's behavior, if they don't want to cooperate with the government, if they don't follow the rules like in the separation of trash;
- The biggest problem in Lebanon is the corruption, for that a clearer and more transparent relationship with the communities from the side of the public entities and private companies is a way of trust.

3.3 MSW management process and costs estimation

3.3.1 Number of waste bins

The daily generation of organic waste is of 1322.1 tons, giving the total of 9,254,76 tons per week as seen in Table 5. The size of the bins is of 2400 dm^3, the waste density is a total average of 290 kg/m^3, and the safety factor is of 0.9, consequently, for the organic waste fraction there will be a total of 2111 bins.

The non-organic waste is divided into 4 fractions: paper/cardboard, plastic/metal, glass and mixed to help citizens in the recycling process. Daily generation in tons of the non-organic waste, and by fraction can be found in Table 5, as well as the specific waste density of each fraction (NPTEL, 2020). It is found that 5017 bins will be needed for the collection of the non-organic waste, divided according to the different fractions: 2447 bins (paper/cardboard), 1346 bins (plastic/metal), 734 bins (glass/metal), and 489 bins (mixed).

As a final scheme, Beirut needs 7128 bins to deposit the waste, of which 2111 are for organic and 5017 are for non-organic, all located in the streets with a system of drop-off points, with a distance of 100 to 300 meters between each group of bins (organic and non-organic).

Waste	**Density (tons/m^3)**	**Composition (%)**	**PPC (kg)**	**Production (tons)**
				Per day
Organic	0.29	52.5	0.69	1322.1
Tot. non-organic		37	0.41	785.6
Non organic by fraction				
Paper	0.085	16	0.20	383.2
Plastic	0.077	11.5	0.11	210.8
Glass	0.195	3.5	0.06	115
Mixed	0.160	16.5	0.04	76.6

Table 5.Organic/non organic waste generation

3.3.2 Number of waste collection trucks

For the organic waste, the compactor truck will collect the waste from the bins every day (to avoid smell, especially in the summer), for the non-organic waste, the collection frequency is 2 times per week (Monday to Saturday).

By applying the equation of CGC to each waste fraction, the truck will reach full capacity once it collects the following number of bins for 1 trip: organic waste (17), paper/cardboard (59), plastic/metal (65), glass (26), and mixed (31). By applying the Eq. 2, 3, 4 and 5, it was determined the collection time, trips per day and number of trucks needed: 110 trips for the organic waste (1.52 hour/trip), 43 for paper/cardboard (3.03 hour/trip), 23 for plastic/metal (3.25 hour/trip), 13 for glass (1.83 hours/trip), and 9 for mixed (2.03 hours/trip).

Number of trucks/day: 21 trucks/1322.1 tons of organic waste, 16 trucks/510.96 tons of paper/cardboard, 10 trucks/281.03 tons of plastic, 3 trucks/153.29 tons of glass and 2 trucks/102.19 tons of mixed waste; therefore, he maximum number of trucks needed to collect the all waste is a total of 52 trucks/day.

GHG emissions from the collection process

Applying Eq. 19, the total GHG emissions equals to 8.02 kg CO_2/ton. GHG emissions can be addressed through the introduction of green fuels, additional truck technology options, such as "hybridizing" the engine with an electric motor and battery system, can reduce GHG emissions in a range of 220 to 300 grams per mile (SHAHEEN and LIPMAN, 2007). Smart transportation system technologies could help in reducing fuel consumption and emissions by selecting optimal available route as distance and time, moderating accelerations/decelerations, and reducing congestion (SHAHEEN and LIPMAN, 2007).

The energy consumption of a truck is affected by its load, speed, road conditions, and engine model. Of these, the load and speed of vehicle can be controlled by the driver, thus affecting energy consumption (Xin *et al.*, 2020).

3.3.3 Cost estimation

The frequency of waste collection considerably influences the waste collection costs, and it depends on many factors such as: quantity and characteristics of waste, generation rate, climate condition, population density, availability of space for bins, available equipment and facilities in the municipalities.

The annual labor cost for 3 workers: $LC_{organic} = 15{,}968.88$ €/year; $LC_{non\text{-}organic} = 13{,}703.04$ €/year, and the annual cost of a compactor truck: $TAC_{organic} = TC + LC_{organic} = 79{,}241.79$ €/year; $TAC_{non\text{-}organic} = TC + LC_{non\text{-}organic} = 76{,}957.95$ €/year. As for bins, the cost of 1 bin = 50 €/year (total = 356,400 €/year). The total cost per ton of each fraction of solid waste together with the total annual cost of using a compactor truck is shown in Table 6.

Waste	**Organic**	**Paper**	**Plastic**	**Glass**	**Mix**
Tons collected per day	1322	510.9	281	153	102.19
Number of trucks in circulation per day	21	16	10	3	2
Tons of waste collected by 1 truck/day	62.96	31.94	28	51	51
Days of work per week	7	6	6	6	6
Tons of waste collected by 1 truck/week	440.7	191.6	168	306	306.57
Weeks worked per year	52	52	52	52	52
Tons collected by 1 truck per year	22916	9963	8768	15942	15941
Total annual cost for 1 truck (€/year)	79241	76957	76957	76957	76957
Cost per ton (€/ton)	3.46	7.72	8.7	4.8	4.83

Table 6: Costs per ton of waste, and annual costs of using compactor truck

The cost of the fuel is the greatest expense in waste collection and transportation. Many studies have revealed that trucks consume more than 60% of their fuel in 'at route' stage, of which between 2.2% to 25.1% was used for idling (Nguyen and Wilson, 2010): $Tl_{Tra} = 35.72$ l/km; $Tt_{Idl} = 0.484$ hours; $l_{Idl} = 1.11$ l/hour; $Tl_{Idl} = 4.44$ l/km; Total fuel cost per trip of Saifi: $FC_{coll} = 17.67$ €.

Entities and companies that are dealing with solid waste collection and transportation are trying to save fuel consumption using diverse techniques such as, on-board idle reduction systems which include auxiliary power systems that are installed on the truck to provide electrical, thermal, or mechanical power for some or all of the options that would normally require the truck engine to idle (Downing and Matthews, 2010). Other possible methods might include smaller and more fuel-efficient vehicles to low density areas, or through the use of newer technologies such as hybrid waste collection vehicles.

To minimize as much as possible, the solid waste management cost, the waste segregation should start from home (Maalouf *et al.*, 2019), another option is to sell these materials to private companies directly by the citizens. Who has garden, He can profit from the organic waste by composting it, to produce fertilizer, in this manner, it could be less waste in the bins to be collected, this leads to a decreasing in the collection frequency, so more saving in collection cost. If the separation of the recyclable materials does not start from home, it will imply additional costs for the waste segregation, then the sale of recycled waste often does not compensate. Municipalities should be in charge of collecting, transporting, treating, and finally disposing MSW, in Lebanon, most municipalities are facing shortage in financial and human resources, Lebanese municipalities usually rely on foreigner financing given by international organization (Abbas *et al.*, 2017).

3.4 Best municipal solid waste collection route

The organic waste fraction of Saifi district in Beirut is referred as an example.

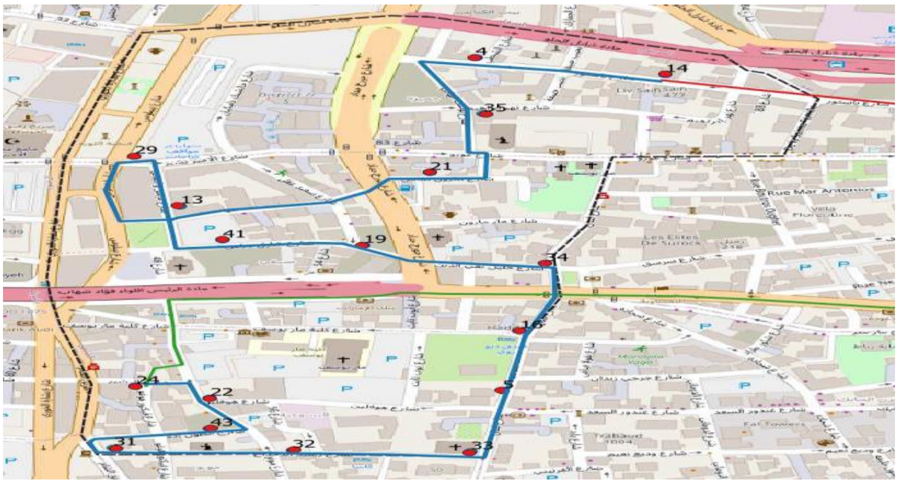

Figure 15: Example of optimized collection route for Saifi [QGIS]

In Saifi district there are 44 bins with a capacity of 2400 dm^3, on a total area of 0.42 km^2. Thanks to QGIS, it was able to create different layers of this area, and to locate the solid waste bins for each quarter of Beirut using a type of vector called "Random Points Inside Polygons", where it created random points inside the layer. The routes were manually traced on the software using the plug-in "Online Routing Mapper", following the best route as per time and distance terms, and changing it with the editing toggle and its components of QGIS.

