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Research article

Economic and environmental assessment of electricity generation using biogas and heat energy from municipal solid waste: A case study of Lesotho

Tsepo Sechoala[1],*, Olawale Popoola[2],* and Temitope Ayodele[3]

[1] Electrical Engineering Department, Tshwane University of Technology, Pretoria 0183, South Africa
[2] Centre for Energy and Electric Power, Tshwane University of Technology, Pretoria 0183, South Africa
[3] Department of Electrical Engineering, University of Ibadan, Ibadan 200132, Nigeria

* **Correspondence:** Email: sechoala6@gmail.com, popoolao@tut.ac.za; Tel: +266 58587747/+2776 3831921.

Abstract: This study examined the potential of electricity generation from biogas and heat energy arising from municipal solid waste (MSW) collected from the year 2021 to 2045 using anaerobic digestion (AD) and incineration (INC) technologies. The goal of this paper is to evaluate the economic and environmental benefits of implementing the aforementioned technologies in Lesotho. The environmental impact was assessed by using the life cycle assessment strategy based on global warming potential for three scenarios, while the economic assessment was carried out by using the net present value (NPV), levelized cost of energy (LCOE) and total life cycle cost. The key findings show that, over 25 years (2021–2045), MSW generation will range from 185.855 to 513.587 kilotons. The methane yield for the duration of the project for AD technology is 44.67–126.56 thousand cubic meters per year. Moreover, the electricity generation will range from 0.336–0.887 GWh for AD technology and 17.15–45.34 GWh for INC technology. Economically, the results demonstrated that the two waste-to-energy technologies are viable, as evidenced by their positive NPV. The NPV for AD was about USD 0.514 million, and that for INC technology was USD 339.65 million. AD and INC have LCOEs of 0.029 and 0.0023 USD/kWh, respectively. The findings demonstrate that AD can minimize the potential for global warming by 95%, signifying a huge environmental advantage. This paper serves to provide the government, as well as the investors, with current and trustworthy information on waste-to-energy technologies in terms of costs, execution and worldwide effect, which could aid optimal decision-making in waste-to-energy projects in Lesotho.

Keywords: anaerobic digestion; biogas; heat energy; incineration technology; Lesotho

1. Introduction

Increasing population growth, economic improvement and industrialization in developing nations account for a portion of the accelerating rate of municipal solid waste (MSW) production and rising energy demand. Studies have demonstrated that, because there is no sustainable MSW management in these nations, most of the MSW is not thrown away hygienically. It is also documented that, in the last 20 years, most developing African countries have been struggling with the management of waste in general [1,2], and the collection efficiency of MSW is below 50% [3]. In countries like Lesotho, sustainable MSW administration is a fundamental pathway for an economical pollution-free environment [4]. Numerous studies have found that the majority of MSW in these nations is organic [5,6], which results in significant emissions of greenhouse gases (GHGs) that have detrimental effects on both human health and the environment [7]. Methane (CH_4) and carbon dioxide (CO_2) gases make up the majority of GHG emissions. It was generally believed globally that, by going entirely green in terms of creating power and producing transportation fuels, environmental degradation could be avoided and the entire world would be safer [8]. Methane (CH_4) is one of the main types of GHGs that makes up 50–55% of landfill gas (LFG) and has a 25 times greater global warming potential (GWP) than carbon dioxide (CO_2) [9,10]. Methane is produced by the organic portion of MSW that goes through anaerobic biodegradation of MSW in landfills. The most common way of disposing of trash in these poor nations is land filling. In Lesotho, all of the MSW is landfilled with no LFG being recovered for use. Using waste-to-energy (WtE) technology to recover energy from the disposed solid waste is one method of managing MSW. Based on the composition of Lesotho MSW, Sechoala et al. claim that LFG to energy, anaerobic digestion (AD) and incineration (INC) technologies are the most appropriate types of energy recovery for the country [4,11,12]. According to Cudjoe and Acquah [13], INC technology has the capability of reducing the mass of MSW that was supposed to be landfilled by 70% to 90%. The air pollution control of INC technology is considered to be safer and more efficient; apart from avoiding methane emissions, it also reduces water and soil erosion [14]. As a result, there are about 1179 MSW incineration plants around the world, and this shows that many countries have opted for INC technology. In 2015, China incinerated around 26.16 million tons of MSW through 220 incinerators [15].

