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Research Article

Potential of Waste to Energy Conversion in Egypt

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This paper proposes a study on the potential of waste-to-energy (WTE) possibility in the Arab Republic of Egypt. WTE is a viable option for municipal solid waste (MSW) management and a renewable energy source. The issue of waste spread is a chronic environmental challenge in the Arab Republic of Egypt. The MSW practices in Egypt are simply done by collecting the waste and dumping it in open landfill sites. This research aims to assess the potential contribution of the WTE facility to meet electricity demand in Cairo City, which is Egypt's capital and the biggest city in population as a sample, and then apply the results to all of Egypt. The paper introduced a step-by-step calculation for the electrical power that can be generated from Cairo MSW. Four scenarios for WTE utilization were developed: Mass Burn without any waste processing, Mass Burn with 25% recycling, Mass Burn excluding 50% of organic material, and Mass Burn excluding 50% of organic material with 25% recycling. The Mass Burn scenario implies full MSW stream incineration; the Mass Burn with recycling scenario considers a partial separation of reusable materials and the waste leftover for incineration; the Mass Burn with excluding 50% of organic material scenario considers a partial separation of organic materials and the waste leftover for incineration; the Mass Burn with excluding 50% of organic material with 25% recycling scenario considers a partial separation of organic materials and partial separation of reusable materials and the waste leftover for incineration. The analyses were done for the period 2011–2031 for Cairo with a total population of about 10 million in Nov 2021. The results show the huge potential of WTE conversion as a source of renewable energy, which is a key factor in Egypt's sustainable development strategy 2030. Available data have been theoretically processed to show the decision-makers in Egypt the amount of electrical power that can be generated by using the WTE options to manage the MSW in Egypt.

1. Introduction

For millennia, humans have faced great challenges in energy supply and waste management. Despite the last decade's huge progress, these issues are still important today. To meet these challenges, every atom should be utilized in the best possible manner, which is called "atom economy." Understanding the underlying mechanisms and processes of energy and waste generation is necessary to achieve these goals. In the last century, energy demand has increased rapidly and will continue as the rate of consumption increases as people strive to improve their living standards. The consequence of that is the rate of consumption should match the rate of conversion and generation leading to continuous power source upgrades from wood to coal to oil to natural gas to renewable energy. The energy sources cycle differs from one to another, biomass needs to be grown, harvested, dried, and processed before use, coal needs to be mined, transported, and processed before use, and oil needs to be transported and refined before use, whereas gaseous fuels, which are ready to use immediately, only need to be transported.

Today, the world's target is energy sources that are distributed and ready for immediate use with preferably no preprocessing, and a very short cycle. Energy is the main factor in any discussion about sustainable development. Solar radiation, wind, waves, and tides are all considered renewable energy sources; most scientists show their reliance on renewable energy technologies (RET) for sustainable development and long-lasting life on this planet earth for their daily energy needs, which have no negative social consequences. Accordingly, the transition to a sustainable renewable resource should be encouraged and developing countries should increase investments in it [1]. Due to inherent uncertainty and intermittency for renewable energy sources, the integration of it has brought huge challenges to the planning and operation of today's power systems. At present, how to handle the uncertainty of renewable generations is currently the difficulty of studying the economic optimization of power systems [2, 3]. This issue has a minor effect on WTE technologies because MSW production depends on human living. Humans for thousands of years have had to take care of the waste effectively and they will have to continue to do so if the human species is to survive.

Over the last decades, and all over the world, many health disasters had occurred; it was a consequence of insufficient or/and underestimates of the importance of treatment or management of waste. Today, particularly in developing nations, essentially all of society's health concerns may be linked back to inefficient waste treatment or management. Initially, waste management focused only on human waste and sewage. It has now evolved into what we refer to as municipal solid waste (MSW), which encompasses all other non-hazardous solid trash and is increasingly concerned with gaseous pollutants [4].

2. Utilization of Waste-to-Energy as a Sustainable Source

WTE meets the two basic renewable energy resource criteria—its fuel source (trash) being sustainable and indigenous. According to Figure 1, after efforts to "reduce, reuse, and recycle," WTE facilities recover valuable energy from the trash. WTE facilities generate clean renewable energy and deserve the same treatment as any other renewable energy resource. Economic Forum's Davos Report identifies eight emerging clean energy sectors including wind, solar, and waste-to-energy. The National Research Council of the National Academy of Science has identified "atom economy-zero waste" as the ideal goal for sustainability in the year 2100. Until we achieve that fully integrated system, today's garbage should be treated to extract energy.

WTE provides two important benefits over other forms of renewable energy. It works 24 hours a day to minimize base-load fossil fuel output and is positioned in densely populated regions where electricity is most required. In Sweden and the rest of the EU, the organic portion of waste-to-energy is recognized as a renewable resource. The United States Environmental Protection Agency USEPA states that waste-to-energy facilities "are clean reliable renewable sources of energy with less environmental impact than almost any other source of energy" [4].

3. Waste-to-Energy Technologies

WTE conversion is divided into main pathway conversions: thermochemical and biological conversion. Conversion technologies consist of various methods for extracting energy from waste materials. Figure 2 provides an illustration of the various energy pathways for WTE [6, 7].

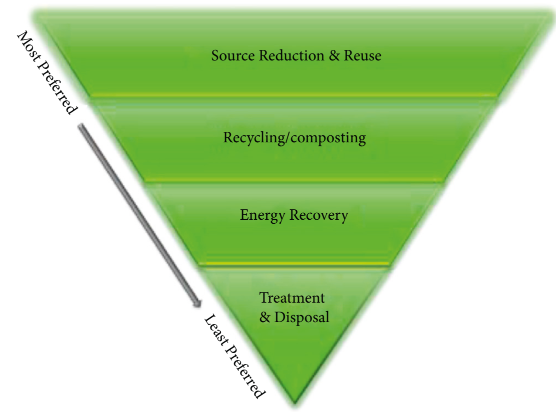

Figure 1: Waste management hierarchy [5].

Worldwide previous estimations related to WTE showed a twofold increase just only within 10 years from 0.68 billion tons/year in 2000 to 1.3 billion tons/year in 2010. Moreover, it is projected to reach 2.2 billion tons per year by 2025 and 4.2 billion tons per year by 2050, which will have huge potential effects on power generation. Thus, WTE is a potentially viable alternative source of energy for the future, since it can cover 10% of the world's annual electricity demand [8].

Another report argues implementing WTE technology to treat potentially 261 million tons of MSW per year by 2022, which would create around 283 tera-watt hours (TWh) of heat and electricity [9]. While solid waste incineration and landfill gas recovery (LFG) systems are the two most often used WTE approaches [10], the most financially viable alternative for the future energy system is combined MSW incineration [11]. For more than a century, several nations, such as Denmark and Sweden, have had well-established energy generating systems based on incineration. According to the statistics, trash incineration systems generate 4.8% of total electricity consumption and 13.7% of total home heat use in Denmark [12]. WTE technologies have received much attention due to significant waste volume reduction along with renewable energy production to meet the present as well as the future energy demands. The global market for these innovations is expanding at a rapid pace, as is the global need for energy and environmental sustainability. In 2013, the WTE market was valued at $25.32 billion USD, with a 5.5% raise over 2012. Thermal energy technologies dominated the market; the market is predicted to be worth approximately 40$US billion by 2023 [13].

