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Waste-to-Energy (WTE) Projects as a Secondary Source of Renewable Energy for Urban Sustainability of Amman

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Abstract:

The current situation in Jordan is not suitable for the promotion of energy independence, thus underlining the importance of Jordan further exploiting its Indigenous sources of energy. The main objective here was to reduce greenhouse gas (GHG) emissions from landfills as well as utilize fresh organic waste to produce methane gas for power generation. Methane gas produced at landfills is a strong contributor to global climate change and has a negative impact on carbon dioxide in the atmosphere. The main objective of this paper is to discuss the challenges that the urban city faces in this regard and the benefits of landfill gas (LFG) recovery and power generation.

The amount of methane gas produced and ultimately burned depends on the amount of municipal waste that is dumped at the landfill. This environmental investment has tangible results: the landfill is made to convert its gases into electrical energy amounting to 4.8MW per hour. This has a value of five million dinars annually, which is equivalent to paying 45% of the value of the annual electricity bill for buildings and streets of the Municipality of Amman.

The conclusion is analysed based on different stakeholders and policymakers as well as from donors, who play a major role in the reduction of pollution by utilizing LFG for energy production and promoting waste recycling, makes LFG projects economically feasible. This assessment can initially contribute to the process of policy formulation and urban planning works for Amman's vision of a sustainable and resilient city.

Keywords: *Ghabawi landfill, Greater Amman Municipality, urban wastes, waste to energy, gas recovery, greenhouse gases emissions, environmental and economic benefits.*

I. INTRODUCTION

The worldwide increase in urbanization has resulted in a dramatic environmental change, including increased temperatures, emission of pollutants, and waste generation. Cities are a major contributor to global climate change, as they emit the majority of anthropogenic greenhouse gases (GHGs) and are also the most vulnerable to the consequences of climate change [1,2].

Municipal solid waste management (MSWM) is presently acknowledged as one of the most challenging issues faced by both developed and developing cities, particularly in rapidly growing urban cities. The generation of municipal solid waste (MSW) is increasing, and this is expected because the population and economy of the city – factors that are highly related to waste generation – are also increasing [3]. The increasing consumption of resources along with economic growth and urbanization has led to tremendous urban waste generation and waste management problems in several developing countries. Currently, most of the waste produced is sent to landfills that surround the cities; however, these landfills are quickly running out of space. They also emit the largest amount of anthropogenic GHG. Urban wastes have a harmful influence on the environment, causing severe degradation of land, air, and water quality and adverse effects on human health.

MSW that's disposed of in a landfill is a source of environmental problems which lead to significant soil, water, air, and aesthetic pollution, associated human health problems, and an increase in the emission of landfill gas (LFG), a GHG from unmanaged landfills [4]. On the other hand, this is a potential resource for renewable energy.

Urban wastes related to biomass present a promising potential for the transition of fossil to renewable energy sources [5, 6]. The goals of MSWM are to promote the quality of the urban environment, generate employment and income, protect environmental health, and support the efficiency and productivity of the economy [7]. Solid-waste management is the application of suitable techniques to execute the functions of collection, transport, processing, treatment, and disposal of solid waste [8]. The process of solid-waste management involves five stages, namely generation, sorting, collection, storage, transport, and finally the safe disposal of waste [9]. Similarly, [10] stated that it is a process of solid waste collection and subsequent transfer, treatment and disposal, recycling, and energy utilization. The composition of the generated waste is extremely variable as a consequence of seasonal, lifestyle, demographic, geographic, and legislation factors that increase or decrease its volume. These variabilities make defining and measuring the composition of waste more difficult and, at the same time, more essential [11].

GHGs from MSW disposal continue to be a major challenge, especially in growing economies. However, these are resources that can be converted to green energy [51]. LFG, which is essentially methane (50%–55%), and carbon dioxide (40%–45%) are both GHG that are generated in landfills by the biodegradation processes of MSW [12]. One of the renewable energy fields as a broader definition is the utilization of LFG which consists of methane and carbon dioxide[13].In the context of sustainable waste management (SWM), sustainability defines the assessment of environmental, economic, and social impacts of available waste treatment options [14]. Certain economic, technical, behavioral, and political challenges need to be overcome for improving urban sustainability initiatives such as waste-to-energy (WTE) projects. Energy recovery from waste can serve as a useful sustainable solution for waste management [15]. WTE transformation includes reducing the environmental problems in urban areas, generating electricity and heat supply for the surrounding urban areas, and increasing the climate benefits in addition to economic ones by reducing the reliance on depleting fossil fuel-based energy [16].

Abdeljawad and Nagy discuss the GAM's environmental challenges, potential mitigating strategies, and the effects of population growth and urbanization during the past decade. Traffic congestion and pollution are two additional significant problems in GAM. To address GAM's environmental problems, the study's initial results showed the need to implement specific measures, such as bus rapid transit (BRT). BRT is supported by policies along the two trunk lines, enabling the city to expand past comprehensive housing projects into more walkable, mixed-use communities with carbon-free electricity and green building standards[24].

The GAM metropolitan area is home to more than four million of the country’s 10 million inhabitants. GAM, which hosts around 30% of the Syrian refugee population in Jordan, is largely affected by the ongoing refugee influx. This puts heavy stress on its infrastructure and, in particular, the solid-waste management system. Due to the rapidly growing population, more waste is being produced and further energy sources are required. To prepare Amman for an urban influx of five million people by 2050, it is critical to create a city that has low carbon levels and is resilient and livable.

In May 2003, the Greater Amman Municipality moved to a newly constructed sanitary landfill at Alghabawiand closed the Russaifah landfill. The new landfill is a well-engineered facility with leachate and gas collection systems. However, the waste collected in Amman was being disposed of at the Al Ghabawi landfill without any regular treatment or recycling. Less than 3% of recyclable materials were recovered by scavengers, NGOs, or private recycling companies [1].