It is affirmed that Denmark and Japan incinerate more than 65% of their MSW [16]. INC technology is also used in Africa, mostly without the intention of harnessing electricity generation, as it is purposed to destroy inert hazardous and medical waste [12]. However, if not practiced appropriately, INC can be very harmful to the environment through direct emissions that result from the combustion. Consequently, it is essential to invest in flue gas cleaning technology that helps to reduce the amount of pollutants emitted into the atmosphere. In contrast, another proposed method is AD technology, which is among the most widely utilized energy recovery technologies in the world [17]. AD technology is used to treat a variety of organic materials, such as food scraps, agricultural waste, livestock manure, municipal waste and wastewater [18]. It is the decomposition of solid waste by microorganisms in an oxygen-free framework, which results in the emission of biogas. AD technology has the ability to harvest high-quality biogas and inoculants for agricultural reasons. AD has gained more popularity in the western world, with over 17,000 plants as recorded in 2016 [19]. It also reduces bad smells, destroys pathogens and produces a raw material that can be processed further for agricultural purposes. Even though the viability of AD has been proven in countries, it still faces the obstacles of high solid content and delayed biodegradability [20].

Like most developing countries, Lesotho faces the pressing issue of fast-growing MSW generation and insufficient electricity [6,11]. It is documented that African countries lose 1–5% of their gross domestic product (GDP) due to insufficiency of the electricity supply [12]. On the other hand, there are several studies which articulated the management of MSW in the capital city (Maseru), and WtE technology in selected districts [4,5,11,21–23]. Mvuma addressed the economic impact of waste in least developing countries [4], using Lesotho as a case study, and Hapazari looked into the generation of waste and its management in relation to producing clay brick [21]. The environmental hazard posed by GHG emissions will be eliminated, and monetary gain can be made by trading electricity with nearby areas due to the application of AD and INC WtE technologies [24]. Similarly, Taele [25] discussed the potential of renewable energy technologies for Lesotho's rural development, and it was found that biomass and biogas are two potential technologies that could be used to produce energy.

To prevent initiatives from failing financially, it is crucial to evaluate their economic viability before implementation of such a project. Landfilling is alleged to be the most economical way to dispose of MSW in poor nations [25,26]. Although these WtE technology techniques are thought to be cost-effective, they are the cause of land loss and have a negative effect on the environment [27]. Thus, the following are the study's goals:

- To assess the viability of deploying AD and INC technologies for MSW-based electricity generation in Lesotho's industrialized districts.
- To detect and assess any potential environmental effects of the application of the two WtE technologies outlined above.

The available literature data were used to calculate MSW generation, potential methane emissions and the amount of power that can be produced by using collected methane. Additionally, the study assesses the potential for global warming and acidification, as well as potential economic viability from the dumped MSW in Lesotho. The study will bridge the gap between Lesotho's inadequate electricity supply and environmental sustainability while also supplying governments and investors with scientific data that will help in decision-making. To the best of our knowledge, no comparable research under energy recovery from MSW has been undertaken in Lesotho to date.

2. Materials and methods

2.1. Area of study and framework

Concurring with the Bureau of Statistics (BoS) Lesotho, 65% of Lesotho's population resides in urban areas [28]. This is probable because industrialization and service accessibility are more prominent in urban regions. This study focuses on the region of Lesotho's Lowlands, which consists of 10 districts, separated into four distinct ecological zones. The districts of focus include Mafeteng, Maseru, Berea and Leribe. In terms of occupancy, Maseru is the most populated one, followed by Leribe, Berea and Mafeteng.

The study's structure and the method of harvesting MSW to generate power are depicted in Figure 1. The investigation involves both thermochemical and biochemical processes. MSW is the input to this structure, the WtE technologies (AD and INC) are the process and the biogas and heat energy are the outputs. Each product is utilized to produce electricity via the corresponding engine.