Different results were found:

- the shortest route takes approximately 44 km to collect all 44 bins of organic waste, with a total time of 1.93 hours;
- the fastest route, will take approximately 50 km with a time of 1.76 hours.

These 2 routes are random paths that don't respect the street directions. It is known that a truck should collect 17 bins to be able to reach full capacity, that it will take approximately 1.52 hours to complete the route starting from Qortadah to Saifi, and from the last bin back to Qortadah.

To have a better solution of the problem, ETSP method was used, where the 44 bins are distributed with uniform randomness in a d-dimensional hypercube and the distance is measured in the Euclidean metric. The continuous route will be divided in 3 trips (2 trips of 17 bins and 1 trip of 10 bins), each trip will come from and go back to Qortadah. The results achieved for each bin is the result of 1 simulation from the solver program, if the solver would simulate the same bin again, the results would give a different feasible path. By applying ETSP with the solver in Microsoft Excel, the most feasible route with the shortest distance gives 142.9 km after making 3 trips. The trips from and to Qortadah have an average of 21.07 km. The generated result by ETSP has shown a reduction in route distance from 170.42 km found using QGIS to 142.9 km, as well, the collection time is reduced from 4.26 to 3.57 hours.

The ETSP can help to find the most efficient route using the matrix, but the results can change every time you run the solver giving better or worst routes.

3.4.1 Comparison of routes

The comparison can be seen in Table 7 and Figure 16, in which the complete collection time of the 44 and 17 bins are showed. The total cost of fuel for the 142.9 km (given by the solver) is 17.67 euros, if this distance is compared with the route provided by QGIS with a total of 170.42 km, a total of 20.70 euros is needed as seen in Figure 17. This cost difference provides a clearer view of why the ETSP is a better path than QGIS suggests. It is clear that the adopted approach is robust, it provides a wide view of the route optimization benefits on the economical, and environmental sides.

	QGIS	**Solver**
Distance of 44 bins collected (km)	44	17.41
3 trips to and from Qortadah (km)	126.42	125.49
Total route collection (km)	170.42	142.9
Truck velocity (km/h)	40	40
Total time during route collection (h)	4.26	3.57
Time for unloading 1 bin (h)	0.011	0.011
Time for unloading 44 bins (h)	0.484	0.484
Total route collection + bin collection (h)	4.74	4.06
Time to unload truck (h)	0.42	0.42
3 times truck unloaded (h)	1.26	1.26
Total time complete collection (h)	6.00	5.32
Collection divided by 3 trips (h)	**2.00**	**1.77**

Table 7: Comparison of routes

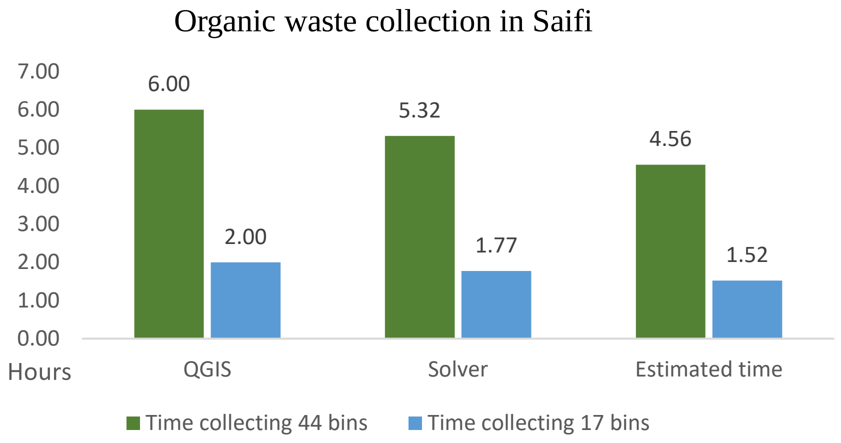

Fig. 16: Comparison of collection times

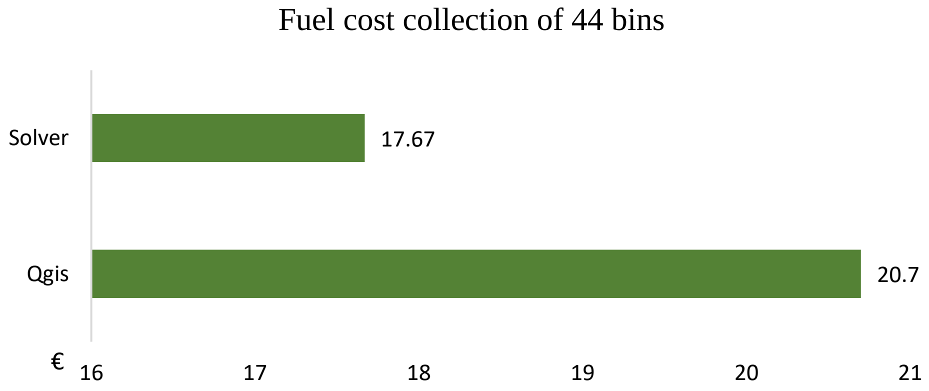

Fig. 17: Comparison of fuel cost

3.5 Future developments in Greater Beirut Area and Lebanon

As it has been demonstrated in the previous section, for an efficient SWM system in GBA, the citizens in should start applying the best waste management practices commencing from their houses by separating the waste into different fractions, and deposit it in the designated bins. After the collection, the waste should be transported to the treatment plant, where it is advisable to apply some of the WtE technologies that helps in saving valuable landfill's land, and producing energy and other useful products.

3.6 AHP method

3.6.1 Priorities of criteria and sub-criteria

The priorities of the main criteria with respect to the goal are shown in Table 8. 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 the environmental pollution and its impacts on the citizens' health.

In Table 9 the priorities of the sub-criteria are presented. Regarding the Environmental-Health criterion, the public health is the top concern of the experts followed by the pollution potential. The availability of technology has obtained the highest priority under the technical criterion, since many WtE technologies are sophisticated and need strong experiences and skilled technical teams, while the net income and the capital cost are of interests when we take into consideration the economic factor, as some technologies need a high financing. As it has been noticed in the literature that the public acceptance is one of the main impediments for many WtE projects in different countries, same result has been shown in our case study, the public acceptance obtained high priority under the social criterion.

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

Table 8**.** Main criteria priorities with respect to the goal

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

Table 9**.** Sub-criteria priorities with respect to the main criteria

3.6.2 Priorities of the alternatives

It can be observed in Figure 18 that composting ranked as the best alternative with a global weight of 0.33. It should be known that the greatest part of GBA dwellings are constituted by high buildings with no or very small green areas to perform the composting process. Anaerobic Digestion (AD) of the solid waste ranked as the second preferred technology with a weight of 0.21, the problem of AD technology is that it treats only some types of solid waste. The selection of the above 2 alternatives shows the importance of the organic waste fraction in the context of waste management in GBA in terms of quantity and the opportunities to be exploit it for the production of energy or other useful products. Although incineration has a significant potential in producing energy more than the other technologies, incineration was the third preferred technology with a weight of 0.14, the reason behind this ranking is that the solid waste incineration is still facing strong public opposition in GBA due to the 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 a WtE technology.

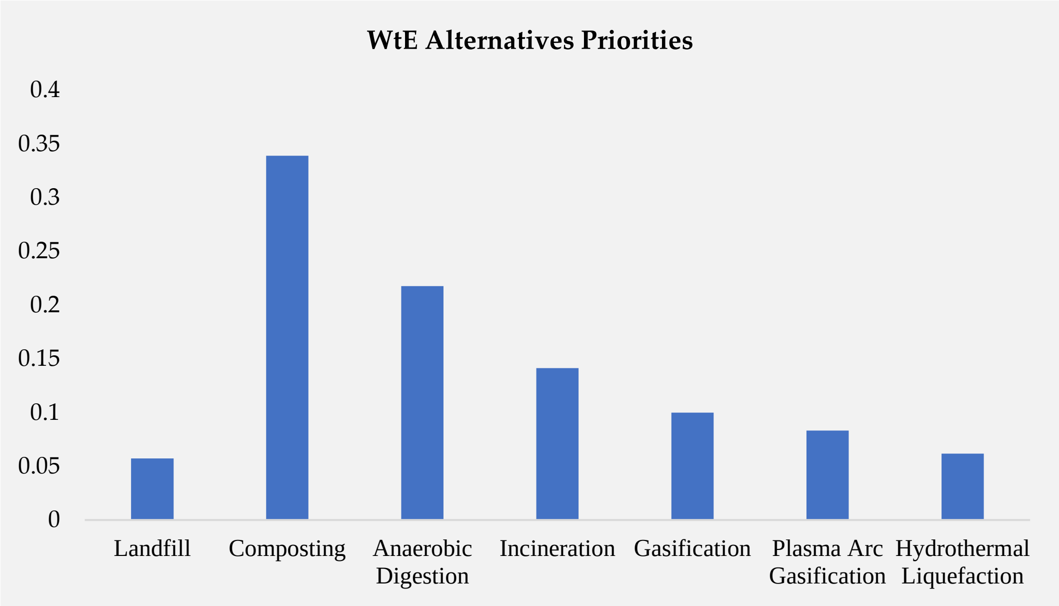

Fig. 18. Global priorities of the WtE alternatives for GBA

3.6.3 Sensitivity analysis

The last step in applying the AHP method is the sensitivity analysis, where the criteria/sub-criteria weights are modified in order to observe their impact on the overall rank, if the ranking of the alternatives does not change, the results are said to be robust.