There have been a number of studies carried out to state the greater possibility of using WTE. Most of previous works did not introduce a simple and clear step-by-step calculation method for the amount of generated electric power that can be produced for WTE using incineration for quick guide for decision-makers. For example, the work in [14] introduced WTE potential in the Western Province of Saudi Arabia with three scenarios by two different technologies: incineration and refused derived fuel (RDF); it also introduced the

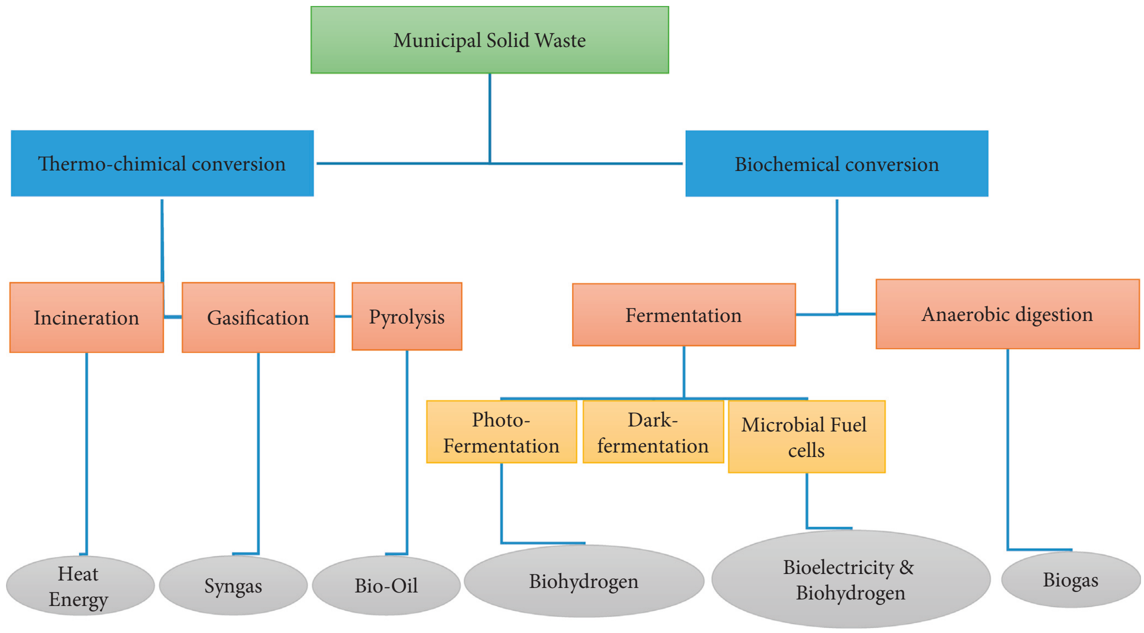

Figure 2: Waste-to-energy technologies [6].

environmental impact of using WTE. In [15], a general short study was conducted to determine the viability of electrical energy generation from the household waste using life cycle assessment (LCA) tool by two scenarios; the models generated for this study did not include the type of technology used in the conversion process but was based on simple basis of using generated gas from the waste to produce electricity. In [16], in a full study for pre-feasibility of a WTE plant, it focused on plant specification and payback; this type of research is the expected future extend work for proposed study. In [17, 18], a general overview of MSW is presented with the feasible waste-to-energy technologies only.

For a research study country, a few studies were carried out to state the greater possibility of using WTE in Egypt. To the authors' knowledge, only three academic research discussed the possibility of WTE technologies. All of them were focused on biochemical conversion for organic/agricultural waste treatment to produce a bioenergy/biogas [19–21].

4. Contribution of This Paper

The main contributions of this paper are summarized as the follows:

(1) This paper proposes an easy, simple, and clear step-by-step calculation method for the amount of generated electric power that can be produced for WTE using incineration for quick guide for decision-makers.

(2) To the authors' knowledge, this is the first work to demonstrate the potential of waste-to-energy conversion in Egypt; it introduces the estimation of amount of electrical power that can be generated by using the WTE technologies by four scenarios including all available possibilities according to Egypt environmental and natural geographical conditions.

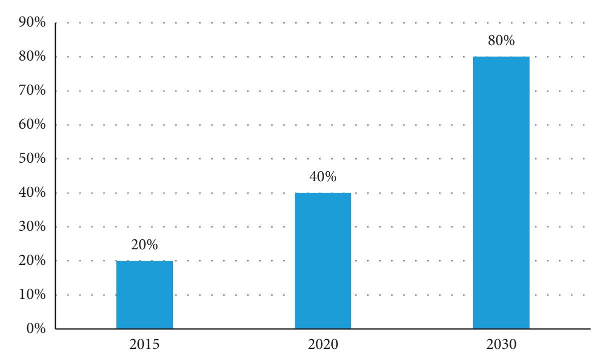

Figure 3: Percentage of solid waste collected and planned to be collected and managed appropriately [22].

(3) Result analysis introduces a plan in three steps to implementation of WTE in Egypt.

5. Solid Waste Management Situation in Egypt

The issue of waste spread is a chronic environmental challenge in the Arab Republic of Egypt. Attention is paid by the State and the Ministry of Environment to this problem. The government has developed a program for developing waste management systems aiming at raising the efficiency of waste collection and transport to 80 percent and recycling efficiency to 25 percent based upon statistics and studies on population numbers and daily waste percentages, which are clearly shown in Figure 3 [22].

The Sustainability Development Strategy and "Egypt's Vision 2030" identified pollution reduction and integrated waste management as a strategic objective to reduce air pollution loads and reduce pollution from untreated wastes with their serious environmental and health impacts while maximizing the utilization of natural resources by exploiting solid waste with a focus on municipal solid waste [23]. Table 1 summarizes Egypt's technical performance.

Figure 4 shows the classification and percentage of waste materials in Egypt, illustrating that 13% plastic, 2% metal, and 4% glass may be recycled. Also, 56% of waste is organic materials plus 10% paper/cardboard which can be used in waste-to-energy conversion.

Table 2 shows the municipal solid waste generated for different governments in Egypt, which shows that Greater Cairo generates 25000 tons of waste daily, which is almost 50% of daily waste generated in Egypt.

Table 1: Egypt technical performance [24].

Population	102.598 million (2021) [25]
MSW generation	21.0 million tons (2010)
Per capita MSW generation	0.7–1.0 kg/day (urban areas) 0.4–0.5 kg/day (rural areas)
MSW generation growth	3.4%
Medical waste generation	28,500 tons/year (2010)
Industrial waste	6.2 MT/year
Hazardous waste	0.2 MT/year
Agricultural waste	23 MT/year
MSW collection coverage	0–35% in rural areas 40–85% in urban areas
MSW final destination	9%: composting 2.5%: recycling 5%: landfilling 83.5%: open dumped

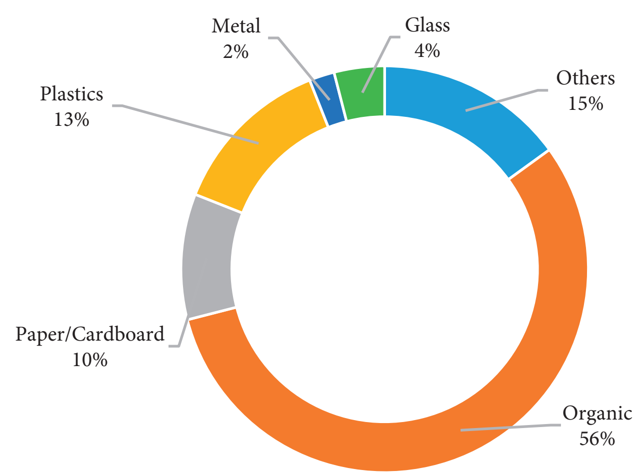

Figure 4: Material composition of Egypt MSW (%) in 2010 [24].

6. Methodology

In this section, a step-by-step full detailed calculation of electric power generated from MSW in Cairo is presented. The calculation process has five main steps as shown in Figure 5.

6.1. Calculation of the Projected MSW Generation in the Period 2010–2031. There are two methods to calculate projected MSW generation in Cairo for the studying period from 2011 to 2031.

6.1.1. First Method. Depending on historical and future population trends in Egypt, 2011–2031 by the Central Agency for Public Mobilization and Statistics (CAPMAS), which are shown in the Population section, assume that per capita municipal solid waste (MSW) generation in 2010 stays the same until 2031 [27].

For projected MSW calculation for Egypt. As mentioned in Section 4, per capita (MSW) generation has two values: 0.4–0.5 (kg/p/d) for rural zones and 0.7–1 for urban zones, assuming average per capita (MSW) generation 0.45 (kg/p/d) for rural zones and 0.85 for urban zones. CAPMAS states in the 2013 population report that in midyear 2012 the total urban population was 35373 (42.9%) and the total rural population was 47177 (57.1%) (OCT. 2021 total population was 102.598 million) [25, 26]. Projected MSW generation in Egypt in two different zones is calculated using

$$P\_MSW\_G = PC\_MSW * ZP, \quad (1)$$

where

P_MSW_G: projected MSW generation

PC_MSW: per capita MSW (Kg/p)/day

ZP: zone population

For projected MSW calculation for Cairo, according to CAPMAS, Cairo city is a purely urban zone and has 11% of Egypt's total population. So, by applying equation (1) and using high per capita (MSW) generation 1 (kg/p/d), as it is urban zones with the highest life expectancy in Egypt, Figure (1) shows projected MSW generation for Egypt (urban and rural zones) and Cairo in the study period 2011–2031 by using the per capita MSW generation value and by using estimated population by CAPMAS. This method gives results lower than that stated in Table 1, which states that all of Egypt (urban and rural zones) in 2010 generated 55250 1000 tons/day and Cairo itself generated 11000 tons/day. On the other hand, this method shows that Egypt in 2011 generated 49590 tons/day and Cairo generated 8775.8 tons/day.