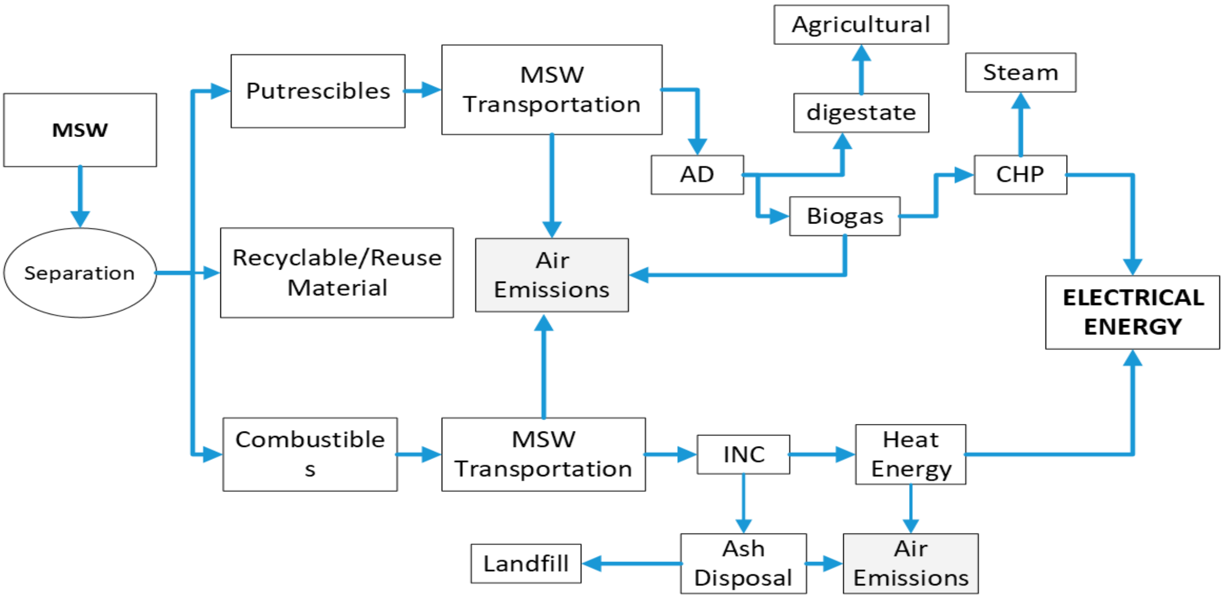

Figure 1. Simplified WtE technology block diagram for AD and INC technologies.

2.2. Projection of population and generation of MSW

According to Alao et al., population growth and GDP have a direct impact on the production of MSW [29]. In determining the population of Lesotho, the policy stipulates that the census must be conducted every 10 years. However, as a developing nation with a largely uneducated populace, there is no policy as to restricting or controlling the population growth rate in Lesotho. Therefore, it is beyond the scope of this study to include any policy regarding the population growth rate/factor. In this study, the Lesotho BoS database was consulted to extrapolate the population from 2020 to 2045.

According to the population settlement, 65% of Lesotho's population resides in urban areas [28]. Figure 2 displays the population growth of Lesotho; the method of projecting the population is used to determine the annual population as follows:

$$P_{tot} = P_{base}\left(1 + P_g\right)^t \quad (1)$$

P_{base} represents the population's reference point, P_g reflects the population increase and t is the time of interest for the project.

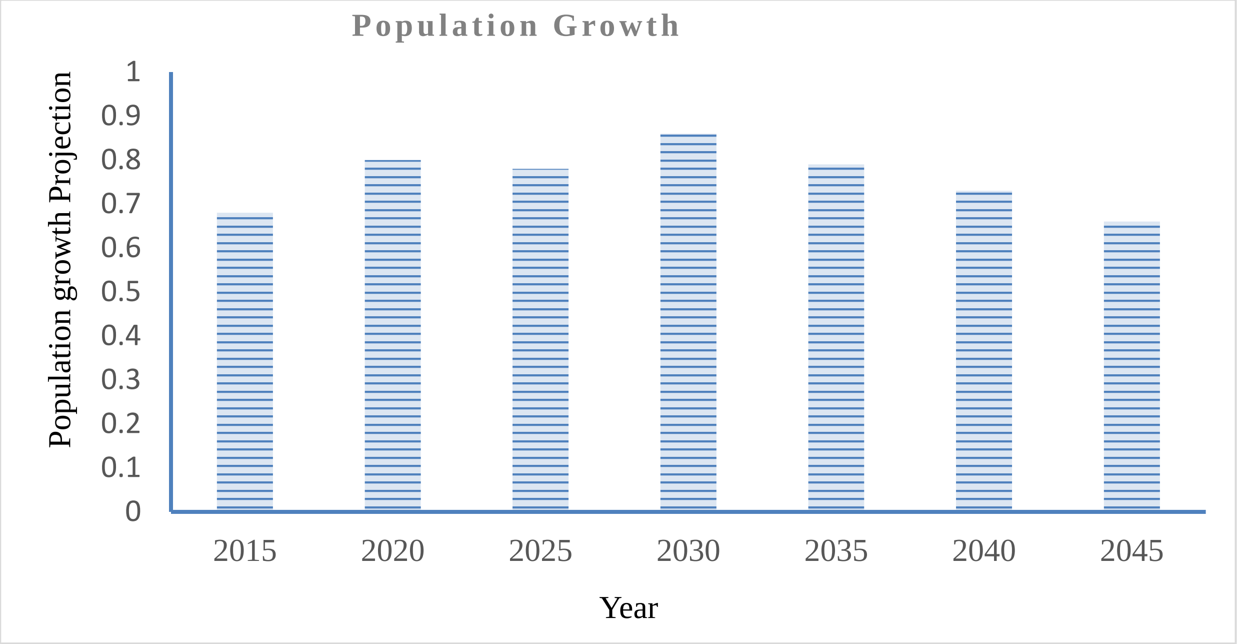

Figure 2. Population growth projection for Lesotho.

According to this investigation's findings, 75% of waste is assumed to be delivered to disposal sites. The amount of municipal solid garbage created is determined by the amount of waste generated per population and the categories of waste generated in a country [18,23,30]. Figure 3 shows the solid waste composition of Lesotho. Per capita waste production in this study was taken as 0.5 kg/capita/day from 2020 to 2025, and 0.8 kg/capita/day from 2026–2045. The annual volume of waste brought to the WtE plant is measured as follows:

$$M_{WtE}(i) = P_{tot} \times w_{pc} \times 365 \times 0.75 \times f(i)(kg/yr) \qquad (2)$$

where w_{pc} is the waste generation per capita and $f(i)$ is the proportion of garbage committed to each type of WtE technology.