GAM has been responsible for solid waste management services in its various areas of jurisdiction. Greater Amman’s established landfill gas projects aim for sustainable energy systems by reducing energy consumption, particularly landfill gas city-integrated renewable energy to satisfy the high-energy demands of growing urban areas. Thus, they enhance environmental quality, encourage resource reuse, and promote waste minimization. Waste management in the municipality is managed within Jordan’s international commitments regarding reducing global warming, climate change, and carbon emissions.

GAM received the funds from the World Bank and the European Bank of Reconstruction and Development (EBRD), and the contractor is a joint venture of two Greek construction companies, namely Christopher D. Constantinidis S.A and HELECTOR S.A.

It was found that evaluations of the WTE plant in the Al Ghabawi landfill together with an analysis of the environmental, economic, and social benefits of the plant as an alternative to landfill use are few in literature. Further, most of these studies were conducted before the project commenced operation. The current research discusses the outcome of energy produced from waste at one of the biggest WTE facilities in the Middle East located in Amman city. It reviews the calculated emissions and revenue of this project and assesses the input-output quality of the achievements with the support of related literature. The major contribution of this study is that it provides an overview of the WTE project, including the current status, challenges, future vision, and overall project benefits to show how the GAM has made a reasonably successful step toward implementing WTE technologies for urban sustainability and resource efficiency. Further, the paper evaluates the sustainability of the WTE megaproject, the cost of generating electricity, and the reduction of GHG emissions to show the potential climate-related benefits of this project. It also assesses the value of waste-based bio-refinery and recycling as a sustainable solution to landfill waste problems and its relevance regarding the production of renewable electricity.

The remainder of the paper is organized as follows: Section 2 presents the data and methods and provides an overview of the existing MSWM context in Amman and MSW stream characteristics. The WTE process in the Al Ghabawi landfill and the electricity generation is described in Section 3. Section 4 presents result and discussion. Finally, the paper’s conclusion and recommendations are provided in Section 5.

II. MATERIALS AND METHODOLOGY

This study was conducted based on secondary data of the Al Ghabawi landfill of GAM by reviewing the literature, conducting site visits, and interviewing the WTE project manager.

III. DATA ANALYSIS AND INTERPRETATION

Al Ghabawi Landfill: Location and Surrounding Area

The Al Ghabawi landfill is the only landfill in Jordan that follows the international best practices (being sited after a feasibility study, receiving an environmental impact assessment, and meeting international standards for design and construction). It is the country’s first engineered sanitary landfill and sets a role model for the future rehabilitation of existing landfills. The landfill’s design and construction comprise a gas collection system that enables the plant to transform waste into energy, which would eventually replace the energy generated by fossil fuels [2]. This landfill was built following the latest construction methods that minimize environmental impacts and maximize energy efficiency [3].

The Al Ghabawi landfill site covers an area of approximately 2 km2 and is located in the Uhud District, which is around 23 km from Amman in the eastern semi-arid desert and under the jurisdiction of the GAM. The landfill is situated on undeveloped military lands that were formerly used for military expeditions and training and whose ownership was transferred to the GAM.

There are no residential areas close to the landfill. The nearest local communities are around 9 km to the west with very low population density, and the only activity in the vicinity of the selected site is a dairy farm located at a distance of 2.5 km to the southwest.

Greater Amman's Role in Solid Waste Management

Article 12 of the Municipalities Law No. 41/2015 empowers GAM to act as an autonomous entity in managing municipal services within its boundaries. These services include the municipal cleaning, waste collection, and final disposal of waste from the city's 22 districts, which span an area of around 800 km2.

GAM's role in managing MSW is complemented by the Ministry of Health (MOH) and the Ministry of Environment (MoEnv) who oversee the management of medical, hazardous, and industrial wastes, respectively.

The responsibility for MSWM services within the metropolitan area of Amman and its suburbs lies with GAM. With a flow of approximately 4,000 tonnes of MSW per day, GAM accounts for approximately 50% of Jordan's total MSW. The Al Ghabawi landfill not only serves the city of Amman but also the Zarqa and Ruseifeh municipalities via a transfer station as well as some private companies, hospitals, universities, and the army.

The Al Ghabawi landfill started receiving waste in 2003, with the closing year expected to be 2031 [4]. Al Ghabawi is the first municipal carbon finance partnership in the Middle East. The landfill has been designed to include nine cells with a full capacity of 40.92 million tonnes of waste by 2031 [5]. Cells 1, 2, 3, and 4 have reached their full capacity, and cell 5 is currently being used (GAM). The remaining cells are to be established and filled over the lifetime of the landfill (GAM). Each cell is a large pit that can accommodate approximately 3–8 million tonnes of compressed waste and is buried in a land area ranging from 150 to 200 dunums (Figure 1 & 2).