SpiceLogic software allows us to verify the influence of each criteria/sub-criteria on the final ranking of the alternatives.

It has been planned to omit the sub-criteria one by one to assess their impact on the alternatives' ranking. The graph in Figure 19 represents the weight attributes of each sub-criteria. It is evident the importance of the public health sub-criteria weight attribute, as it was mentioned before, that it is due to the fact that the citizens in GBA have concerns about possible polluting emissions that might be released from some of WtE technologies, knowing that many Lebanese citizens are having lethal diseases because of the environmental pollution, therefore in adopting a potential WtE technology that might have environmental impact, an accurate prevention measurements should be taken into consideration to avoid such impact.

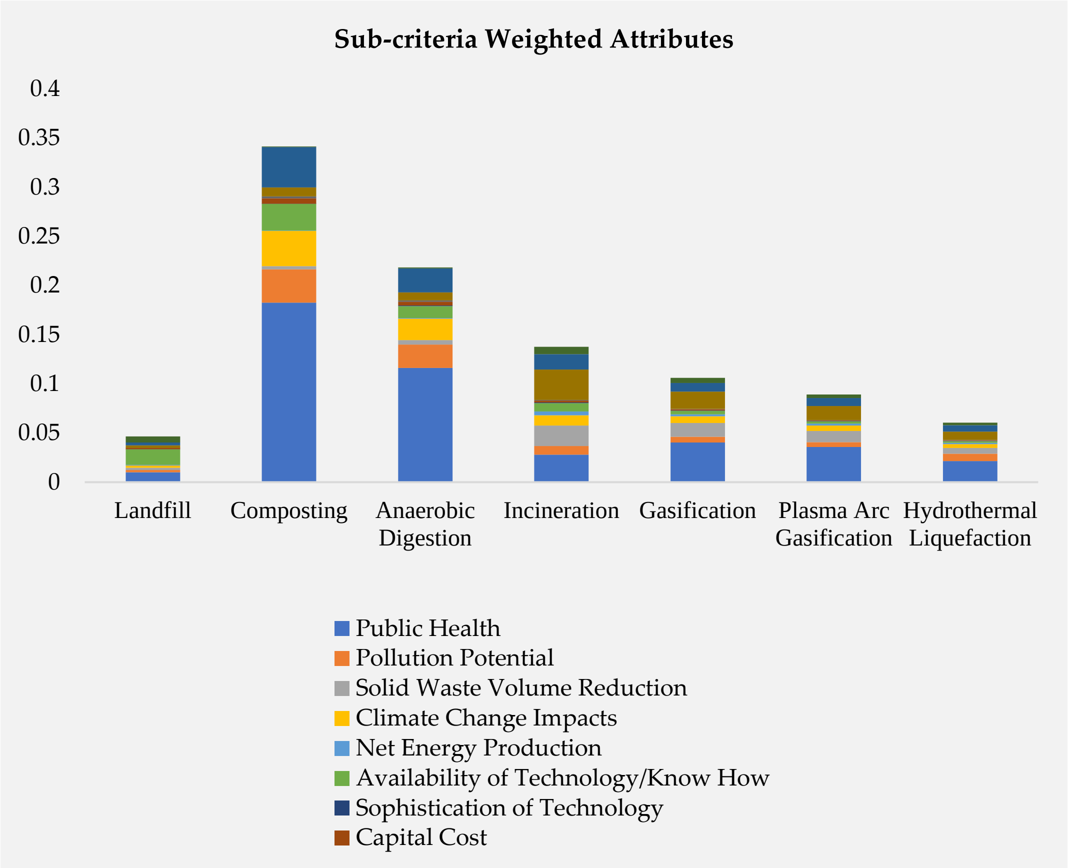

Fig. 19**.** WtE technologies ranking with respect to the considered sub-criteria

Omitting the public health sub-criterion, incineration alternative will become the second preferred technology followed by AD, Figure 20, while omitting the other sub-criteria has no significant impact on the ranking of the alternatives.

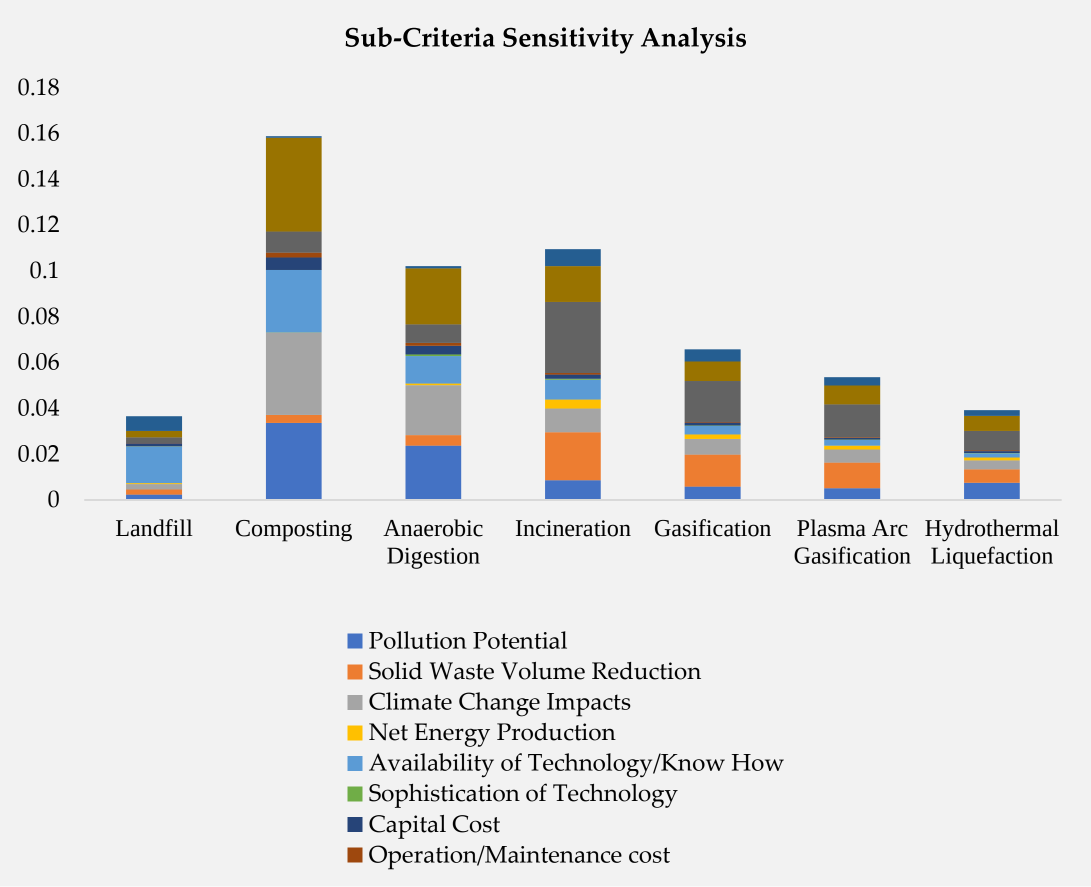

Fig. 20. WtE technologies ranking with respect to the considered sub-criteria (omitting public health option)

To ensure the consistency of the experts' judgments, a further sensitivity analysis was performed at the criteria level to examine the impact on the alternatives ranking, if the participants would change the scores in the comparison process.

As it can be seen in the Figures 21, 22 and 23, moving the vertical line through the scale 1 to 9, no changes in the priorities will take place, even for the less 3 preferred alternatives, only a slight change in the priorities will take place, as a result, the consistency and the robustness of the experts' judgments is obvious.