6.1.2. Second Method. Quantity of municipal solid waste (MSW) generated in 2010 (21 million tons) as stated in Egypt Technical Performance assumed to be the base of the study and by using an MSW growth rate of 3.4% the projected MSW generation in the studying period will be calculated. Figure 7 shows the projected MSW generation for the whole of Egypt and Cairo in the studying period 2011–2031 by using an MSW growth rate of 3.4% with the year 2010 as a base. It shows also that the generated MSW will double in 20 years (the studying period) so if the solution does not start today, the problem will become a crisis in the near future.

Figures 6 and 7 show that the projected MSW generation calculated by the 2nd method is higher than those calculated by the 1st method. The 2nd method is more accurate than the 1st method, so in this study generated MSW calculated by the 2nd method will be used and results from the 1st method will not be taken into consideration.

Table 2: Municipal solid waste generated in different governorates [26].

Area	Governorate	Urban (%)	Rural (%)	Generated waste (tons/day)
Greater Cairo	Cairo	100	0	11000
	Giza	60	40	4000
	Qalubya	47	53	3500
	Helwan			4000
	6th October			2500
Delta	Sharkeya	23	77	1800
	Monofeya	20	80	2000
	Damietta	39	61	900
	Gharbeya	31	69	3000
	Kafr Sheikh			2500
	Dakhleya	30	70	4500
	Behyra	24	76	3000
Upper Egypt	Fayoum	22	78	600
	Beni Suef			750
	Menya	18	82	1000
	Assuit	30	70	700
	Sohag	22	78	900
	Qena	20	80	1000
	Luxor	30	70	250
	Aswan			650
	Wadi Gedid	50	50	100
Coastal zone	Alexandria	100	0	3700
	Matrouh	60	40	250
	Port Said	80	20	650
	Suez	100	0	400
	Ismailia	44	56	600
	Red Sea	96	4	450
Sinai	North Sinai	60	40	200
	South Sinai	51	49	350
Total				**55250**

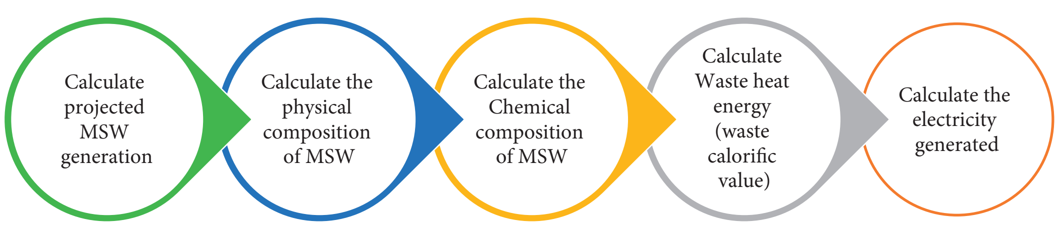

Figure 5: Calculation process of electric power generated from MSW.

Figures 6 and 7 state that Egypt's Governor should handle and manage at least 57000-ton residential MSW every day. In this study, other waste types, industrial waste (6.2 million tons/year) and agricultural waste (23 million tons/year), are not taken into consideration.

In both methods, the material composition percentage of MSW (organic 56%, plastics 13%, paper/cardboard 10%, metal 2%, glass 4%, and others 15%) will also be assumed to be constant over the studying period 2011–2031. This assumption is not fully right because the material composition percentage of MSW for any community depends on its life level and it is not true that Egypt's life level over about 20 years will be constant, but for simplifying study conditions this assumption will be considered. Another assumption will be used in this study; municipal solid waste percentage generated in different Egypt governorates from the total generated MSW will be assumed to be constant from the year 2010 until 2031. As shown in Table 2, in 2010 Cairo generated about 20% of the total MSW generated in Egypt, so if this percentage is still constant for the studying period, the MSW generated in Cairo will be as shown in Figures 6 and 7. Cairo governorate is chosen to be a case study for the following reasons:

(i) As mentioned previously, it produced about 20% of the total MSW generated in Egypt

(ii) It has a very high MSW collection coverage percentage of about 90%

(iii) All areas are urban; any new system can be implemented more easily than in rural areas

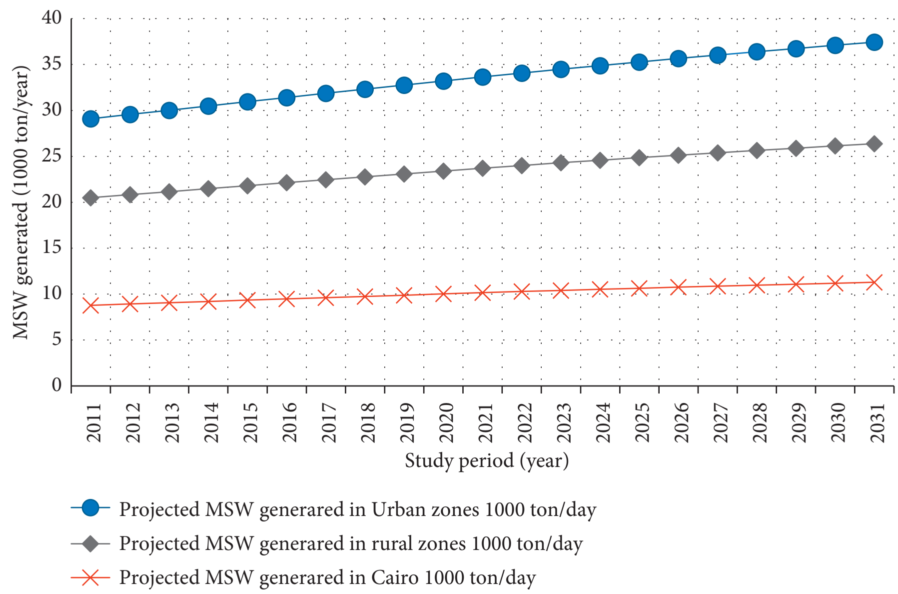

FIGURE 6: Projected MSW generation for Egypt (urban and rural zones) and Cairo in the studying period 2011–2031 by the 1st method.

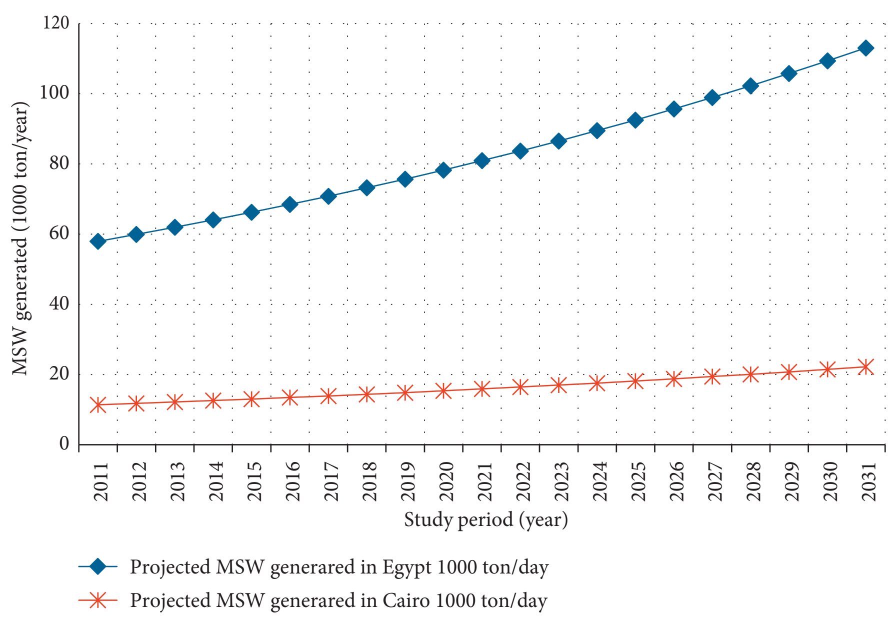

FIGURE 7: Projected MSW generation for Egypt (urban and rural zones) and Cairo in the studying period 2011–2031 by the 2nd method.

6.2. First Scenario: Mass Burn

6.2.1. Calculate the Physical Composition of Solid Waste. Information and data on the physical composition of solid wastes include

(i) Identification of the individual components that make up municipal solid wastes

(ii) Analysis of particle size

(iii) Moisture content

(iv) Density of solid wastes

The waste composition percentage for Cairo is assumed to be like Egypt which is tabulated in Table 1 and Figure 4. First, calculate the total weight or wet weight for each waste component by using waste calculation data for the year 2016, which is tabulated in Table 3. Second, by using typical moisture content (MC) data, the dry mass of each type of waste is calculated according to

$$DW = TW - MC * TW, \quad (2)$$

where

DW: dry weight

TW: total weight

MC: moisture content

Table 3: 2016 Cairo MSW composition: percentage weight, wet weight, and moisture content (MC) % of each waste component.