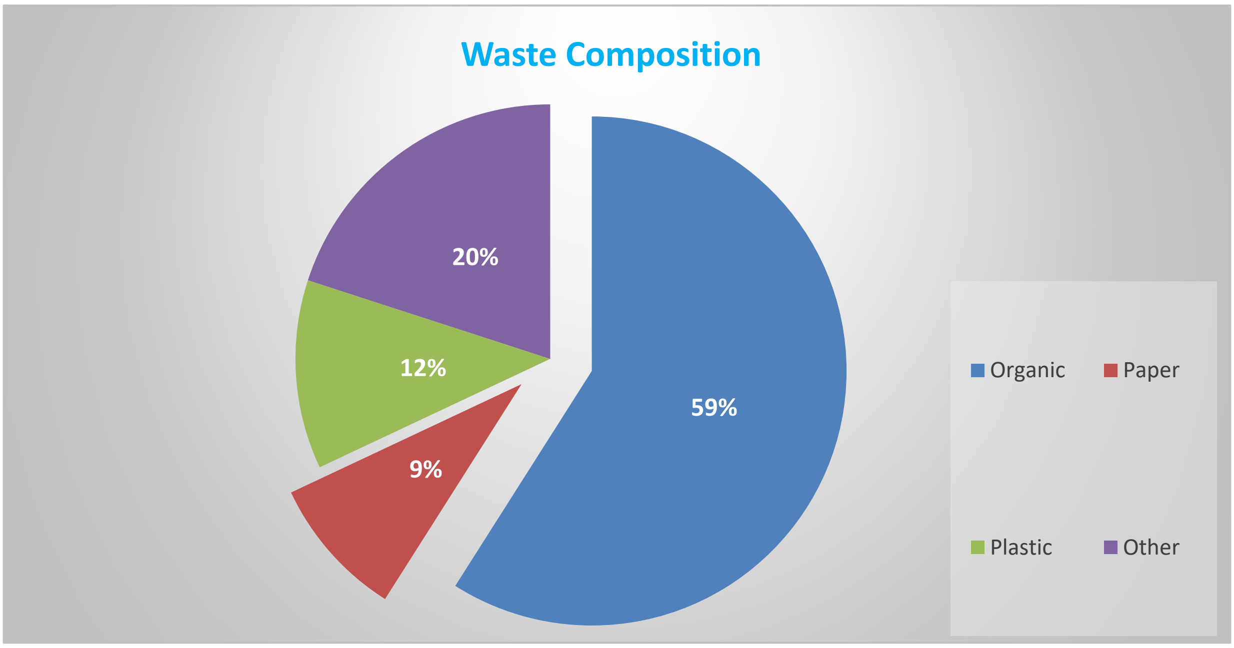

Figure 3. MSW composition of Lesotho urban areas [4,5].

2.3. Production of electrical energy using AD and INC technologies

This component of the study determines the potential electrical energy that can be harvested using AD and INC technologies. The electricity generation from both technologies is depicted in Table 1.

2.3.1. Potential for electricity generation using AD technology

Food waste is harnessed through the use of AD technology inside a digester to produce electrical energy. During this process, food waste decomposes and biogas is generated. The biogas is therefore channeled to the internal combustion engine (ICE) with the intention of generating electricity. The electricity under this section can be calculated as follows:

$$E_{AD} = \frac{0.85 \times \eta \times LHV \times M_{AD}}{CF} \tag{3}$$

where η is the thermal efficiency, M_{AD} is the putrescible solid waste and CF represents the conversion factor and is given as 3.6.

2.3.2. Electricity generation potential of INC technology

The potential amount of energy that can be created by INC technology can be calculated using the following formula:

$$E_{INC} = M_{comb} + LHV + H_{eff} + 0.913 \tag{4}$$

where M_{comb} is the combustible MSW and H_{eff} represents the heat-to-electrical energy factor and is given as 25%. The plant is assumed to run at least 334 days per year.

Table 1. Electrical energy projection of AD and INC technologies [22,23].

Year	AD	INC
	GWh	
2021	0.335	17.154
2022	0.353	18.064
2023	0.371	18.987
2024	0.395	20.183
2025	0.413	21.133
2026	0.432	22.102
2027	0.457	23.354
2028	0.477	24.360
2029	0.497	25.384
2030	0.522	26.703
2031	0.543	27.763
2032	0.564	28.833
2033	0.591	30.199
2034	0.612	31.294
2035	0.634	32.401
2036	0.661	33.810
2037	0.684	34.944
2038	0.706	36.086
2039	0.734	37.535
2040	0.757	38.702
2041	0.781	39.928
2042	0.810	41.417
2043	0.834	42.616
2044	0.857	43.820
2045	0.887	45.343

2.4. Evaluation of economic feasibility of WtE technologies

Before capitalizing on any project, it is important to know its economic viability. During this stage of the research project, an investigation into the economic viability of AD and INC in certain parts of Lesotho was carried out. For the evaluation, the following metrics were computed: payback period, total life cycle cost (TLCC), net present value (NPV) and levelized cost of energy (LCOE). The economic evaluation of this WtE technology is at a point where it is ideal for investment by both the government and private investors.