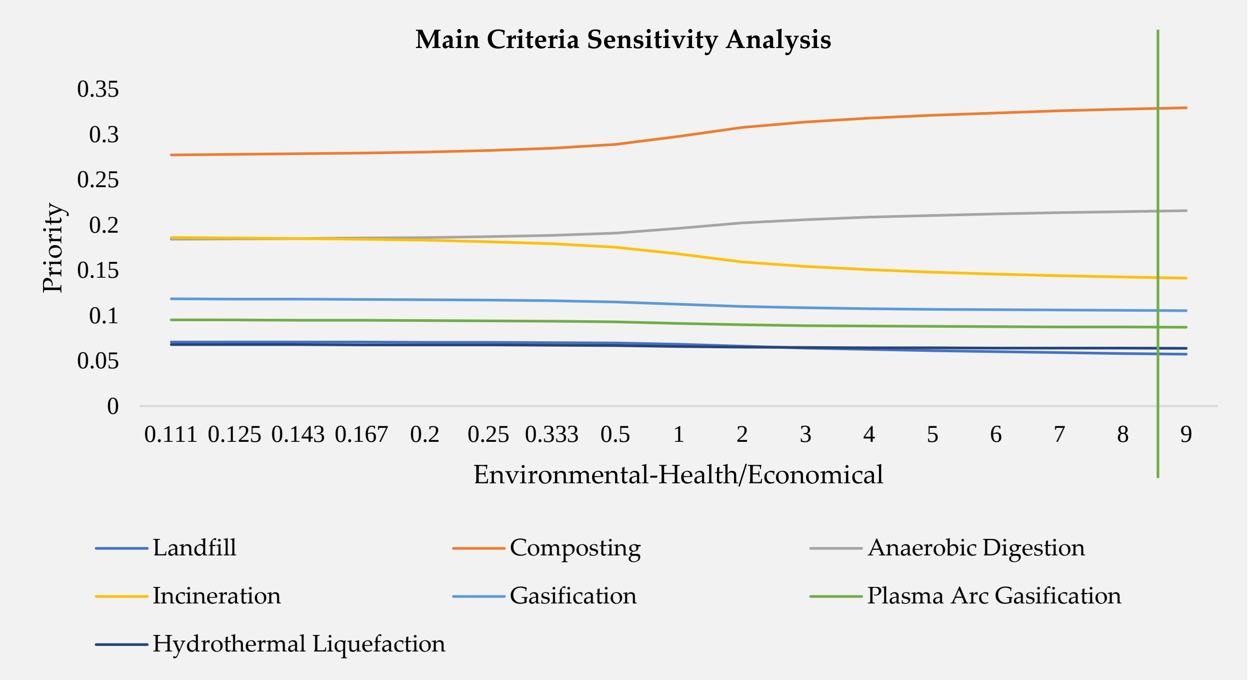

Fig. 21. Main criteria sensitivity analysis

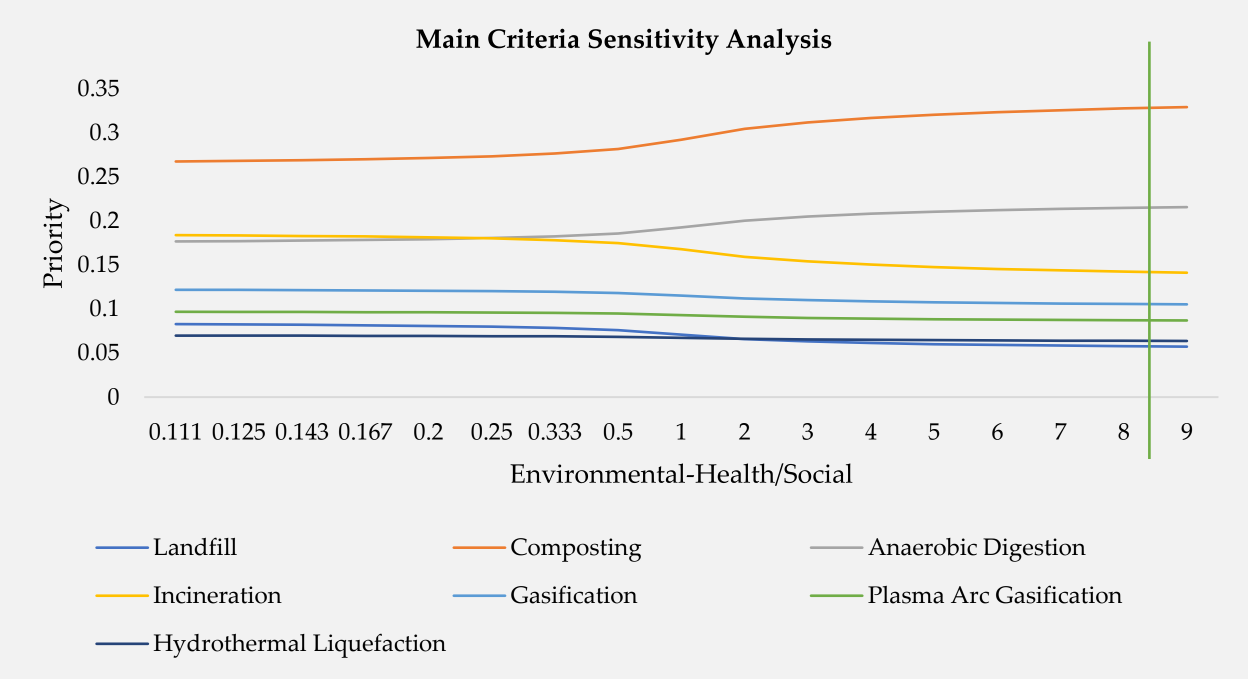

Fig. 22. Main criteria sensitivity analysis

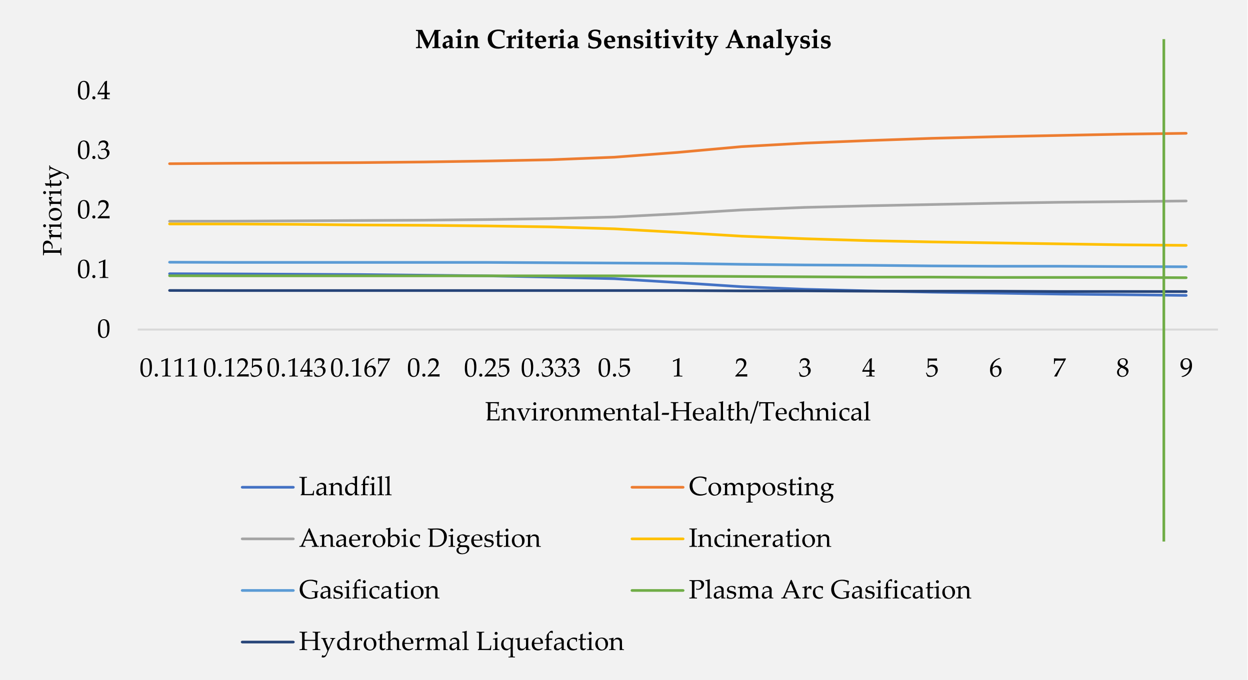

Fig. 23. Main criteria sensitivity analysis

3.7 Waste recycling in GBA

The percentage of the waste recycling in GBA is the same as the national level.

Current Status of Recycling in Lebanon (%)	6-8
Recycling Target in Lebanon by 2030 (%)	30
Recycling Target in Europe by 2030 (%)	60

Table 10. Waste recycling percentage

- Paper and glass waste merit to be recycled, since their recycling is beneficial due to the economic and environmental profits. Paper can replace the plastic products in many applications, the total yearly quantity of paper sorted and sold was estimated at around 110,160 tons. The price paid for sorted paper was estimated to be 29 USD-198 USD per ton, depending on quality and grade, this represents an economic gain of 2.6 million to 21.81 million USD from material recovery in the paper value chain.
  It can be roughly estimated that collection and transportation of 1 ton of glass would cost approximately 169 USD. ACTED estimates that the cost of importing virgin glass bottles into Lebanon is approximately 500 USD per ton (1 ton = approx. 2500 bottles), including customs and taxes, by simple calculation it will be evident that recycling of 1 ton represents a saving of about 330 USD.
- Construction and Demolition waste may be a big asset for the material circularity, considering that a large amount of this waste is used by the private civil contractors as filling material for new construction sites; furthermore, the C&D waste recycling plant system is not technically complicated and it is available in Lebanon.
- Before talking about plastic recycling, it is better to avoid its generation by replacing it by recycled paper where possible. Elimination of plastic waste requires design innovation to reduce the presence of plastics in products and packaging, improve the recyclability of plastics, reduce

leakages in recycling systems, and improve plastic designs to remove hazardous additives and chemicals. Realistically, plastic will continue to dominate our packaging, especially for food, because it is moisture-proof and airtight. Even in European countries with strict waste management strategies, only 31% of plastic waste is recycled.