Material	Waste composition (%)	Total weight (Kg)	Moisture content (MC) %	Dry weight (Kg)
Organic material	56	7528.421819	70	2258.526546
Plastic	13	1747.669351	1	1730.192657
Paper	10	1344.361039	5.5	1270.421182
Glass	4	537.7444156	3	521.6120832
Metals	2	268.8722078	3	260.8060416
Other materials including textiles	15	2016.541559	10	1814.887403
Total		13443.61039		7856.445913

Specific weight is defined as the weight of a material per unit volume (e.g., kg/m^3, lb/ft^3); usually, it refers to uncompacted waste. It varies with geographic location, the season of the year, and the length of time in storage. Table 4 shows typical specific weight values according to the processing method. MSW specific for Egypt is assumed to be taken as 330 kg/m3.

The composition of waste components is critical for recycling and recovery, even more so when mechanical techniques such as trammel screens and magnetic separators are utilized.

Table 4: Typical specific weight values.

Condition	Density (kg/m^3)
Loose MSW, no processing or compaction	90–150
In compaction truck	355–530
Baled MSW	710–825
MSW in a compacted landfill (without cover)	440–740

6.2.2. Identifying the Chemical Makeup of Solid Waste. Chemical information on solid wastes is critical for assessing potential processing and energy recovery alternatives. If solid wastes are to be utilized as fuel, the following four qualities must be recognized:

(i) Proximate analysis:

  (1) Moisture (loss at 105)
  (2) C for 1 h
  (3) Volatile matter (additional loss on ignition at 950°C)
  (4) Ash (residue after burning)
  (5) Fixed carbon (remainder)

(ii) Fusing point of ash

(iii) Ultimate analysis:

  (i) Percent of C (carbon), H (hydrogen), O (oxygen), N (nitrogen), S (sulfur), and ash

(iv) Heating value (energy value)

In the previous Section 6.2.1 dry mass is calculated; then the amount of carbon, hydrogen, oxygen, nitrogen, sulfur, and ash content is calculated for each type of waste using a standard table of ultimate analysis of combustible waste (Table 5 and equation (3)).where

EC: element content

DM: dry mass

SUAMP: standard ultimate analysis mass percent

$$\mathrm{EC} = \frac{DS}{100} * \mathrm{SUAMP}. \tag{3}$$

From Table 3, dry waste weights are 7856445.913 kg, and the total waste weights are 13443610.39 kg. Then, subtract the weight of the dry waste from the total weight of waste to give the weight of the water in the waste.

$$13443610.39 - 7856445.913 = 5587164.47 Kg\mathrm{H2}O. \tag{4}$$

Now to determine how much hydrogen and oxygen in kg there are in the waste, we do this by using

$$\left[\frac{TW}{MWt-W}\right] * MMWt - H, \tag{5}$$

where

TW: total moisture in kg

MWt-W: molecular Wt of water

MWt-H: molecular Wt of hydrogen

$$\left[\frac{5587164.47}{8.165}\right] * 0.907 = 620643.99 Kg\,H,$$
$$\left[\frac{TW}{MWt-W}\right] * MMWt - O, \tag{6}$$

where MWt-O is the molecular Wt of oxygen.

$$\left[\frac{5587164.47}{8.165}\right] * 7.257 = 4965836.19\,\mathrm{Kg\,O}. \tag{7}$$

Now, revised mass is calculated for solid waste, as moisture in solid waste converts into hydrogen and oxygen due to heat in incinerators. The final revised mass of element content of whole Cairo solid waste can be seen in Table 6.

6.2.3. Calculation of Waste Heat Energy (Waste Calorific Value). To calculate heat energy or calorific values (higher heating values HHV) generated by the whole of Cairo city's solid waste, Dulong's formula needs to be applied. Dulong's formula is described in equation (7).

$$\mathrm{HE\,(HHV)} = 337\mathrm{C} + 1428\left(\mathrm{H} - \frac{\mathrm{O}}{8}\right) + 9\mathrm{S}, \tag{8}$$

where

Table 5: Typical percent by weight.

	Percent by weight (dry basis)					
Component	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash
Organic						
Food wastes	48.0	6.4	37.6	2.6	0.4	5.0
Paper	43.5	6.0	44.0	0.3	0.2	6.0
Cardboard	44.0	5.9	44.6	0.3	0.2	6.0
Plastics	60.0	7.2	22.8	—	—	10.0
Textiles	55.0	6.6	31.2	4.6	0.15	2.5
Rubber	78.0	10.0	—	2.0	—	10.0
Leather	60.0	8.0	11.6	10.0	0.4	10.0
Yard wastes	47.8	6.0	38.0	3.4	0.3	4.5
Wood	49.5	6.0	42.7	0.2	0.1	1.5
Inorganic						
Glass	0.5	0.1	0.4	<0.1	—	98.9
Metals	4.5	0.6	4.3	<0.1	—	90.5
Dirt, ash, etc.	26.3	3.0	2.0	0.5	0.2	68.0

Table 6: Revised element content.

Element	Mass w/o water (kg)	Revised Mass w water (kg)	Percent by mass (%)
C (carbon)	3650622.484	3650622.484	27.85
H (hydrogen)	465170.2949	1085814.285	8.28
O (oxygen)	1865341.273	6831177.463	52.12
N (nitrogen)	125850.7454	125850.7454	0.96
S (sulfur)	15749.18957	15749.18957	0.12
Ash	1396652.65	1396652.65	10.66
Total	7519386.637	13105866.82	

HE = heat energy (kJ/kg)

C = carbon (%)

H = hydrogen (%)

O = oxygen (%)

S = sulfur (%)

N = nitrogen (%)

Putting percent by mass value from Table 6 into Dulong's formula, HHV generated by Cairo city's total waste is obtained:

$$\textbf{Cairo waste}\,(\textbf{HHV}) = 337X27.85 + 1428\left(8.28 - \frac{52.12}{8}\right) + 9X0.12 = 11906.95\left(\frac{kJ}{kg}\right). \tag{9}$$

The calorific values were again calculated by using the Dulong equation, considering nitrogen in

$$\text{HE}\,(\text{HHV}) = 337\text{C} + 1419\,(\text{H} - 0.125\text{O}) + 93\text{S} + 23\text{N}. \tag{10}$$

$$\textbf{Cairo waste}\,(\text{HHV}) = 337X27.85 + 1419\,(8.28 - 0.125X52.12) + 93X0.12 + 23X0.96 = 11923.225\left(\frac{kJ}{kg}\right). \tag{11}$$

The difference between calculations using equations (8) and (10) is very small. So, less HHV value will be considered.

Lower heat value (kJ/kg) (LHV) is the net energy released on combustion.

$$LHV = HHV - (2.766XW), \tag{12}$$

where

LHV (KJ/KG): lower heat value.

W = moisture content

2.766 kJ/kg = coefficient of heat requirement for evaporation.

$$\textbf{Cairo LHV} = 11906.95 - (2.766X41.56) = 11809.645\left(\frac{KJ}{Kg}\right). \tag{13}$$

In the next sections, the lower heat value (LHV) for Cairo city's waste will be used, which is the net heat energy generated = 11809.645 kJ/kg.

6.2.4. Calculation of Electricity Generated. To figure out how much power a building needs, many processes must be taken. The heat created is first utilized to compute steam energy, which accounts for 70% of heat energy. A net electric power produced by solid waste is estimated after subtracting station service allowance and heat losses from the steam energy calculation. All of this may be seen in the gallery:

$$\text{SEA} = 70\%\text{of } HE, \quad (14)$$

where SEA is the steam energy available.