2.4.1. NPV

A dollar's present value is contrasted with its future value while accounting for inflation and returns. NPV is the appellation for this comparison. By examining the cash inflows and outflows from revenues over the course of the project, it is determined [31]. Revenues, tax breaks and subsidies are examples of cash inflows, whereas investments, maintenance costs and income taxes are examples of cash outflows. The indices listed in Table 2 were taken into account for this analysis.

Table 2. Lesotho's economic indicators [32,33].

Indices	Rate of inflation ($\boldsymbol{e}$)	Nominal discount rate	Marginal tax rate	Electricity cost (USD/kWh)	Project lifespan
Value	5.70%	10.05%	25%	0.15 (AD) 0.11 (INC)	25

A potential project should be approved if its NPV is positive, because it is economically feasible [34]. The two techniques of WtE technology in this study's NPV were as follows:

$$NPV_{(i)} = \sum_{n=0}^{N} \frac{F_n}{(1+d_r)^n} = F_0 + \frac{F_1}{(1+d_r)^1} + \frac{F_2}{(1+d_r)^2} + \ldots + \frac{F_N}{(1+d_r)^N} \tag{5}$$

where F_0 is equal to the project's initial investment cost, d_r is the real discount rate per year and F_n is the net cash flow rate. Additionally, *i* stands for the WtE technology type, which could either be INC or AD, and *n* denotes the overall length of time of study. F_n and d_r are clarified as follows:

$$F_n = \Re v(i) - V_{LFcost}(i) - C_{OM} - C_{tax} \tag{6}$$

$$d_r = \left(\frac{1+d_n}{1+e}\right) - 1 \tag{7}$$

where $Rev_{(i)}$ is the amount of income generated by the project, INV_{LFcost} is the overall investment expense, C_{OM} is the cost of operation and maintenance and C_{tax} is the amount of tax owed on the project's profit. Under the discount rate, d_n is the nominal discount rate, assumed to be 10.05%, and *e* is the rate of inflation, assumed to be 5.7% [32]. Alternatively, revenue and tax paid were determined by using the following formula:

$$\Re v(i) = E_p(i) \times F_d \tag{8}$$

$$C_{tax} = PR_i \times Tax_{mar} \tag{9}$$

where PR_i is the money raised from utilizing a particular type of WtE technology, E_p is the overall amount of electrical energy obtained from the considered WtE technology, F_d is the cost of sale of electricity in USD/kWh (1 USD = R15) according to projections made by the Lesotho Electricity and Water Authority and Tax_{mar} reflects the marginal tax of Lesotho, and it was taken from the Central Bank of Lesotho (CBL) [32]. Table 2 contains the data used for this consideration.

Computation of the capital expenditure and cost of operation and maintenance of AD technology

According to Cudjoe et al. [19], investment costs, operating costs and maintenance costs for AD technology can be calculated as follows:

$$C_{inv} = 51827.082 \times M_{f(AD)}^{0.55} \tag{10}$$

$$C_{OM} = 25340.71553 \times M_{f(AD)}^{-0.61} \tag{11}$$

where $M_{f(AD)}$ is the capacity of the system in tons/year.

Determination of investment, operation and maintenance costs of INC technology

The initial investment cost, together with the operation and maintenance costs of the INC technology, may be computed based on the following [31]:

$$C_{inv} = 4900 \times M_{f(INC)}^{0.8} \times Q \times R \times S \tag{12}$$

$$C_{OM} = 700 \times M_{f(INC)}^{-0.29} \times Q \times R \times S \tag{13}$$

where $M_{f(INC)}$ specifies the amount of MSW that is flammable. Q is the USD-to-EUR exchange rate of 1.0815, R is the inflation rate of 0.057 [33] and S is the Euro-to-USD purchasing power parity adjustment of 1.0400 [33].