- Composting is of substantial aspect in treating the organic waste, but it is essential to overcome various challenges, such as, the needed area for the composting plant, the quality of the compost produced, and the competition by the European compost products.
- Even if there are not so many biogas generation plants in Lebanon/GBA, but it appears that it is a promising technology from an economic and environmental perspectives.

3.8 Waste management scenarios in GBA

In table 11 a comparison of the different solid waste management methods, where there are estimated the material recovery quantity and the energy generation. The aim of this comparison is to evaluate the waste management capacity of each of the mentioned methods.

Method	Waste Quantity (tons/year) Waste Type	MWh/year	Material Recovery tons/year
Recycling	360193 Non OF*	0	As per 2030 target: 108058 As per current status: 21611
Composting	398109 OF	0	As a typical value (30%): 119432 As per current status (15%): 59716
Incineration	758302 OF + non OF	424649	Metals from residual ash
Incineration Non OF	360194 Non OF	201708	Metals from residual ash
AD	398108 OF	119432	Digestate (liquid & solid portions)
WtH_2	398108 OF	270148	Biochar
Incineration + Electrolyzer	758302 OF + non OF	121328	Metals from residual ash

+*OF: Organic Fraction

Table 11. Waste management scenarios in GBA

The incineration process requires 8400 kJ/kg to produce electricity, the organic waste fraction in Lebanon is around 52%, as such, MSW calorific value is low, this means that the maximum calorific value that can be reached with this waste is around 6500 kJ/kg, therefore it needs to add a lot more fuel and other burning waste to have the burner reach the optimal temperature of 850°C, by doing so, WtE facilities will be directly competing with the recycling markets for these valuable paper and plastic materials. The only material that WtE facilities are claiming to recycle is metal, not because of their commitment to recycling, but rather because metals do not burn and are a contaminant in the furnace.

AD has advantages such as easy of operation and maintenance, a reduced capital expenditures, but on the other side AD has a high running expenses particularly energy expenditures and it can only treat organic waste.

Although modern Waste to Energy (WtE) technologies reduce many air pollutants, fly ash and pollutants may be released into the atmosphere, and a great deal of toxic bottom ash is left over, that ash will usually be disposed of in landfills. WtE plants pollute much less than their fossil fuel which come at 0.778 tons of CO_2 emitted per MWh produced for heavy fuel and diesel oil and 0.443 tons/MWh for natural gas, while for example biomass gasification emits 0.03 tons of CO_2 per MWh (El Helou *et al.*, 2022).

In terms of CO_2, both Incineration + Electrolyzer and WtH_2 have emissions associated mainly to the carbon content of waste combustion (1.43 $kgCO_2/kg$ of waste) and in a minor amount to auxiliary fuel if RE technologies are not used in the case of the WtH_2 plant system. The carbon footprint changes from around 3.9 kg of CO_2 per Nm^3 H_2 to 0.94 kg of CO_2 per Nm^3 H_2 in passing from WtE + Electrolyzer to WtH_2 (A.T. Kearney Energy Transition Institute, 2014).

The comparison in Table 11 evidences that the combustion-based configuration WtE + Electrolyzer produces about 121,328 MWh, conversely the gasification scheme (WtH_2) produces about 270,148 MWh, knowing that for WtH_2 only the organic fraction is being treated (398,108 tons/year), while for Incineration + Electrolyzer all the MSW quantity is going to be treated (758,302 tons/year). The results show that WtH_2 results more competitive under the assumption made in terms of energy generation and CO_2 emissions.

H_2 production has many advantages, such as:

- Less emissions that methane (from AD);
- High calorific value;
- Versatility of applications;
- High energy conversion efficiency;
- No CO_2 emission occurs if it is used in fuel cells;
- Electric power in Lebanon/GBA is extremely expensive, Hydrogen can help in increasing energy security by allowing Lebanon to locally produce an extremely versatile fuel that can be stored over long time periods and requires only renewable power and water.

The high organic fraction in GBA induces promising prosperity for Hydrogen production by biomass gasification, perhaps using RE technologies such as solar energy to minimize the emissions from the gasification plant. Hydrogen applicability in GBA will face challenges, such as the lack of the infrastructure for Hydrogen transportation, lack of financing even if the Hydrogen production technologies have had improvement in cost and performance.

Green energy generation from Hydrogen results as a potential technology for GBA, and since it has a significant increase in PV solar systems installation in GBA, so it is worth to make an economic evaluation of these 2 technologies in the aim to assess their feasibility for the near and far future in the context of circular economy.

3.9 Hydrogen vs Solar Energy for Energy Generation in GBA

In the previous paragraph, it was evident the advantages of the WtH_2 technology in terms of energy and environmental benefits. In addition, the PV solar systems are becoming an essential component of the GBA's residential sector due to their affordable prices; their uncomplicated installation: and their low maintenance; therefore, it was essential to identify the economic benefits and burdens of these 2 emerging technologies.

3.9.1 Hydrogen cost

Along with the cost reductions of electrolyzers, the rapidly declining cost of renewable electricity is translating into lower costs for green hydrogen production. Noting that each kg of H_2 produced from Gasification has a cost of 1.77-2.77 USD (Ghasemi *et al*., 2020). In the table 12 there are the production costs of the different types of Hydrogen in the period time 2020-2030 (IRENA, 2021).

Hydrogen	Cost (euro/Kg)
Grey H2	
2020	0.7 to 1.2
2025	0.7 to 1.2
2030	0.7 to 1.2
Blue H2	
2020	1.3 to 1.7
2025	0.8 to 1.3
2030	0.7 to 1,2
Green H2	
2020	3.5 to 4.5
2025	1.2 to 2
2030	0.7 to 1.3

Table 12. Hydrogn cost by type

Price parity between blue and green Hydrogen will start to be achieved by 2030, this rapid reduction in green Hydrogen cost is expected to accelerate, perhaps reaching as low as 0.68 €/kg H_2 by 2050.
Most Hydrogen produced today is used near the point of production, so large-scale global Hydrogen transport and storage infrastructure needs to be developed, it is difficult to predict future global transport and storage costs, but they have been estimated to be approximately 1.20 €/kg H_2 to 2.20 €/kg H_2 by 2030 (ETN Global, 2022), which would nearly double the cost of Hydrogen at the point of delivery, depending on the production method and location.
Fuel cells are also becoming cheaper, more durable and more efficient. From costs perspective, Hydrogen use appears most attractive for relatively large commercial buildings and for district energy networks. Fuel cells, co-generation units or other hybrid systems could be used in such cases with energy storage capacity to meet heating, cooling and electricity demand, taking advantage of on-site renewables energy.
Table 13 shows the CAPEX of some types of Fuel Cell.

Fuel Cell Type	**CAPEX by 2024**	**CAPEX by 2030**
Micro FC CHP (0.3 – 5 kW)	5400 €/kW	3500 €/kW
Mid-size FC (5 – 400 kW)	5000 €/kW	2800 €/kW
Large scale FC (>400 kW)	2000 €/kW	1500 €/kW
	OPEX by 2024	OPEX by 2030 .
Micro FC CHP (0.3 – 5 kW)	2700 €/kW	2250 €/kW
Mid-size FC (5 – 400 kW)	1900 €/kW	1100 €/kW
Large scale FC (>400 kW)	2400 €/kW	2000 €/kW

Table 13. Fuel Cell CAPEX (Cigolotti, 2021)

3.9.2 PV solar system cost

The average cost of a solar system in Lebanon is 0.28 USD per watt, the average solar panel system size in Lebanon is around 3-5 kilowatts. The PV solar system are aesthetically integrated into buildings with low running cost, and low maintenance; as well, PV solar systems are safe add they have an investment pay back of about 5-8 years. On the other hand, PV solar system is more suitable for decentralized and residential applications, it is especially attractive for regions with abundant sunlight such as GBA.

It is interesting to simulate the best alternatives for energy production in GBA in terms of CE's modeling. To perform such simulations, HOMER-Pro software was used.

3.10 HOMER-Pro simulations

Solar resources

The solar resources of GBA were collected from the NASA surface meteorology and solar energy database through HOMER-Pro software. A scaled annual average of 5.32 kWh/m^2/day has been given by the software, the monthly solar radiation in GBA is presented in Figure 25, it can be seen that the maximum and minimum solar radiations occurred in June (8.2 kWh/m^2/day) and December (2.4 kWh/m^2/day) respectively.