Now, put the net heat energy value (LHV) from the previous section.

$$\text{SEA} = 0.70X11809.645 = 8266.752. \quad (15)$$

The turbines are driven by the steam energy calculated above; these turbines are linked to generators that generate electricity. The heat rate is the amount of energy needed to generate one unit of electricity (kWh).

$$1KW = 3600\frac{KJ}{h}. \quad (16)$$

According to the preceding calculation, assuming energy conversion is 100% efficient, 3600 kJ of energy is needed to generate one unit of electricity. However, no energy conversion is completely efficient; in fact, a conversion efficiency of 31.6% is necessary for a heat input of 3600. 31.6% = 11395 kJ/kWh in a power plant. Thus, 11395 kJ of steam energy is needed to generate 1 kWh of electrical energy.

$$1KW = 11395\frac{KJ}{KWh}. \quad (17)$$

Therefore,

$$\text{EPG} = \text{SE} \div 11395\frac{KJ}{KWh}, \quad (18)$$

where

SE: steam energy

EPG: electrical power generation

$$EPG = 8266.752 \div 11395 = 0.7255\frac{KWh}{Kg}. \quad (19)$$

Total weight of solid waste collected from Cairo city = 10704.24 tons/day.

$$\textbf{Total EPG} = (0.7255X13443610.39) = 9753339.3379\frac{KWh}{\text{day}}. \quad (20)$$

Now,

$$\text{SSA} = 6\% \text{ of total } EPG, \quad (21)$$

where SSA is the station service allowance.

$$\text{SSA} = (0.06X9753339.3379) = 585200.36\frac{KWh}{\text{day}}, \quad (22)$$
$$\text{UAHL} = 5\%\text{of total } EPG,$$

where UAHL is the unaccounted heat loss.

$$\text{UAHL} = (0.05X9753339.34) = 487666.97\frac{KWh}{\text{day}},$$
$$\begin{aligned}\text{Net EPG} &= \text{EPG} - (\text{SSA} + \text{UAHL}),\\ \text{Net EPG} &= 9753339.3379 - (585200.36 + 487666.97)\\ &= 8680472.0\frac{KWh}{\text{day}} = 8680.47\frac{MWh}{\text{day}}.\end{aligned} \quad (23)$$

The amount of daily energy created is 24 hours long; thus utilizing this net electric power is computed on an hour-by-hour basis.

$$\begin{aligned}Net\ EPG &= 8680.47\frac{MWh}{24h},\\ Net\ EPG &= 361.686MW \approx 362MW.\end{aligned} \quad (24)$$

Thus, it is possible to generate 8680.47 MWh/day by using WTE to incinerate Cairo's 13443.61 tons of solid trash each day, or 362 MW. Figure 8 shows the results of applying all of the processes for calculating the amount of power generated in 2016 throughout the whole period of research from 2011 to 2031.

Assume that all Egypt MSW can be fully utilized for WTE production. The result leads to that Egypt has the potential to generate 1842 MW from residential waste only in the year 2016. This is not applicable because the MSW management system which is essential for WTE implementation does not cover all of Egypt. For a more realistic assumption, assume that 50% of Egypt's MSW can be fully utilized for WTE production. The result leads to only 50% of Egypt's MSW having the potential of generating 921 MW from residential waste only in the year 2016. As shown in Figure 9, this power increases with waste increasing which is naturally according to population growth and increase life living standard as mentioned in the previous sections.

6.3. Second Scenario: Mass Burn with Recycling. Sustainable waste management necessitates that all recyclable and compostable products be separated from the MSW stream as much as feasible. So that the expense of sorting recyclable materials may be paid equally by generators (in terms of labour hours) and municipalities, these materials should be separated at the source, i.e., in homes, companies, and institutions (in terms of separate collection vehicles and processing systems).

A landfill will be created if there is no need for source-separated waste. More than 80% of the US plastic garbage created is landfilled, despite significant efforts by the petrochemical industry and many towns to promote plastic recycling. This is an example of the lack of markets for some commodities. According to critics, waste-to-energy (WTE) discourages people from recycling. Those willing to invest time and resources in recycling often find that there are material and economic limits to how much of the MSW component may be recycled. Once they have exhausted all other options, they turn to WTE's energy recovery to further reduce their reliance on garbage. The Earth Engineering Center's Sustainable Waste Management Ladder demonstrates this impact (Figure 10). Recycling and waste-to-energy programs have been the key to reducing or eliminating landfilling in many countries.

As shown in Figure 9, the highest recycling percentage was in Germany with about 50% of its generated MSW. In this study, one recycling percentage will use 25% of the EGYPT target in 2030. Some researchers [12] assumed a 100% recycling percentage, it is not applicable for the high-

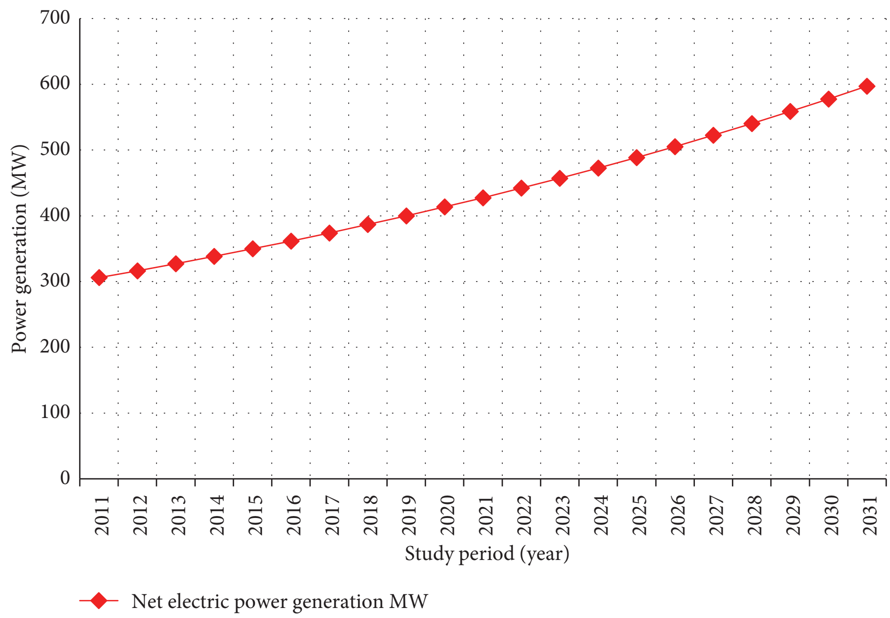

FIGURE 8: Net power generation potential (MW) for Cairo city for years 2011–2031 without recycling.

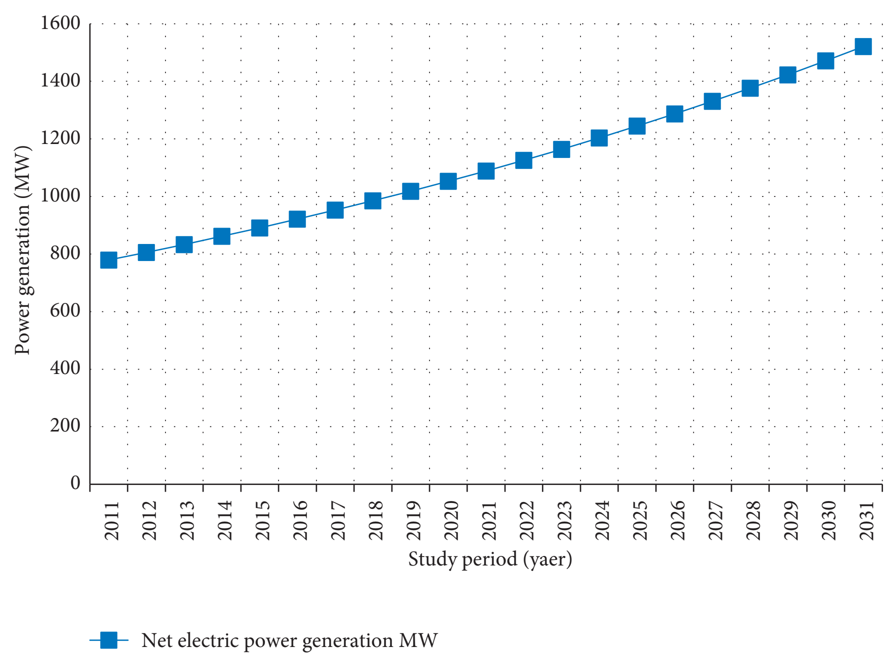

FIGURE 9: Net power generation potential (MW) for 50% of Egypt's MSW for the years 2011–2031.

income country as mentioned above, and it is impossible for a mid-income country like Egypt which has not started any steps toward an actual waste management system.

Before starting the calculation, recyclable materials that are already used in Egypt are stated as follows:

(i) Paper: (newspaper-white paper-mixed cardboard)

(ii) Plastic: (mixed plastic-polyethylene plastic (high and low density) polyethylene plastic injection-PET bottles

(iii) Metal: (copper-aluminium-tin cans-iron)

(iv) Glass

(v) Other: textiles-bones

The only waste component that is not recyclable is food. The first calculation of the new projected MSW is generated, by applying recycling percentages on the projected MSW generated for Cairo for the studying period that is calculated in Section 6.1. Figure 11 shows the new projected MSW generated for Cairo with a recycling percentage value of 25%.