2.4.2. LCOE

LCOE is the minimal price per kWh at which the power produced must be sold for the project to break even during its lifetime [35]. According to Ayodele et al., the break-even point is reached when the capital cost of the project matches the operating and maintenance expenditures [36]. By using the NREL [37] technique, the economically feasible technology in WtE technology is distinguished as follows:

$$LCOE_{(i)} = \left(\frac{TLCC_{(i)}}{E_{G(i)}}\right) CRF \tag{14}$$

where *TLCC* represents the total project life cycle cost and *CRF* represents the capital recovery factor. According to Cudjoe and Han [38], the aforementioned TLCC and CRF can be computed over the duration of the project as follows:

$$TLCC = C_{invt} + \sum_{n=1}^{N} \frac{C_{OM(i)}}{(1 + d_n)} \tag{15}$$

$$CRF = \frac{d_n(1+d_n)^N}{(1+d_n)^N - 1} \tag{16}$$

2.5. Life cycle assessment-based evaluation of the environmental impact of WtE technologies

This study utilized a life cycle assessment (LCA) as a technique to assess the environmental implications of WtE projects over the course of their lifetime [39–41]. At this juncture, the focus is on the two aforementioned technologies, so the LCA was employed to evaluate the environmental impact of biogas production from AD and heat from the process of combustion. In this situation, all environmental problems resulting from the production of a solid waste product are disregarded. This section is based on International Organization for Standardization standard ISO 14404/43, since the objective was to evaluate the decrease in GHG emissions resulting from the deployment of WtE projects (i.e., AD and INC technologies) in Lesotho [38]. GHG is a mixture of several gases, including methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), perfluorocarbons, sulfur hexafluoride (SF_6)

and hydrofluorocarbons [37]. In this study, the probability for MSW management to contribute to global warming was evaluated using the following scenarios:

Scenario A: In this plan, the majority of MSW (putrescible and combustible waste) is landfilled without energy recovery. The recyclables are not disposed of in landfills; hence, they are not considered in this analysis. This form of MSW practice is prevalent in impoverished nations, and Lesotho is no exception.

Scenario B: Here, putrescible waste is transported to the AD plant, it is placed inside a digester and processed. The captured biogas from this technique is subsequently used to generate power through an ICE. During this energy recovery, digestate is produced as a by-product, and it can be processed further to produce fertilizer; however, it is neglected in this study.

Scenario C: In this scheme, the dry waste in the form of combustibles is delivered to the INC plant. The waste is then deposited in an incinerator and burned to generate steam that will be utilized to produce power using a steam engine. The heat energy from this process can also be used for teleheating.

2.5.1. Potential global warming under Scenario A

All MSW is disposed of in a landfill without energy recovery in this scenario. Garbage is not sorted before disposal in landfills; energy recovery from waste is not currently practiced, despite interest in WtE technology; nor is leachate treated [42]. The anaerobic decomposition of biodegradable waste emits methane (CH_4), carbon dioxide (CO_2), as well as trace amounts of hydrogen sulphide (H_2S), hydrochloric acid gas (HCl), hydrogen fluoride (HF) and other chemical substances [7].

According to the International Renewable Energy Agency, plastic waste and other inert materials do not contribute to the generation of LFG [43]. The environmental harm posed by GHGs includes all of these gases, although methane is the most significant emitter. Its contribution to climate change and the loss of the ozone layer is 25 times that of CO_2 [30]. In light of the Cudjoe et al. argument, the quantity of CO_2 emitted by the putrescible waste is equal to the amount of CO_2 absorbed by the matter during its life cycle [44], so the focus of this investigation is on methane production. According to the IPCC (2006), 90% of the produced methane is released into the atmosphere, while the remaining 10% is immediately converted to carbon dioxide by bacteria [45]. The LandGEM mathematical model was used to determine the annual emission rate of methane for 25 years (2021 to 2045). Therefore, in the equation applied to determine the methane emission equivalent of carbon dioxide for an untreated landfill, the volume of methane can be multiplied by the GWP:

$$CH_4(kgCO_2eq) = CH_{4(LFG)} \times 0.9 \times GWP_{(CH_4)} \times 6.67 \times 10^{-4} \times 1000 \tag{17}$$

where $GWP_{(CH_4)}$ is the GWP of methane and is assumed to be 25 $kgCO_2$ [30], and 0.000667 is the LandGEM model conversion factor from m^3/yr to ton/yr.

2.5.2. Potential global warming under Scenario B

Carbon dioxide is produced during the combustion of biogas inside a CHP or ICE plant that is of biogenic origin, which are assumed to be carbon-neutral. In this scenario, the emission of CH_4 and nitrogen dioxide (NO_2) is ignored due to the small amount [46]. However, there will still be minor CH_4 emissions from the reactor, which is the largest contributor to GHG emissions in AD facilities. As per the Intergovernmental Panel on Climate Change and Mohareb et al., the biogas digester only spills 5% of its biogas [46,47]. The amount of methane leaking from the digester is obtained as follows:

$$M_{CH4(AD)} = 0.05 \times CH_{4(AD)} \times \rho_{CH4} \tag{18}$$

where $CH_{4(AD)}$ is the actual amount of methane emitted into the environment during the AD process, 0.05 represents the 5% leakage from the digester and ρ_{CH4} is the density of methane, which is assumed to be 0.717 kg/m^3 [46,47]. Figure 4 depicts the effects of AD adaptation prior to and following gas recovery. However, the carbon dioxide equivalent of methane for this leak can be calculated as follows:

$$AD_{GWP}(kgCO_2eq) = M_{CH4(AD)} \times CH_{4(GWP)} \tag{19}$$

where $CH_{4(GWP)}$ represents the GWP of methane equivalent to carbon dioxide; 25 $kgCO_2$ is used [30].