Fig 1: Al Ghabawi landfill boundary

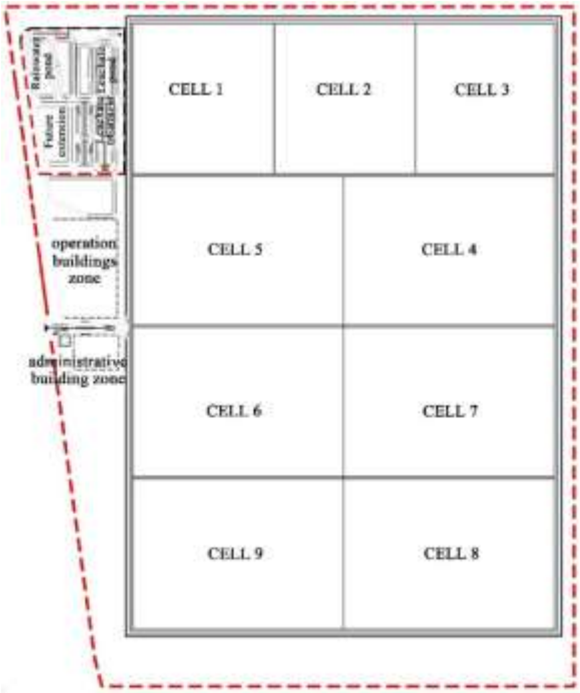

Fig 2: General layout of Al Ghabawi landfill

MSW Composition and Waste Generation in Amman City

The largest amount of waste comes from the capital, Amman, followed by the governorate of Irbid. The latter takes approximately seven years to fill one cell, while the former mobilizes one cell within three years.

The waste quantity received at the landfill is measured on a daily basis by a single weighbridge which was recently connected to a computerized management system. The landfill accepts only MSW, which includes residential, commercial, and non-hazardous industrial wastes. The waste composition received at the Al Ghabawi landfill (as shown in Table 1) mainly includes 50% organic waste, 15% plastics, 15% paper and cardboard, 4% glass, 4% metals, and 12% unclassified combustibles.

TABLE 1: Physical composition of MSW in Amman city (Source: Royal Scientific Society (RSS) in 2011)

Solid waste component	Percentage [%]
Organic waste	50
Paper and cardboard	15
Plastics	15
Metals	4
Glass	4
Others	12

The solid wastes disposed of in landfills over the next years have been forecasted to greatly increase, considering the yearly increase in solid waste generation rates[6]. The site receives, on average, 4,300 tonnes of solid waste daily and around 1.5 million tonnes a year. These quantities have significantly increased due to the high percentage of population increase with the refugees from Iraq and Syria [7] (Figure 4 and figure 5). According to AL-Husban Z (2019), the values are expected to increase by about 5% by 2031, and the waste disposal at the landfill closure is expected to be around 40,582,200 tonnes (Table 2).

TABLE 2: Amount of waste received in the landfill each year[8]

Year	Amount of waste (TN)
2003	447945
2004	696293
2005	752688
2006	785987
2007	795188
2008	742888
2009	892464
2010	966658
2011	937645
2012	995907
2013	1048612
2014	1121540
2015	1172980
2016	1344017
2017	1413915
2018	1529625
2019	1456074

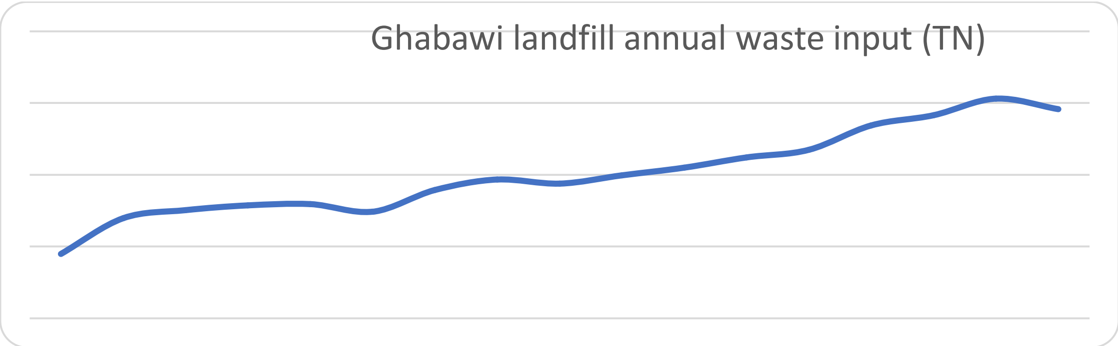

Fig 4: Al Ghabawi landfill's annual waste input

Fig 5: Waste disposal in a cell at the Al Ghabawi site

WTE Process and Electricity Generation in Al Ghabawi Landfill

Brief Description and Pros and Cons of Landfill Gas

Currently, there are two LFG power plants at the AlGhawabi and Rusaifeh landfills with capacities of approximately 5 MW and 3.5 MW, respectively. LFG comprises captured methane from landfills which can then be used in a gas turbine. AlGhawabi is planned to be expanded to 14 MW by 2027.

The WTE technologies were assessed based on four main criteria: environmental, economic, social, and other criteria (Figure6)[9]

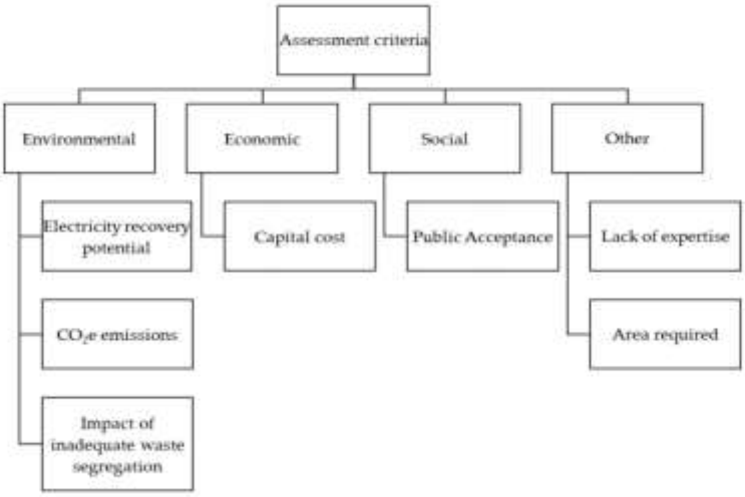

Fig 6: Assessment criteria of choosing the best technology of WTE

WTE Anaerobic Digestion (AD):