Calculation of the total weight or wet weight for each waste component is by using waste calculation data for the year 2016. Then, by using typical moisture content (MC)

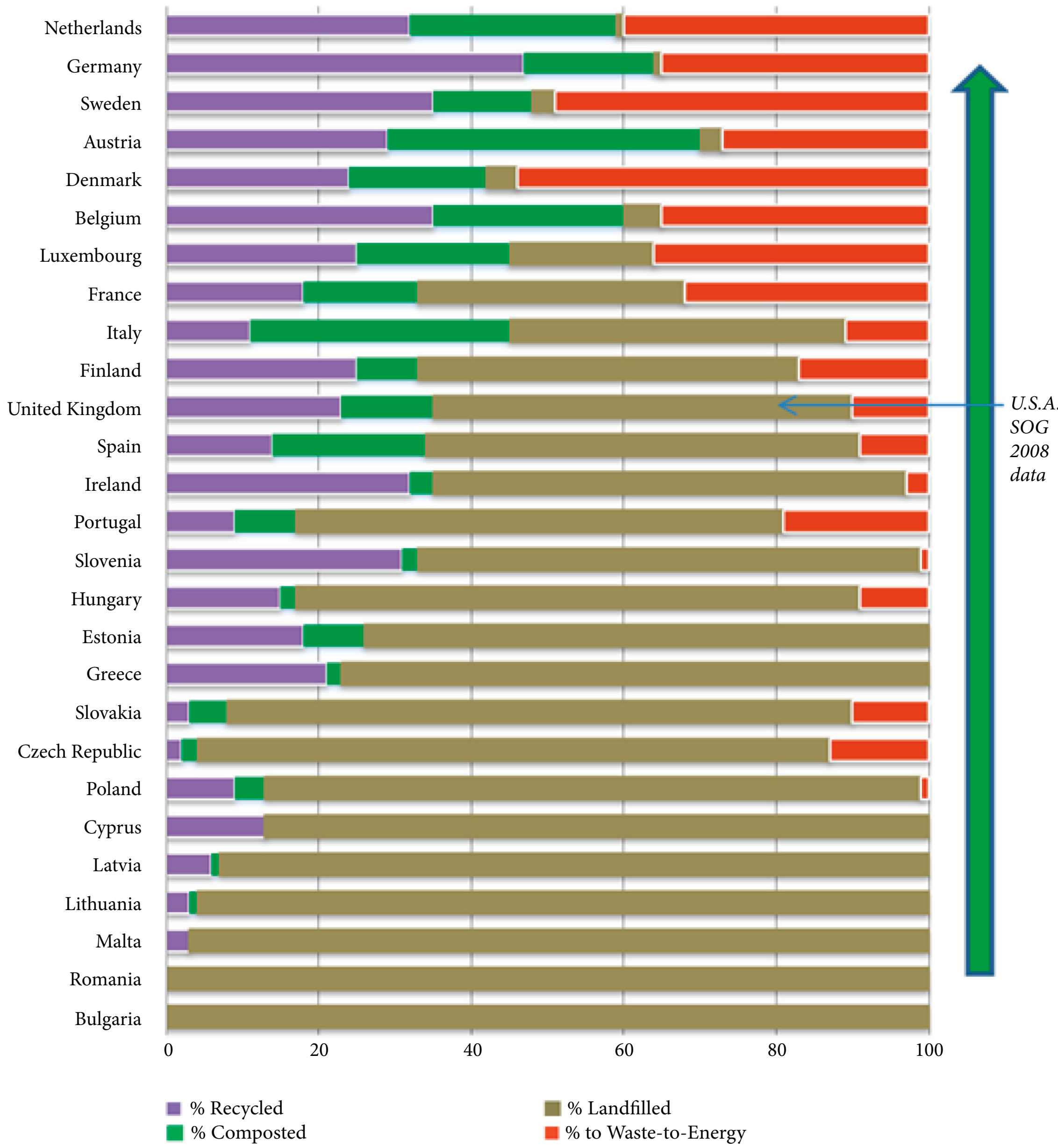

FIGURE 10: The sustainable waste management ladder produced by the Earth Engineering Center, Columbia University (based on Eurostat 2008 data) [4].

data, the dry mass of each type of waste is calculated according to equation (1) for a 25% recycling value; see Table 7.

To determine the chemical composition of solid wastes, repeat the same procedure as described in previous Section 6.2.2.

For recycling purposes, the mass of solid waste has been recalculated. Table 8 shows the final corrected mass of element content for all of Cairo's solid waste after excluding 25% of recyclable material.

For Cairo, the net energy released during combustion may be estimated by repeating Section 6.2.3 and using higher heating values (HHV) and lower heating values (LHV) as in the preceding section.

For 25% recycling,

$$\text{HHV} = 10904.58\ \text{KJ/Kg}, \qquad \text{LHV} = 10774.49\ \text{KJ/Kg}. \tag{25}$$

To determine the amount of energy recovered from Cairo's municipal solid waste (MSW) with a 25% recycling rate, we may use the same methodology described in Section 6.2.4.

$$\begin{gathered}\text{SEA} = 0.70X10774.49 = 7542.143\frac{KJ}{Kg},\\ \text{EPG} = 7542.143 \div 11395 = 0.66\frac{KWh}{Kg},\\ \text{Net EPG} = 7896.77\frac{MWh}{24h},\\ \textbf{Net EPG} = 329.032\textbf{MW} \approx 329\textbf{MW}.\end{gathered} \tag{26}$$

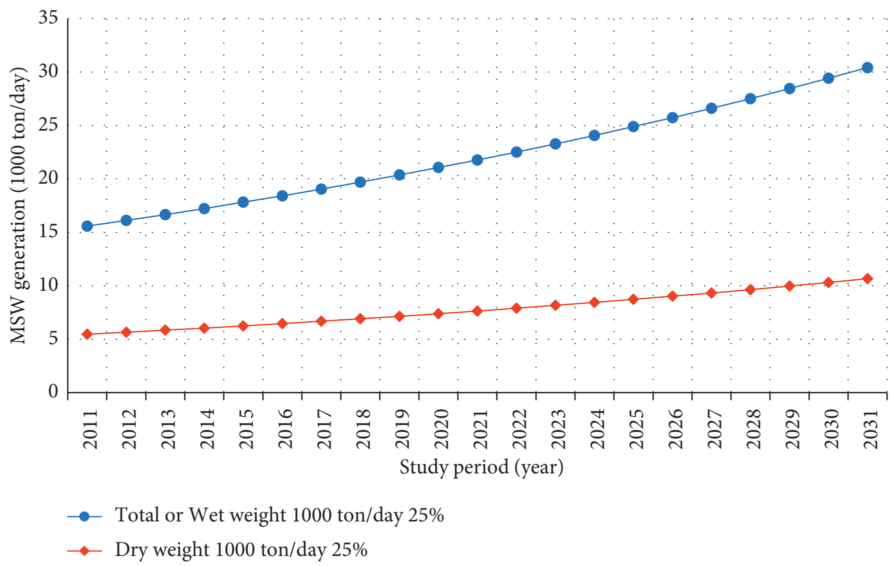

Figure 11: Projected MSW generation for Cairo (wet and dry) for 25% recycling percentage in the studying period 2011–2031.

Table 7: 2016 Cairo MSW composition: percentage weight, wet weight, and moisture content (MC) % of each waste component for 25% recycling.

Material	Waste composition (%)	Wet weight (kg)	Moisture content (MC) %	Dry weight (kg)
Organic material	62.92	7528421.819	70	2258526.546
Plastic	10.96	1310752.013	1	1297644.493
Paper	6.41	1008270.779	5.5	952815.8865
Glass	3.37	403308.3117	3	391209.0624
Metals	1.69	201654.1559	3	195604.5312
Other materials	12.64	1512406.169	10	1361165.552
Total		11964813.25		6456966.071

Table 8: Revised element content for 25% recycling.

Element	Mass w/o water (kg)	Revised Mass w water (kg)	Percent by mass (%)
C (carbon)	3008.990049	3008.990049	25.69
H (hydrogen)	385.0141459	996.8472616	8.51
O (oxygen)	1611.30745	6506.646943	55.56
N (nitrogen)	109.0684816	109.0684816	0.93
S (sulfur)	14.07041873	14.07041873	0.12
Ash	1075.72107	1075.72107	9.19
Total	**6204.171614**	**11711.34422**	

Figure 12 shows the potential of electrical power generated from Cairo MSW by using WTE facility with 25% recycling of recyclable material.