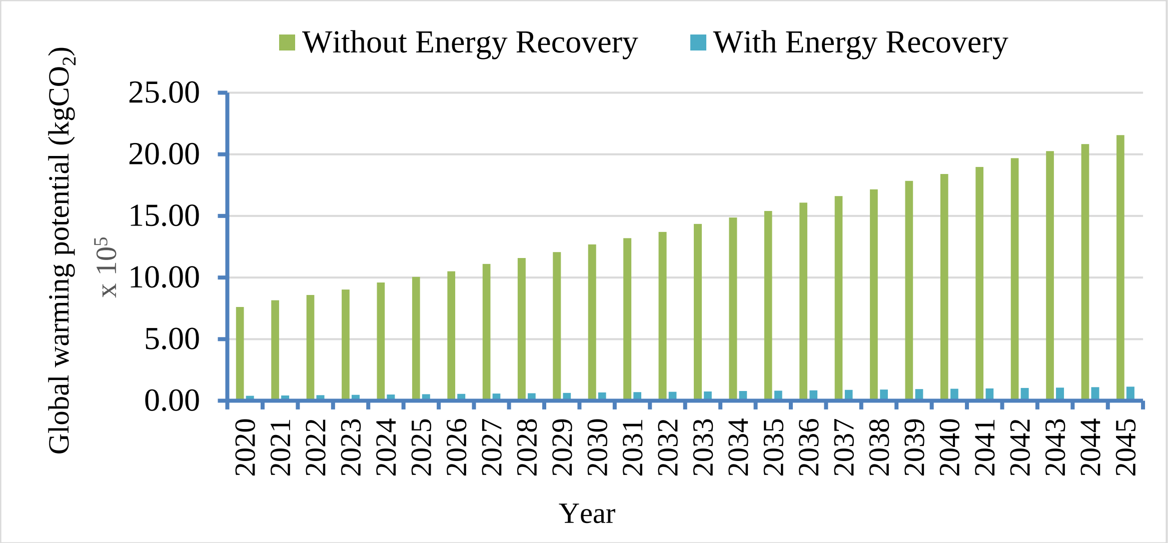

Figure 4. Global warming potential from AD technology.

2.5.3. Potential global warming under Scenario C

A thermochemical process implies the controlled heating or oxidation of MSW to produce heat. Moreover, under this section of the study, MSW is combusted inside a burn/water walled design INC plant with appropriate capacity. According to Ayodele et al., for this process to operate efficiently, an air pollution control system that includes an acid gas control spray dryer, activated carbon injection control to deal with mercury, urea or ammonia injection and filtering systems in terms of bag houses for particulate matter are engaged [31]. As a result of INC, the emitted GHGs include CO_2, CH_4 and N_2O [32]. Additionally, depending on the characteristics of the waste, other pollutants like heavy metals, NOx, HF, SO_2 and HCl are released into the atmosphere [48]. In addition to gaseous emissions, bottom and fly ash comprise 20 to 30% and 2 to 6%, respectively, of the total feedstock [7,49–51]. This procedure uses the IPCC's 2006 and USA EPA’s mathematical models to determine national GHG inventories and emissions for criterion air pollutants, acid gases and dioxins and furans, respectively [52,53]. The GHGs were calculated by determining the emissions of carbon dioxide from the INC process and the total anthropogenic methane, including nitrous oxide emissions converted to the carbon dioxide equivalent, and then adding them together. The CO_2 emitted from INC was determined by finding the product of fossil carbon, combustible MSW, the oxidation factor and conversion from carbon to carbon dioxide (CO_2). Other emissions were determined by the waste's heating value, whereas the anthropogenic or non-biogenic origins of CO_2 and N_2O were respectively determined by the carbon and nitrogen contents of each component of burnt MSW. Consequently, the direct combustion of MSW is equal to the sum of the two emissions converted to CO_2 equivalent using the 100-year GWP [25,54]. Only GHG emissions originating from plastic, paper and textile waste were considered for this study, and they can be calculated as follows:

$$E_{GHG} = E_{CO2} + \sum_{k=1}^{n} E_k \tag{20}$$

where k denotes the type of GHG under consideration. E_{GHG} is the emission of GHGs from the process of INC, E_{CO_2} is the emission of carbon dioxide that results from INC and E_k refers to the total anthropogenic CH_4 and N_2O emissions converted to CO_2 equivalent [7,55].