- Anaerobic decomposition of biodegradable waste in a sanitary landfill
- Wells with pipes in the landfill for retrieving the gas Pros
- Cheapest option
- Not a complex process
- Gas produced can be used to generate power or directly to produce heat

Cons

- Low power generation efficiency
- Requires large land area
- Pollution may be caused by surface runoff during rain
- Leachates may be released into the groundwater
- Spontaneous explosions can occur because of methane accumulation

WTE components

The WTE project started in 2014, as it was in the biogas extraction phase. That means that the conversion of the biogas to electricity had not started before 2014, and after the project was implemented in 2014, the biogas was burnt at a flare. In 2018, the power station started producing electricity as scheduled because of the energy needs of the city of Amman. To collect the biogases and the leachates generated from the solid wastes, a set of different pipes was installed at the base of the landfill. Besides, geo-membrane, which is made up of HDPE, was used as the lining material (Figure 6) [10].

Fig 7:The cell covered with a layer

Until now, four cells have been filled and safely capped, and methane gas is being extracted; the fifth cell has been filled and will be capped and connected to the biogas system shortly. Donors continue to fund the development of the project to build additional cells and cap the filled ones. The site received around 4,300 tonnes per day on average and 1,548,000 tonnes in total in 2018.

LFG systems involve the following (as simplified on Figure8):

- Gas collection operations, which involve drilling and installing vertical LFG wells to withdraw methane (including casing, piping gravel packing, and bentonite plugs to variable depths and to connect wellheads, etc.)
- Gas moisture removal and cooling units
- Gas flaring units, which receive dry, cool gas and combust it using high-temperature flares
- Gas engine (operation of three 1.3 MW gas engines, use of oil/fuel tanks to support operation, use of a small compressor to operate the gas engines, etc.)
- Gas monitoring units, which measure and record the undisturbed probe pressure/vacuum, leak test the entire sample train, and check surface emission and ambient air sampling
- Leachate management, which comprises different activities such as suction, pumping, ensuring that the leachate management system is functional, etc.
- Workshop, which involves different maintenance operations such as inspections and mechanical repairs, oil and air filter change, charging batteries, welding, etc.
- Management, which involves day-to-day activities to run the landfill operations (record-keeping, staff care, medical care, outreach and community engagement, emergency response services, etc.

Landfill Gas Capture [11]

In the course of operating an engineered or sanitary landfill, LFG, which consists of 35–55% methane, is generated by the AD of organic matter in the landfill body. To capture the methane generated, an LFG recovery plant is installed consisting of an extraction system and flaring system.

Extraction System

Gas is extracted from landfills using different components such as vertical perforated pipes, horizontal perforated pipes, and ditches. The membrane is sometimes used to cover the landfill under which the gas produced is collected. The most common method of active gas collection is through vertical perforated pipes that are injected into the waste mass to collect gas while avoiding the entry of air and water into the system.

Flaring System

In cases where the use of LFG for energy purposes is not economically feasible, the gas has to be flared off. Flaring is done to reduce the methane emissions that can affect local air quality and contribute to the greenhouse effect [36, 49]. Flaring also reduces odors and the risk of fire and explosion (Figure 9 and figure 10).

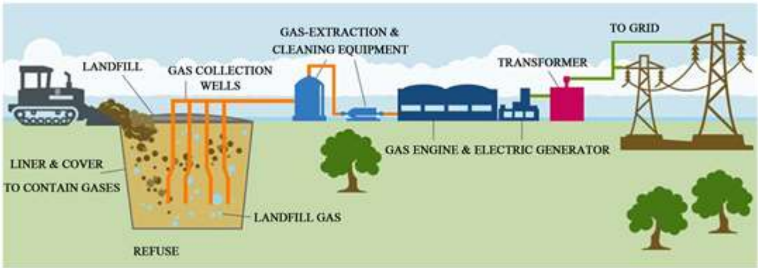

Fig 8: WTE process (Source:[12])

Fig 9: WTE project area

Fig 10: Flaring system

The LFG collection is regularly monitored and adjusted to optimize the effectiveness of the collection system. A portable gas analyzer is used to measure the LFG composition, flow, and suction at the flare, including the quality and quantity of LFG that enters the flare, along with a portable digital manometer that measures suction and differential pressure. (Figure: 11)

Fig 11: Regular measurement of gas concentration in the manifolds

Since methane is 28–36 times more powerful than carbon dioxide in terms of the 100-year global warming potential (EPA, 2016)[13], the practice initially was to flare the collected biogas without energy recovery. At the end of 2019, three electric generators with a total capacity of 4.8 MW were installed to utilize the biogas from the three completed cells at the AlGhabawi landfill; these generators were connected to the grid, and the electricity was produced was sold to the National Electric Power Company. For every MWh generated at the site, and according to the calculations made for the renewal of the crediting period of the CDM, the avoided emission of CO2 is 4.96 t CO2/MWh. The electricity generated by the engines is shown in Table 3(GAM, 2021).

TABLE ***3: The electricity generated by the engines from June 2019 to 31 January 2021***

Month		Electricity Generation		Comments
2019	June	3,217,140	kWh	
2019	July	3,189,656	kWh	
2019	August	3,151,984	kWh	
2019	September	3,086,030	kWh	
2019	October	3,027,510	kWh	
2019	November	2,742,640	kWh	
2019	December	3,082,530	kWh	
2020	January	2,784,300	kWh	
2020	February	2,718,470	kWh	
2020	March	2,044,650	kWh	Problem with electricity cables of the plant
2020	April	1,954,790	kWh	Problems with Generators G1 and G2 (stop)
2020	May	136,680	kWh	G3 also stopped
2020	June	0	kWh	Power plant out of service
2020	July	0	kWh	Power plant out of service
2020	August	1,231,130	kWh	Operations started by mid-August
2020	September	2,346,200	kWh	
2020	October	2,411,900	kWh	
2020	November	2,380,190	kWh	
2020	December	3,028,670	kWh	Cell4 connected to LFG network
2021	January	3,035,620	kWh	
TOTAL		45,570,090	kWh	Until 31/01/2021

Note:

- *The electricity generated on 30thand 31stof May 2019 is included in the date for June 2019(the operation started on 30/05/2021).