6.4. Third Scenario: Mass Burn excluding Organic Material. In this scenario, a wider vision of the environmental and natural geographical conditions of Egypt is introduced. Egypt's economy relies heavily on agriculture; Egypt has 9.4 million feddans [25] (approximately 40,000 square kilometers) of agricultural lands which need a regular suppling of compost/fertilizers. Organic waste is a rich source of compost/fertilizers; organic waste material forms about 56% of total Egypt MSW. Elfeki 2016 [20] demonstrated that applying biological treatment technologies to Egyptian municipal organic solid waste leads to the production of an amount of around 11.2×106–12.8×106 tons/year of compost and this amount of compost increases the compost production in Egypt with around 54% and contributes in compensating the shortage of compost demand in Egypt with an annual increase by the increase of waste generation.

For the same reasons presented in the previous section for the recycling percentage, using 50% of organic material in biological treatment technologies is a future optimistic target.

Calculation of the total weight or wet weight for each waste component is by using waste calculation data for the year 2016. Then, by using typical moisture content (MC) data, and dry mass of each type of waste is calculated according to equation (1) excluding 50% of organic material; see Table 9.

To determine the chemical composition of solid wastes, repeat the previous section 6.2.2. Table 10 shows the final

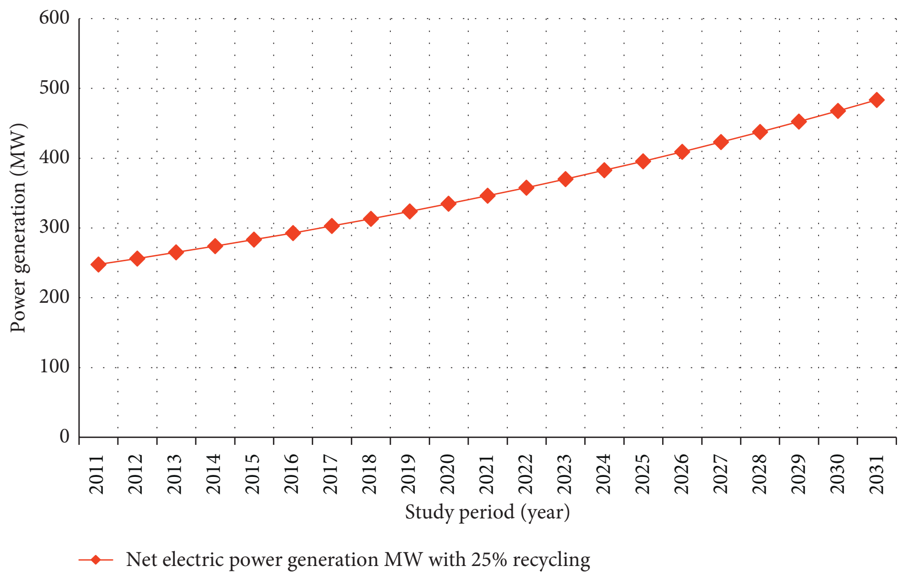

Figure 12: Net power generation potential (MW) for Cairo city for years 2011–2031 with 25% recycling.

Table 9: 2016 Cairo MSW composition: percentage weight, wet weight, and moisture content (MC) % of each waste component excluding 50% of organic material.

Material	Waste composition (%)	Total weight (kg)	Moisture content (MC) %	Dry weight (kg)
Organic material	38.89	3764210.91	70	1129263.273
Plastic	18.06	1747669.351	1	1730192.657
Paper	13.89	1344361.039	5.5	1270421.182
Glass	5.56	537744.4156	3	521612.0832
Metals	2.78	268872.2078	3	260806.0416
Other materials including textiles	20.83	2016541.559	10	1814887.403
Total		9679399.482		6727182.64

Table 10: Revised element content excluding 50% of organic material.

Element	Mass w/o water (Kg)	Revised Mass w water (kg)	Percent by mass (%)
C (carbon)	3008.990	3108.576	33.56
H (hydrogen)	385.014	720.841	7.78
O (oxygen)	1611.307	4235.219	45.72
N (nitrogen)	109.068	109.068	1.18
S (sulfur)	14.070	14.070	0.15
Ash	1075.721	1075.721	11.61
Total	6204.172	9263.496	

corrected mass of element content for all of Cairo's solid waste after excluding 50% of organic material.

For Cairo, the net energy released during combustion may be estimated by repeating Section 5.2.3 and using higher heating values (HHV) and lower heating values (LHV) as in the preceding section.

For excluding 50% of organic material,

$$\begin{aligned} \text{HHV} &= 14270.49\ \text{KJ/Kg}, \\ \text{LHV} &= 14182.34\ \text{KJ/Kg}. \end{aligned} \tag{27}$$

For Cairo MSW with excluding 50% of organic material, repeat Section 5.2.4 to compute the power produced.

For excluding 50% of organic material,

$$\begin{aligned} \text{SEA} &= 0.70X14182.34 = 9927.64\frac{KJ}{Kg}, \\ \text{EPG} &= 9927.64 \div 11395 = 0.87\frac{KWh}{Kg}, \\ \text{Net EPG} &= 7494.76\frac{MWh}{24h}, \\ \textbf{Net EPG} &= 312.3\textbf{MW} \approx 312\textbf{MW}. \end{aligned} \tag{28}$$

Figure 13 shows the potential of electrical power generated from Cairo MSW by using WTE facility after

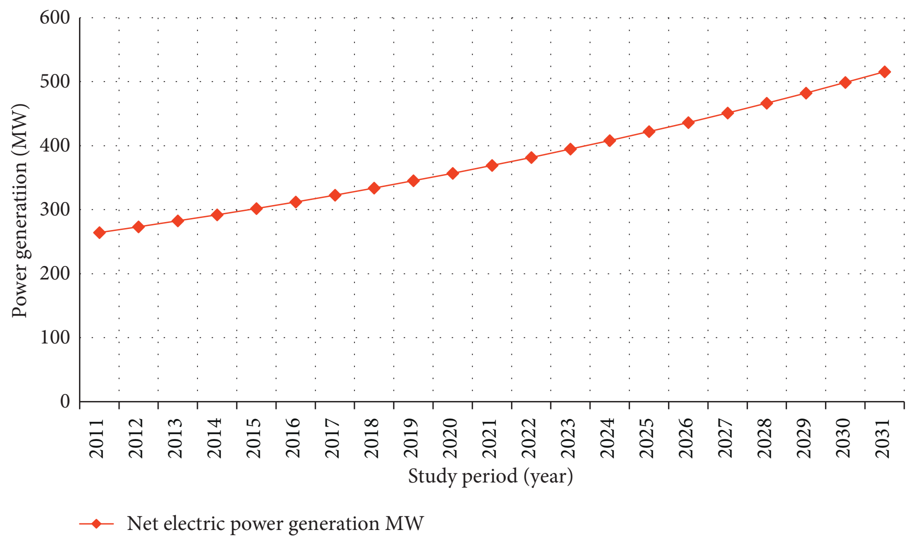

Figure 13: Net power generation potential (MW) for Cairo city for years 2011–2031 excluding 50% of organic material and without recycling.

Table 11: 2016 Cairo MSW composition: percentage weight, wet weight, and moisture content (MC) % of each waste component excluding 50% of organic material and 25% recycling.

Material	Waste composition (%)	Total weight (kg)	Moisture content (MC) %	Dry weight (kg)
Organic material	45.90	3764210.91	70	1129263.273
Plastic	15.98	1310752.013	1	1297644.493
Paper	12.30	1008270.779	5.5	952815.8865
Glass	4.92	403308.3117	3	391209.0624
Metals	2.46	201654.1559	3	195604.5312
Other materials including textiles	18.44	1512406.169	10	1361165.552
Total		8200602.339		5327702.798

Table 12: Revised element content excluding 50% of organic material and 25% recycling.

Element	Mass w/o water (kg)	Revised Mass w water (kg)	Percent by mass (%)
C (carbon)	3008.990	2466.944	29.15
H (hydrogen)	385.014	631.874	7.47
O (oxygen)	1611.307	4164.722	49.21
N (nitrogen)	109.068	109.068	1.29
S (sulfur)	14.070	14.070	0.17
Ash	1075.721	1075.721	12.71
Total	6204.172	8462.400	

excluding 50% of organic material for the production of compost by biological treatment.

6.5. Fourth Scenario (Optimal Scenario): Mass Burn excluding Organic Material and with Recycling. The optimal future target scenario is a fully integrated scenario that includes material recycling and biological treatment technologies for organic solid waste; it is a combination of the second and third scenarios.