Electrical load in GBA is shown in table 14.

GBA	
	Electrical Load
Scaled annual average kWh/d	11.130
Scaled Peak Load kW	2.3640

Table 14. Electrical load in GBA

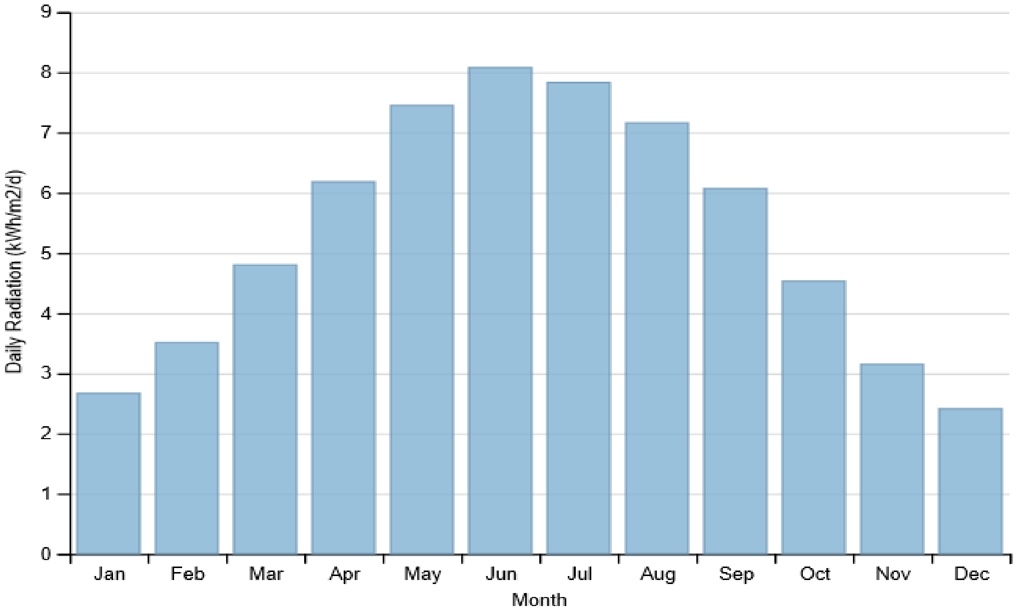

Fig. 24. Monthly solar radiation in GBA

In our study, the simulations are performed for the systems presented in Table 15.

System
Current status in Lebanon (Generators running on petroleum products)
PV Solar Power (PV)
Fuel Cell (FC)
PV + FC

Table 15. Energy generation systems

The parameters values given to the software for running the simulations are listed in Tables 16 and 17. The PV solar system given values are based on the current Lebanese market, while for FC system, the values are gathered by literature research (Al-Badi *et al.*, 2022).

PV Inputs	
Capacity (kW)	1
Capital ($)	1500
Replacement ($)	800
O&M ($/year)	10
Annual real interest rate (%)	5
Project Lifetime (years)	25
Derating factor (%)	80

Table 16. PV inputs-HOMER Pro

FC Inputs	
Capacity (kW)	250
Capital ($)	500000
Replacement ($)	375000
OM ($/hour)	0.1
Annual real interest rate (%)	5
Project lifetime (years)	25

Table 17. FC inputs-HOMER Pro

All systems are simulated in off-grid, the project life was taken to be 25 years with an annual interest rate assumed to be 5% over the life of the project. Capital, Operation and Maintenance (O&M) costs, were included with the system components detailed above, no territorial, or municipal government subsidies were considered.

3.11 Simulations results

3.11.1 Economic comparison

	Current Status in Lebanon (Generators running on petroleum products) 2.7 kW	**Generic Flat Plate PV 3.96 kW (PV)**	**Generic 250 kW Fuel Cell (FC)**	**PV + FC**
Nominal Discount Rate (%)	**10**	**10**	**10**	**10**
Total NPC ($)	21823	16959	1048913	483795
LCOE ($)	0.6	0.47	23.57	13.43
Operating Cost ($)	2285	640	50674	2859
CAPEX ($)	1080	11145	500650	509747
O&M Cost ($)	6440	1993	9477	2149
Replacement ($)	4104	4106	572049	4180
Salvage ($)	30	286	35230	32455
Annualized				
CAPEX ($)	118.98	1227	46273	56157
O&M Cost ($)	709	219	876	236
Replacement ($)	452	452	52872	460
Salvage ($)	3.3	31	3256	3575

Table 18. Economic comparison between energy generation systems

During the simulations, many configurations are designed out to find the optimal one for reaching a minimum investment and operation costs, and so to meet the technical and emission constraints. With a Nominal Discount Rate of 10%, off-grid solar PV system presents the lowest Levelized Cost of Electricity (LCOE) of 0.47 $/kWh, followed by PV + FC system with LCOE of 13.43 $/kWh, while the FC's LCOE is the higher one. An increase of the systems capital cost results to an increase of NPC (Net Present Cost) and LCOE. Although the low initial cost of the diesel generators compared to high costs of the other RE's systems, the disturbing noise and the environmental pollutants emissions from these generators affect adversely the surrounding area, noting that the main goal is to produce green energy to satisfy the energy demand in GBA.

The operating cost of the PV system shows the lowest value, same for the O&M cost. The replacement cost of the FC system is too high, while for PV + FC system this cost is alike the PV system one.
By analyzing the annualized costs, the PV + FC system shows promising results; the great advantage of this system is the production of H_2 from the organic waste using gasification and FC system.
PV solar power is highly advantageous due to the long sunny days in GBA, the small solar PV projects could be a better alternative since they were rapidly developed between 2010 and 2023, and strongly encouraged by the investors in Lebanon. A suitable option is to integrate the solar power for supplying the energy needed for running the biomass gasification plant.
Figure 25 illustrates the cash flow through 25 years of the PV system's life cycle, the initial investment is 11,600 USD, and around 3800 USD as additional replacement cost each 6-7 years. The operating cost is not significant and it is stable over the years. A salvage value of about 3000 USD is available at the end of the system's life cycle.
Figure 26 shows the cash flow of the FC system's life cycle, the initial investment is high 500,000 USD, an additional replacement cost of about 39,000 USD is estimated every 6 years. The operating cost is not significant, a salvage value of about 210,000 USD is available for the system at the end of its life cycle.
For the PV + FC system, the capital cost is high due to the FC cost, the operating cost is not significant, the salvage is about 320,000 USD. The replacement cost is not significant in the PV + FC system at the contrary of the single PV and FC systems.