- ** Additionally, during the commissioning tests performed between May 16th and 30th, the electricity generation was 1,488,470 kWh. The total generation including the commissioning is 47,058,560 kWh until 31/01/2021.
- ***Source taken from WTE manager engineer Ameen Al-Saraireh.

The recovered gas is calculated based on 0.75% from total LFG generated according to the estimates as shown in table 4 below:

TABLE 4: LFG from cells 1 to 4 in (m3/hr)

Year	LFG cell#1 (m3/hr)	LFG cell#2 (m3/hr)	LFG cell#3 (m3/hr)	LFG cell#4 (m3/hr)	LFG total (m3/hr)	LFG recovered (m3/hr)
2019	1142	1015	2095	0	4252	3189
2020	1044	935	1922	0	7365	5524
2021	955	844	1760	3290	6849	5137
2022	892	779	1622	3125	6418	4814
2023	845	706	1464	2967	5982	4487
2024	797	654	1351	2819	5621	4216
2025	735	606	1224	2677	5242	3932
2026	710	554	1134	2544	4942	3707
2027	669	530	1051	2418	4668	3501

Considering the data of Cell4, the estimated potential capacity of the installed power plant is between 3.3 and 2.4 MW for the coming eight years.

However, it is necessary to consider the progressive depletion of the LFG to be collected from Cells 1 to 3.

Further, considering that Cell5 will come shortly later, it would be reasonable to request some additional capacity between 3 to 4 MW. Since it is a request for additional capacity and does not compromise the effective selling of electricity, the extension of the plant can take place in two steps:

- Extension stage 1: one additional generator (1560 kW) for a total installed power of 6.2 MW
- Extension stage 2: one additional generator (1560 kW) for a final installed power of 7.8 MW

The life span for closing the landfill and not receiving waste until 2032gas withdrawal and extraction may continue until 2080. Currently, the capacity of the power plant is 4.8 MW, and it is expected that it will reach about 7.5 MW during the peak of the station's work in 2025.

IIII Results and Discussion

Landfilling is the most common way to deal with MSW; however, it is not the only method. Several additional waste processing technologies are currently employed around the world that fall under the categories of incineration and biological processing.

The amount of methane gas produced at the landfill and ultimately burned for power generation depends on the amount of dumped waste. The Al Ghabawil and fill has the capacity to produce more than 4.8MW per hour. The methane gas produced at landfills is a strong contributor to global climate change, causing 21 times the negative impact of carbon dioxide on the atmosphere. LFG emissions have a number of pollutants of concern to human health and the environment; therefore, landfills are identified as hazardous air pollutant sources under the Urban Air Toxics Strategy [14].

Environmental, Energy-Related, and Economical Benefits of WTE Technology

Environmental Benefits

A study conducted by the World Bank in 2006 estimated the cost of environmental degradation in Jordan to be 2.35% of the country's GDP [15]The cost of environmental degradation caused by improperly disposed waste was ranked third at 0.23% of the GDP, whereas water ranked second at 0.81% of GDP) [16]

LFG is considered one of the major contributors to methane gas unless recovery control systems are implemented [17]. The second-largest emitter of GHG in Jordan is the waste management sector, derived from methane gas produced by organic waste that is not properly pre-treated. One of the methods to reduce GHG emissions is capturing LFG [18]. LFG is produced when organic material decomposes anaerobically, consisting of 45–60% methane gas, 40–60% carbon dioxide, and 2–9% other gases which are mostly emitted to the atmosphere. The methane reduction effect depends on how much methane can be converted into carbon dioxide based on the type of LFG electricity technology that is used.

WTE projects are safe for the environment as they are monitored and controlled regularly. Their utilization of the recovered LFG from landfill sites is considered a useful process to provide a significant amount of electric power and simultaneously treat organic wastes [19,20].

The LFG produced from the WTE project yields a good amount of energy that covers a good percentage of the energy demand of the city, making Amman less dependent on oil and gas [21]. WTE plants are able to destroy completely hazardous organic materials, reduce risks due to pathogenic microorganisms and viruses, and concentrate valuable as well as toxic metals in certain fractions [22]. It also reduces associated emissions of VOCs, odors, and other local air pollutants.

The project contributes to reducing the emission of an equivalent of 175 thousand tonnes of carbon dioxide by burning about 19 million cubic meters of biogas annually (Source GAM).

The project complies with the environmental protection policy as it has the following positive environmental impacts: odor prevention at the disposal site, reduction in discharge of pollutants into the atmosphere (due to LFG collection), prevention of fire at the disposal site, and the effect from the substitution of deteriorated power generation systems.

4.1.2 Energy Benefits

Biogas is produced from biomass through several chemical reactions and anaerobic decomposition processes with the appropriate temperature and humidity levels. Solid waste can be considered a renewable source of energy, as wastes are continuously produced.