Calculation of the total weight or wet weight for each waste component is by using waste calculation data for the year 2016. Then, by using typical moisture content (MC) data, the dry mass of each type of waste is calculated according to equation (1) excluding 50% of organic material and 25% recycling; see Table 11.

To determine the chemical composition of solid wastes, repeat Section 5.2.2.

Table 12 shows the final corrected mass of element content for all of Cairo's solid waste after excluding 50% of organic material and 25% of recyclable material.

For Cairo, the net energy released during combustion may be estimated by repeating Section 5.2.3 and using higher heating values (HHV) and lower heating values (LHV) as in the preceding section.

For excluding 50% of organic material and 25% recycling,

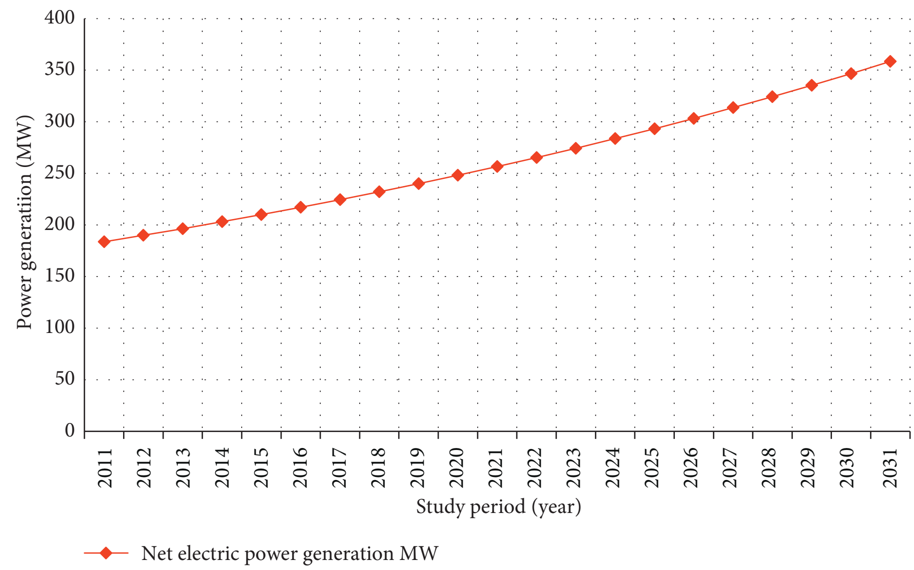

Figure 14: Net power generation potential (MW) for Cairo city for years 2011–2031 excluding 50% of organic material and with 25% recycling.

Table 13: The year 2031 estimated power generation in Cairo with different scenarios.

Net electric power generation MW without recycling	Net electric power generation MW excluding 50% of organic materials	Net electric power generation MW with 25% recycling	Net electric power generation MW excluding 50% of organic material and with 25% recycling
597	516	484	359

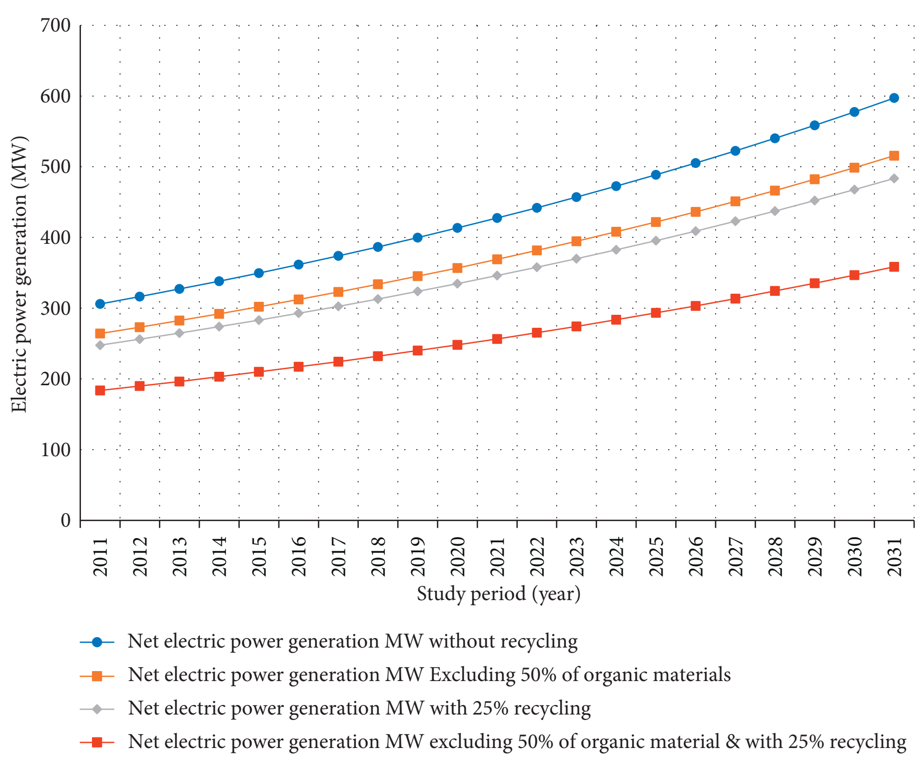

Figure 15: Net power generation potential (MW) for Cairo city by using WTE facility with four scenarios for the years 2011–2031.

$$\text{HHV} = 11713.64\,\text{KJ/Kg},$$
$$\text{LHV} = 11619.74\,\text{KJ/Kg}. \tag{29}$$

For Cairo MSW excluding 50% of organic material and 25% recycling, repeat section 5.2.4 to compute the power produced.

For excluding 50% of organic material and 25% recycling,

$$\begin{aligned}
\text{SEA} &= 0.70X11619.74 = 8133.818\frac{KJ}{Kg},\\
\text{EPG} &= 8133.818 \div 11395 = 0.714\frac{KWh}{Kg},\\
\text{Net EPG} &= 5211.155\frac{MWh}{24h},\\
\text{Net EPG} &= 217.13MW \approx 217MW.
\end{aligned} \tag{30}$$

Figure 14 shows the potential of electrical power generated from Cairo MSW by using WTE facility after excluding 50% of organic material for the production of compost by biological treatment and excluding 25% for recycling of recyclable material.

7. Results Analysis

Thus far, the paper formulated the problem of MSW in Egypt based on the previous information and data. The problem is that the annual growth of the population leads to the growth of solid waste generation and consequently the MSW. Available data have been processed to show the decision-makers in Egypt the amount of electrical power that can be generated by using the WTE options to manage the MSW in Egypt.

This paper introduced a step-by-step calculation for the electrical power that can be generated from Cairo MSW. Four scenarios are presented, and they may be used as an implementation plan of WTE technologies in Egypt in three steps (Table 13):

1st step (first scenario) is to apply the mass burn without any waste processing, this step will help to control the amount of MSW and demonstrate the benefits of using WTE systems.

2nd step (second and third scenarios) is to start applying waste processing (excluding organic material for biological treatment to produce compost and recycling) with mass burn; this step will be divided internally into many stages according to MSW processing implementations.

3rd step (optimal future target) is the required target, the future target is excluding 50% of organic material and 25% recycling, but it should be continually updated.

Figure 15 shows the potential of electrical power generated from Cairo MSW by using WTE facility for the four scenarios presented in the paper during the studying period from 2011 to 2031.

8. Conclusion

The issue of waste spread is a chronic environmental challenge in the Arab Republic of Egypt. It is estimated that 40% of the total waste generated is left uncollected and that only a fraction of this collected waste is treated and disposed of in facilities with a generally acceptable level of environmental control. The remainder is dumped on open land and along with watercourses, roads, railways etc. without any environmental controls.

Unplanned waste dumping contributes to the contamination of the surface and ground waters, the spread of disease, and the degradation of the landscape. This situation is very harmful in a general way to the economic development of the country. A study by the World Bank (2019) has assessed that the estimated cost of health effects due to air and water pollution was equivalent to 2.5% of Egypt's GDP in 2016/17 [28].

This research aims to assess the potential contribution of the WTE facility to meet electricity demand in Cairo City, which is the EGYPT capital, and the biggest city in population as a sample, and then apply the results to all of Egypt and to provide an alternative solution to landfills. The analyses were completed for CAIRO with a current total population of about 10 million. The results show that, by the year 2031 and according to the lowest scenario, it has the potential to produce about 359 MW of electricity based on the mass burn with excluding 50% of organic material and with 25% recycling.

Data Availability

Data are available upon request via the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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