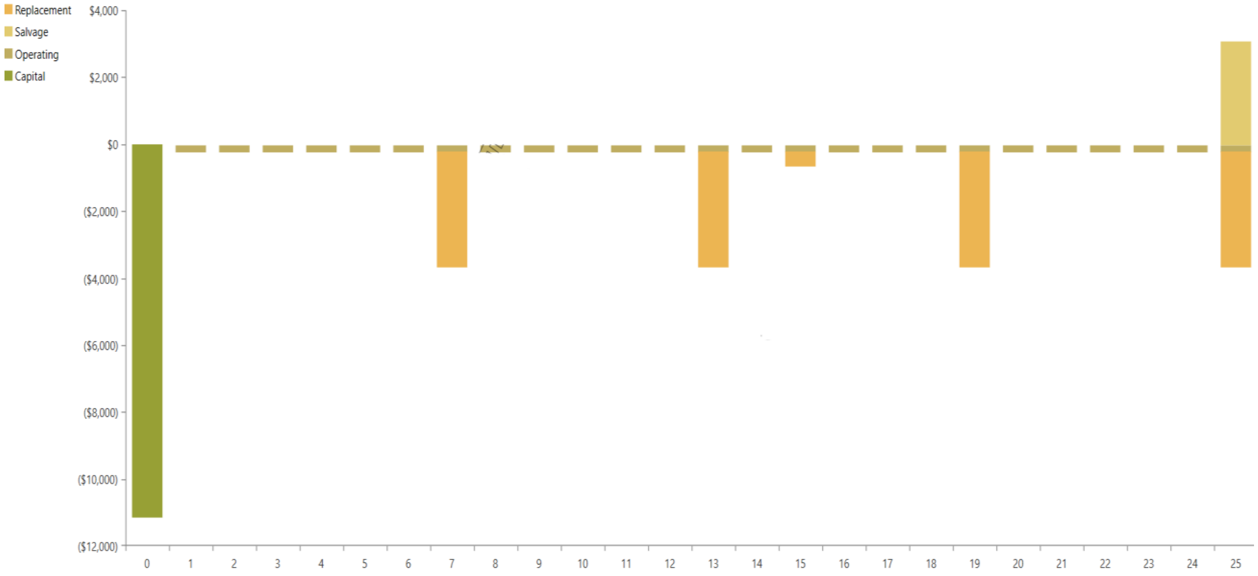

Fig. 25. PV solar system-cash flow

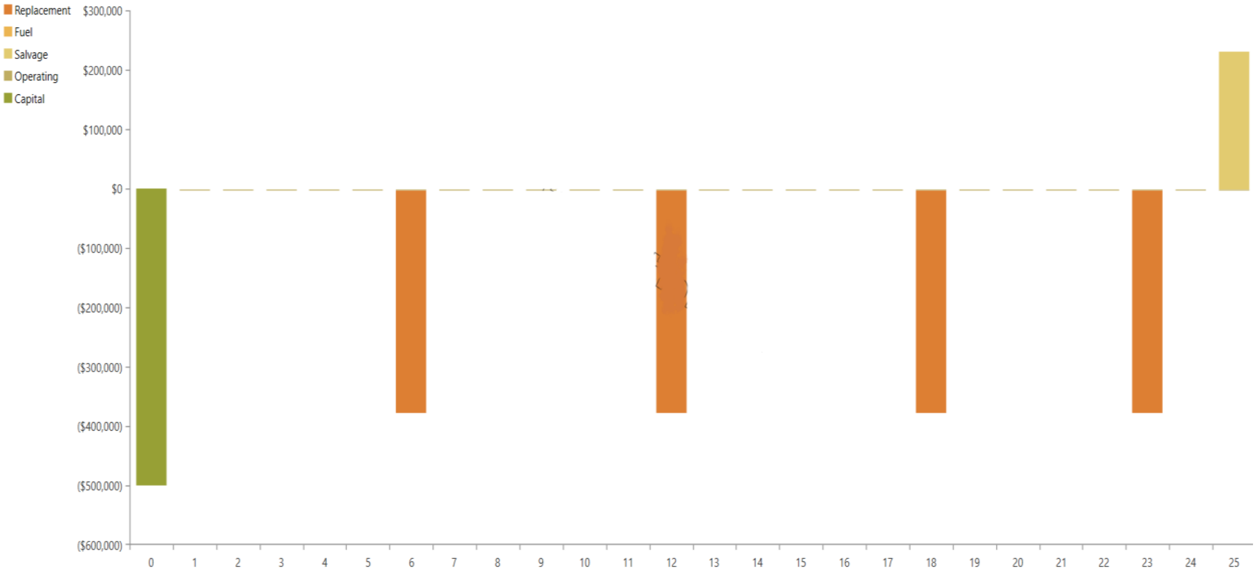

Fig. 26. FC system-cash flow

PV + FC

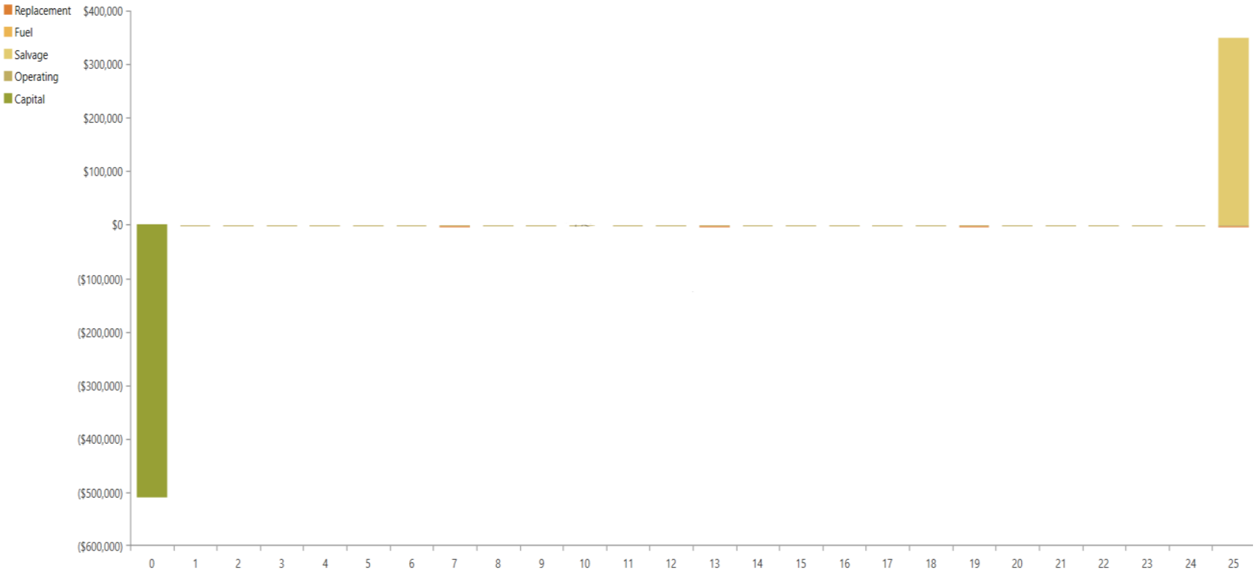

Fig. 27. PV + FC-cash flow

3.11.2 Electrical comparison

System	**Production KWh/yr**	**%**
PV		
Generic Flat Plate PV	6749	100
FC		
Generic 250 kW Fuel Cell	4329	100
PV + FC		
Generic flat plate PV	5510	92.3
Generic 250 kW Fuel Cell	459	7.69
Total	5969	100
Generator		
Autosize Genset	6336	100
	Unmet Electricity Load kWh/yr	**Capacity Shortage kWh/yr**
Generic Flat Plate PV (PV)	146	204
Generic 250 kW Fuel Cell (FC)	0.4	1.66
PV + FC	92.5	145
Generator	0	0

Table 19. Electrical comparison

The value for unmet electricity is the lowest for the diesel generators, followed by the FC system. The PV +FC's capacity shortage at yearly basis is acceptable.
It is evident that the PV + FC association overcame the intermittency problem inherent with PV.

As shown in Figure 28 the PV power production varies during the year due to changes in solar radiation and the temperature of the solar panels. The output power of the PV solar system reaches the highest value in the months of July and August, in December the production level is at lowest value.

Fig. 28. PV solar system energy production

The monthly average electricity production of the solar PV system and fuel cell is shown in the Figure 29; it is evident the notable power production from the solar power in the period from April to August. The FC system production is more significant in the period from September to March, anyway the main scope of the FC system is to generate electricity continually owing to the high organic fraction in GBA treated by gasification to produce H_2.

The PV + FC system reduces the high capital cost associated with FC and also reduces the fuel, operation and maintenance costs associated with the FC.

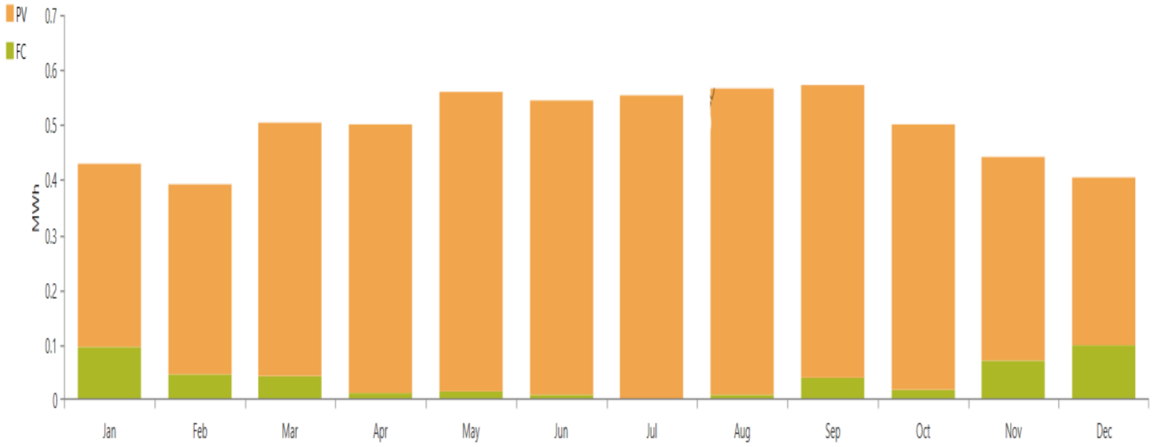

Fig. 29. PV + FC systems-monthly average energy production

3.11.3 Renewable energy

In both cases the renewable energy penetration is high which it is of great asset for the CE modeling. At high penetration levels, a combination of the following actions is required to maintain system integrity, such as, enabling system generation to follow the load, changing demand levels in response to power supply variability, and policies that promote a flexible power market structure.

Energy-based metrics	PV	PV + FC
Maximum Renewable Penetration (%)	1722	1512

Table 20. Renewable energy penetration

3.11.4 Environmental Comparison

In the table 21 the emissions from the diesel generator are listed as per Homer-Pro simulation results.

Diesel Generator	
Substance	**Emissions Kg/yr**
Carbon Dioxide	7,374
Carbon Monoxide	46.5
Unburned Hydrocarbons	2.03
Particulate Matter	0.282
Sulfur Dioxide	18.1
Nitrogen Oxides	43.7

Table 21. Emissions from diesel generator

An estimation of the emissions for different H_2 production and from PV solar system are shown in the Table 22 (Legarreta *et al.*, 2023).