Since Jordan does not produce oil, the energy requirements are covered by importing oil and natural gas. The cost of importing energy places a financial burden on the national economy, as Jordan spends more than 10% of its GDP on the consumption of energy [19. 23].LFG is an independent source of energy because it generates energy 24 hours per day and 7 days per week [25]

The WTE project helped achieve a large part of Amman's strategy for energy self-reliance, in line with the National Energy Strategy. The project follows a design with international standards. Its goal is to produce energy from clean sources that are transmitted to Amman through the National Electricity Company and then to distribute the electricity through the so-called "transit distribution" system. This means that the energy produced from the landfill is taken in the form of a balance for the Municipality of Amman, which is deducted from the total energy consumed. The generated electricity from the project is used to power the landfill, while the remainder is sent to the national grid. The WTE project is connected with the Jordan Electricity Company's grid and generates 4.8 MW per hour by burning methane collected from the waste at the Al Ghabawi landfill, with a serious direction in the near future to expand the project after connecting the new cells to raise the percentage of energy produced and fully cover the energy consumption of Amman Municipality.

The process of extracting biogas from waste is carried out on a daily basis with an average of 106 MWh per day being generated, and the electrical energy produced (4.8 megawatts per hour) is equivalent to paying the equivalent of 45% of the value of the annual electricity bill for buildings and streets of the Municipality of Amman, with a value of five million dinars annually. The generators are running at 41.8% of the rated load, with an availability of 97.9% after discounting the required maintenance tasks. The self-consumption occurring at the plant itself constitutes less than 4.5% of the generated energy [26].

To develop renewable energy capacities, several support mechanisms have been introduced, starting with the Renewable Energy and Efficiency Law No. 13 in2012. This law and its by-laws enable independent power producers (IPP) to provide electricity from renewable sources to NEPCO with long-term power purchase agreements (PPA) and to ensure the purchase of energy from renewable sources [27]. The Electricity Regulatory Commission (ERC) issued two regulatory directives, one for small-scale projects (< 5 MW), for which no license is required, and another for large-scale projects (> 5 MW). For large-scale projects, the reference price for electricity from biogas incineration is 0.06 JD/kWh and that of electricity from biomass incineration is 0.09 JD/kWh [19].

Profiting from Waste-to-Energy Technology

Economical aspects of MSW utilization for energy recovery

Capturing methane emissions from solid waste contributes to carbon reduction, and it can be used to produce electricity as a form of green energy as well, both of which attract revenue [29,30, 51]. Waste recovery plays an important role in the operational and economical aspects of waste management. There are several types of wastes that can be recovered for sale. LFG plants can turn the waste disposal problem into a profitable solution by producing electricity, connecting it to the national electricity grid, as well as generating profits from selling electricity and carbon emission reduction certificates in certified carbon development mechanism enterprises [31].

A simple evaluation was conducted by consultants and researchers to establish the amount of energy that would be recovered based on the characteristics of the MSW if it is incinerated [32]. This megaproject alleviates GAM's financial burdens by cutting the municipality's electricity bill by five million JD a year by the replacement of fuel oil with the generated biogas [33]. These financial savings are directed to other services for the Jordanian citizens in Amman. The annual average electricity bill for the Municipality of Amman is 13–14 million JD, and that includes the lighting for buildings and streets as well. This amount can be provided by taking advantage of this alternative energy.

The economics of LFG utilization depends on a number of factors including LFG quantity, local energy prices (electricity, steam, gas, or other derived products), and equipment choice. The economic criterion of the LFG electricity generation technology is generally determined by a cost and profit analysis. The cost is divided into capital cost, annual operation and maintenance (O&M) cost, and carbon and energy taxes which will be added in the principal factors for the climate agreement, where the profit is the sales revenue of electricity generation [34].

Many studies have estimated the benefits of using the landfill biogas from the Al Ghabawi landfill; one of these studies were conducted by Al-Husban (2019) who evaluated the economic and environmental outcome of biogas generation at Al Ghabawi landfill by predicting the amount of LFG generated. The study revealed that the amount of energy produced for the whole project is about 2,116,315MWh with a reduction of about 10283 thousand tonnes of CO2 equivalent. Thus, LFG is a good source for power generation, and it can be used to replace fossil fuels. The results of the feasibility study show positive financial benefits of about 5,723,790 JOD in different aspects such as system feasibility income, externalities of health, and adjacent lands [35]

Alnwaiseh (2007) also estimated methane emission using the first-order degradation (FOD) model and found that the Al Ghabawi landfill produced 10 Gg/year of methane. The costs included in the analysis were the capital as well as O&M costs. The expected benefits were sales of electrical energy and carbon credits through the Clean Development Mechanism. The net revenue from the Al Ghabawi plants was estimated to be JD37 million over the project's lifetime [36]

A step towards implementing the Kyoto protocol, signed by Jordan in 2001, was the establishment of the biogas company at the closed Al Russeifa landfill in 1997(a non-profit organization) owned equally by the central electricity generating company and Greater Amman Municipality). The Al Ghabawi landfill biogas would not only generate green energy but also create a source of revenue by being sold through the mechanism of the Kyoto protocol [37]. Within the Kyoto Protocol, developing countries are granted "virtual carbon emissions" that can be used in the country or sold to developed countries that have surpassed their emission limits. In this transaction, the industrial country will buy the number of carbon emissions of a developing country at a global carbon market rate in the form of funding for alternative energy projects and direct financial support tailored for climate change mitigation and adaptation as well.

Sustainability Issues

SWM includes the recycling of materials and energy recovery from waste, which can produce revenues and reduce waste management costs towards applying circular economy approach as shown on (Figure 12). Many studies have reviewed the sustainability of WTE technologies. They defined it as an opportunity for the sustainable production of energy. WTE projects have proven themselves to be an environmentally friendly solution to the disposal of MSW and the production of energy. WTE systems now facilitate a clean, renewable, and sustainable source of energy.

GAM and other municipalities seek to reduce the number of waste dumps from 23 landfills to 10 healthy and environmentally friendly landfills by 2034 to collect the largest amount of waste in specific areas to increase the amount of gas extracted from them that is used for energy production.

Biomass material from municipal waste represents one of the most important sustainable renewable energy sources that can be used as a replacement for fossil fuel, forming solutions for environmental problems, depleting energy supplies, and reducing the negative impact of the waste on the environment, resulting in great importance from economic and environmental perspectives [38,39,40]. Producing energy from LFG is an opportunity for green growth as it "will boost resilience by improving Jordan's energy security" and help in managing the increasing waste in urban areas due to population growth [42]. One of the important issues is how to promote urban energy security for achieving urban sustainability, which involves overall energy, economic, and environmental factors [18, 28, 42].

In response to the government's target goal of obtaining 10% of its energy needs from renewable energy resources by increasing electricity generation share from the present 1.13 GW–1.8 GW by 2020. Based on the present population of Jordan (10,203,134 million in 2020) and given that half of the MSW in Jordan is disposed of in the AlGhabawi landfill with an average generation rate of MSW of 0.9 kg/cap/day, the total daily amount of MSW generated is around4.3 tonnes/day. Jordan's demand for energy is growing at a rate of 3% annually and, if utilized well, would result in annual savings of about US$ 7 million.

WTE technologies and pathways in the context of circular economy principles address a number of SDGs, including good health and well-being, clean water and sanitation, affordable and clean energy, industry, innovation and infrastructure, sustainable cities and communities, responsible consumption and production, climate action, life below water, and life on land [43, 48].

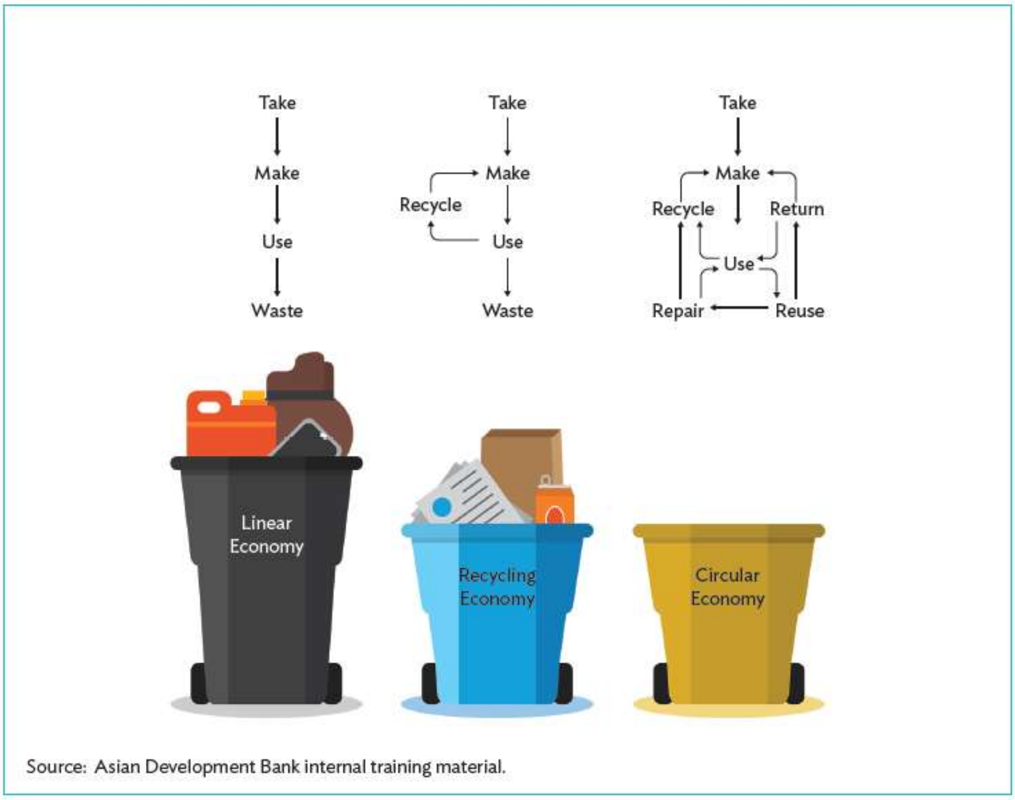

Fig12: Simplifying the circular economy

The actions to be taken to make Amman a sustainable city are as follows: resource recovery and proper waste management; litter prevention; environmental innovation and protection; establishment of partnerships between the community, government, and industries to protect environmental resources and promote water conservation, re-use initiatives, and energy innovation by focusing on renewable energy and addressing climate change issues.

GAM has adopted a new sustainability approach that increases the chances of achieving environmental, societal, and economic sustainability; this confirms GAM's attention to applying the concept of sustainable development at the institutional level to effectively protect the environment, encourage the rational use of natural resources, and make the community participate in achieving high and stable levels of economic growth for the city.

Therefore, in summary, WTE technology is a sustainable waste management practice with positive socio-economic and environmental impacts and multiple benefits.

Future Vision for Adopting Better Sustainable Technology

The AlGhabawi landfill implements the AD process as a source of renewable energy because the methane-rich biogas produced is suitable for energy production and can replace fossil fuels. As part of an integrated waste management system, AD reduces the amount of methane that would be sent into the atmosphere if the waste was just sent to the landfill. AD occurs in four separate phases: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [44]. Methanogenesis is the last stage, where the biogas is produced. It can contain up to 50%–70% methane which can be used for heat and power applications. The AD technique takes 30 days for the methane to be produced after adding the organic material to the digestion process.