Hydrogen	**Carbon Impact (Kg CO_2/Kg H_2)**
Brown	18-20
Grey	10-12
Blue	0.6-3.5
Green	0
PV solar system	0

Table 22. Carbon impact

It is evident that both PV solar system and green H_2 have zero carbon impact, nevertheless a very important aspect merits the be highlighted, it is the huge amount of waste that will generated from the PV solar panels at the end of their life, given that the PV panels contain toxic materials, that can cause environmental pollution. Companies and researchers are now racing to prepare for the emerging PV waste dilemma, they are developing technologies that promise to recover far more of the useful materials from cells while reducing the costs and environmental impacts.

3.12 Circular economy model for GBA

As discussed previously, the aim of the proposed CE model is to close the gaps of the current waste and energy management status in GBA.

Current status in GBA

Recycling (6%) + composting (15%) + landfills (44%) + dumpsite (35%) + small amount of energy production from waste

Proposed circular economy model

Avoiding generation of waste (plastic, nylon, etc.) + recycling (30% as per 2030 target, specially paper, glass, C&D) + WtH_2 (for the organic waste) + solar energy

	Avoiding generation of waste (%)	Recycling (%)	Composting (%)	Landfills (%)	Dumpsite (%)	Energy from petroleum products (%)	Bio-Energy (%) (MWh)	Solar Energy (MW)	WtH$_2$ + Solar Energy (MWh)
Current Status in GBA	0 to little initiatives	6	15	44	35	92	9%	250 MW	-
Proposed CE Model	11.5 % plastic waste + some percentage of the other waste (11%)	30 % (full recycling of glass, paper/cardboard and C&D)	As per adopting or not WtH2	Only a part that cannot be recycled or composted (8 to 12%)	0	As minimum as possible	FC ≈ 270148 MWh	3000 MW As per 2030 target	WtH$_2$ ≈ 270148 MWh + solar energy 3000 MW as per 2030 target
LCOE ($/kWh)						0.62	23.57	0.47	13.43

Table 23. Circular economy in GBA

The proposed CE model is based on adopting the best waste management practices, choosing the best alternative in terms of energy production and environmental benefits, and taking into account an acceptable economic perspective.

This CE model is of great benefits for long term sustainability development in GBA. Avoiding 12 to 18% of waste generation, will have a significant impact in reducing the waste management cost by about 1,114,7051 USD, indeed it will create a profit when the plastic products being avoided and replaced by paper ones that come from paper waste recycling. Regarding the environmental side, using RE such as PV solar system and green Hydrogen will prevent a high percentage of GHG emissions, knowing that the diesel generators in GBA have a high GHG emissions impact.

Challenges:

- not all the waste can be recycled or composted, hence 8 to 12% of the waste should be sent to landfills, for that it is indispensable to avoid the generation of waste as much as possible;
- industries should be shifted to produce eco-friendly product;
- importation of no eco-friendly products to Lebanon should be minimized;
- no infrastructure for H_2 supply in GBA, it is crucial the installation of Fuel Cell in the H_2 production site.

CHAPTER 4

4. Conclusion

The improper management of solid waste in developing Countries is linked to the fragmentation of various solid waste functions with limited cooperation among stakeholders, weak governance, institutional structures and management capabilities. Key common challenges facing developing Countries include the scarcity of financial resources, the use of primitive treatment technologies and disposal methods, low collection coverage and irregular collection services, lack of political commitment, limited public awareness on proper waste management practices, and the lack of effective tracking material flow data.

Lebanon is a major oil importer country despite the existence of significant RE potentials. RE is still modestly used in the field of electricity generation. The main contributor to greenhouse gas emissions in Lebanon remains the electricity generation and transportation sector.

The current SWM system in GBA has many disadvantages such as unorganized source reduction programs, high cost of sweeping and collection, and low percentage of waste recovery. The main concerns of this MSWM system are the lack of the adequate legislation, weak public institutions, and absence of law enforcement. It is required a strengthening of the MSW management aspects from an institutional, legal, financial, environmental and social points of view. Improving the waste management system is a crucial factor, such as, organizing public awareness programs, increasing efforts for recycling, keeping in mind future population growth, resource recovery, and encouraging public and private partnerships.

For a proper SWM system, 7127 bins are needed to be distributed in the streets of Beirut at a distance of 100 to 300 meters, and 52 trucks are enough to collect the waste from these bins. ETSP application resulted in significant improvement of the solid waste collection process, since it can help finding the most efficient route, but the results can change every time that the solver will be run giving better or worst routes. It is important that GBA implements the technologies of a smart city, benefiting from Internet of Things for optimizing their services in SWM for substantial savings in time, trip length and utilization of number of trucks, and so monetary costs. To be able to reduce GHG emissions in the waste collection and transportation, the trucks can replace the diesel fuel by a green one, another factor to reduce emissions is increasing the efficiency of the trucks technology and providing the truck a proper maintenance plan.

Based on waste characterization, it is clearly noted that the waste in Lebanon could be used in different WtE technologies such as pyrolysis, anaerobic digestion, incineration.

The WtE technology selection is considered a complex decision process, especially in GBA where the solid waste management became a pressing issue that should be solved in a sustainable manner.

AHP is widely used as a decision making tool for MSW management, a hierarchy structure from 4 levels 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 ranking of criteria and sub-criteria, it is obvious the importance of the 3 connected pillars determined by the need for energy production from a potential WtE technology, keeping the environment and public health protected while balancing the net income to the capital cost adopting such type of 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 weight of 0.33, AD obtained a weight of 0.21, and so it is placed as the second preferred technology, while Incineration was ranked as a third preferred technology with a weight of 0.14. The last step of the AHP method decision process was the sensitivity analysis to verify the influence of each criteria/sub-criteria on the final ranking of the alternatives, and to ensure the consistency of the experts' judgements. To assess the sensitivity of the sub-criteria ranking, the sub-criteria were omitted one by one to see their impact on the alternatives' ranking. The importance of the public health sub-criterion weight attribute is evident, since by omitting it, the incineration alternative will become the second preferred technology followed by AD, the experts' judgements have shown consistency and robustness. From the results obtained, in adopting a potential WtE technology for the solid waste treatment in GBA, it is obvious the indispensability in protecting the environment and the citizens health, while it is evident the pressing need to have an electrical energy source keeping a financial feasibility of this potential technology. For a well and an efficient functioning of a WtE plant, an appropriate MSW's supply chain system should be guaranteed, thus reiterating the needful filling of the gaps for an efficient integrated solid waste management in GBA.

The waste in GBA provides a large source of recycled materials and energy, therefore, applying best waste management practices and switching from fossil fuels to renewable energies is an unavoidable approach for an efficient CE strategy in GBA. The transition to a circular economy should take into account the recycling opportunities, waste processing technologies, modernization of existing industries, and the development of biotechnology-based products.

The waste composition in GBA is made by 52.2% of organic waste which it can be exploited for the production of H_2 by gasification, H_2 is playing an important role in supporting the decarbonization of various sectors. Fuel cells are inherently reliable, rugged, quiet and versatile, the price of electricity produced by fuel cells makes the technology somewhat prohibitive, however prices are expected to fall dramatically as the ability to mass produce increases.

Additionally, PV solar systems have gained a huge market in Lebanon, especially for residential sector, due to electricity blackouts. Based on current market and technology conditions, distributed rooftop solar PV systems are cost competitive for the majority of buildings in Beirut.

In base of a CE modelling goal, four configurations of electrical power supply for GBA were simulated using HOMER-Pro software in order to find out useful economic, electrical and environmental parameters. The outcomes got from the HOMER-Pro software give various options achievable systems with various levels of renewable assets entrance.

With a Nominal Discount Rate of 10%, off-grid solar PV system presents the lowest LCOE of 0.47 $/kWh, followed by PV + FC system with LCOE of 13.43 $/kWh, while the FC's LCOE is the higher one. An increase of the systems capital cost results to an increase of NPC and LCOE. Despite the low initial cost of the diesel generators, the disturbing noise and the environmental pollutants emissions from these generators affect adversely the surrounding area. The operating, O&M costs of the PV system shows the lowest value. The PV + FC system reduces the high capital operation and maintenance costs associated with the FC. The replacement cost of the FC system is too high, while for PV + FC system this cost is alike the PV system one. For PV and FC systems the renewable energy penetration is high.

As per the annualized costs, the PV + FC system shows promising results. PV solar power is highly advantageous due to the long sunny days in GBA, the small solar PV projects could be a better alternative especially for the residential sector.

A suitable option is to integrate the solar power for supplying the energy needed for running the biomass gasification plant.

The proposed CE model is of great benefits for long term sustainability development in GBA. Avoiding 12 to 18% of waste generation, will have a significant impact in reducing the waste management cost by about 11,147,051 USD, and a profit will be created thanks to the recycling processes.

Regarding the environmental side, knowing that the diesel generators in GBA have a high GHG emissions impact, using RE such as PV solar system and green H_2 will prevent a high percentage of GHG emissions.

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