When comparing the most commonly used landfill management methods in Jordan regarding the old closed open dumped landfill (Rusaifeh landfill) and the Al Ghabawi landfill, a large fraction of the potential energy of LFG was found to be missing in the old method compared with the sanitary Al Ghabawi landfill. This is due to the loss of LFG during waste disposal activities, before and during the energy recovery system's implementation, and the typical inhibition phenomenon occurring once the anaerobic process starts, which can affect the methanogens phase. Other negative impacts arising from the old open dump include the migration of gas and leachates from the landfill body into the surrounding environment, which presents a serious environmental concern and leads to air and groundwater pollution, negative climate impacts due to GHG emissions, and public health hazards [45].

However, both methods need a long period of time (around 30 days) for a large fraction of LFG to be produced, which makes the energy recovery not sustainable. Further, in the case of the open dump, the low degradation rate of the organic material in the waste also results in a high pollutant content of the landfill leachates for a long time, making its management a serious and costly problem. All these negative impacts can be addressed by a different management concept that is based on the sustainable landfill scheme [46].

For instance, GAM is now working on a pilot project to sort waste from the source, which aims to reduce non-degradable wastes in the initial stage and to increase the lifespan of the project as well as enable the transition to a more sustainable waste management method, such as a bioreactor, in the future.

It is recommended for GAM to adopt a new alternative management strategy to enhance the natural, biological process occurring in the body of the landfill to achieve a more rapid stabilization of the disposed waste. One of the solutions is to combine the sanitary landfill with a bioreactor, which would lead to some advantages such as an increase in energy recovery from LFG along with a reduction of the time required to reach a high level of stabilization of the waste [47]. However, the bioreactor method is more sensitive than the WTE sanitary landfill method, and as a solution to avoid any possible inhibition phenomenon that may occur during anaerobic degradation, there should be a pre-treatment and monitoring of PH and leachate recirculation that should be done before disposal. The mechanical biological treatment (MBT) pre-treatment can produce an increase in the recoverable waste material together with a reduction in the volume used for landfill as well as the positive effect on the quantity and quality of the LFG produced.

A Pilot Project to Sort Waste from the Source

Al-Radwan site at Zahran district was selected for the pilot phase of the project because it contains a diversity of organizations, including residential homes, commercial stores, government institutions, schools, hotels, hospitals, and embassies.

The Amman Municipality collected about 300 tonnes of recyclable materials in the Radwan neighborhood of Zahran during the year 2020 as part of the waste sorting project from the source, funded by the German Ministry for Economic Cooperation and Development in cooperation with the German Agency for International Cooperation.

The project aims to reduce the cost of waste management and extend the life of the Al Ghabawi landfill by reducing the volume of waste sent to it by 20%, in addition to reducing direct GHG emissions and providing new job opportunities in the field of solid waste management. The percentage of sorted waste reached 14% of the total waste collected in the neighborhood, with a purity rate of 81%.

The preparation of the work plan and necessary designs for the second and third pilot phases of the project, which will commence during the first middle of 2021, has been completed in the Al-Rawaq and Al-Jarir neighborhoods in Basman district and the Medina district (downtown) within the commercial sites.

To reduce fuel consumption and gas emissions, 2.8 cubic meters of electric vehicles and 500 liter small electric vehicles have been provided to collect waste and recyclable materials, thus enhancing Amman's role as a smart, resilient, and environmentally friendly city. This project will extend the life of the landfill and provide an opportunity for improvements to the biogas project.

X CONCLUSION

The landfill is one of the most environmentally friendly and cheapest means of waste disposal, therefore the government should encourage and indulge in sustainable landfill management. Cities around the world are running out of places to send their waste, and landfills are reaching their limits and shutting down. The organic fraction of MSW constitutes the main part of the methane produced from landfills and is a powerful GHG that directly contributes to anthropogenic global warming. Therefore, urban areas play a significant role in the transformation to sustainable energy utilization, for example, through proper urban energy planning and the implementation of WTE projects. Coupled with recycling, these technologies could provide manageable solutions for the growing waste concerns for both municipal and private urban institutions. The increase in waste recycling and reuse would be economically feasible in the urban cities since the costs for landfilling would decrease as the utilization of waste material increases.

In general, renewable technologies are characterized by relatively high capital costs and low operation and maintenance costs, and with the development of electricity deregulation throughout Amman, renewable energy is facing more competitive challenges. The results imply that waste utilization for energy recovery and the development of WTE projects represents a win-win situation and could make potential contributions to the mitigation of GHG and air pollutant emissions. Regional sustainable development could be promoted in terms of urban energy security and environmental improvement.

GAM has succeeded in disposing of waste in a way that would economically benefit the community, by using biogas, a renewable fuel, for renewable energy production. This study is expected to be useful for both decentralized and centralized waste-based energy planning by policymakers in Amman urban city. It can be concluded that the project can be sufficiently profitable as long as it is approved by the government as a CDM undertaking and the market price of carbon credits is 8 US$/t-CO2 or higher (Shimizu Corporation, 2007; Fiscal 2006 CDM/JI Project Study Consigned by the Ministry of Environment).

The waste generated by the increasing population and urbanization of humans will soon become unmanageable. Therefore, its recommended for municipalities to promote innovation in technology to strengthen the potential of waste-to-resource and WTE processes, carry out recycling and agricultural compost activities that may serve as promising strategies in terms of significant savings and reducing the risk of air and water-borne diseases, especially in urban areas, raise public awareness and conduct training activities related to solid waste management, and enable further enforcement of waste legislation. The separation and sorting of waste at the source can not only increase the recovered materials but also contribute to a reduction in environmental degradation through the organized work of scavengers. Further, increasing the investment and the involvement of the private sector in this field will help to achieve the goal and design an intelligent system such as sensors in the waste collection container to facilitate content estimation and collection optimization.

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