$$E_{CO2} = FC \times M_{MSWcomb} \times \alpha \times \frac{M_{CO2}}{M_C} \tag{21}$$

where FC is the fossil carbon component (fossil carbon fraction in percentage of plastic and paper total carbon is 1 and 100, respectively), $M_{MSWcomb}$ is the amount of combustible MSW, α is the oxidation factor (taken as 1) [47], the conversion factor of M_{CO2}= 44 kg/mole and M_C= 12 kg/mole represents the element of carbon to carbon dioxide [41,56].

$$E_k = EF_k \times GWP_k \times LHV_{total} \times M_{MSWcomb} \times \%F_{anthr} \tag{22}$$

where EF_k represents the emission factor for 30 kg/TJ for methane and 4 kg/TJ for nitrous oxide, respectively [45] and k denotes the fraction of emission (CH_4 or N_2O) under consideration; GWP_k is the GWP equivalent to 25 kgCO_2 [30], LHV_{total} is the lower heating value of the burned waste, considered as 37.2 MJ/m^3, and F_{anthr} is the 20% anthropogenic component of the combustible MSW. The results of incinerating municipal waste with the intention of producing heat are illustrated in Figure 5.

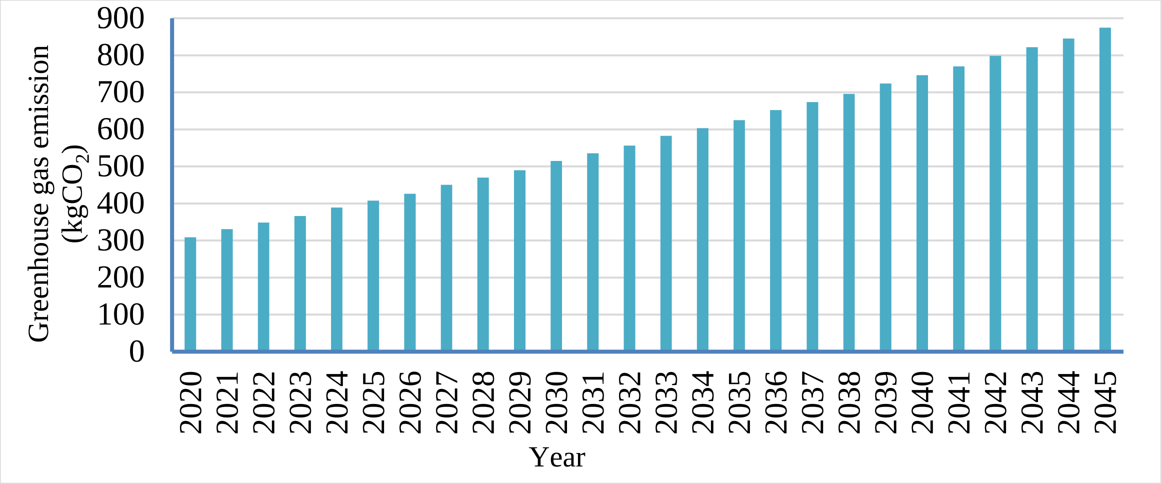

Figure 5. Potential global warming caused by INC technology.

Projection of acidification potential emissions

During the process of INC, there are emissions of gases like SO_2, NO_x, HF, HCl and H_2S are emitted into the atmosphere [13]. According to Cudjoe et al., the emission of these gases results in acid rain and forest demeaning; however, in this study, only HCl and SO_2 were regarded as the major contributors of acid rain [19]. Therefore, to determine the emission of these acid rain-causing gases, the product of acid gases (HCl and SO_2) needs to be measured in the equivalent of sulfur dioxide (SO_2eq); the potential of acidification can be determined as follows:

$$E_{INC(ap)} = E_{SO_2} \times E_{HCl} \tag{23}$$

where E_{SO_2} is the release of sulfur dioxide into the atmosphere, and E_{HCl} is the release from the gas of hydrogen chloride. They can both be estimated as follows:

$$E_{SO_2} = SE_{SO_2} \times M_{MSWcomb} \times EF_{SO_2} \tag{24}$$

$$E_{HCl} = SE_{HCl} \times M_{MSWcomb} \times EF_{HCl} \tag{25}$$

where SE_{SO2} and SE_{HCl} are the detailed release factors of SO_2 and HCl, and they are given as 0.277 and 0.106 kg/tons, respectively [13,57]. On the other hand, EF_{SO_2} and EF_{HCl} are the equivalency elements that involve HCl and SO_2, both given as 0.88 and 1.0 $kgSO_2eq$, respectively [14].

Dioxins potential assessment

This section calculates the dioxins known as polychlorinated dibenzo-p-dioxins and dibenzofurans. Public health is threatened by the high carcinogenicity and toxicity of persistent organic pollutants that are created unintentionally during the burning process [7,56,58]. Dioxins are produced from precursors and new synthesis; they are also produced from compounds that result from incomplete combustion [7]. Therefore, emission factors were harnessed; the dioxin emissions from INC can be calculated as follows:

$$E_{INCdioxin} = SEF_{INCdioxin} \times M_{MSWcomb} \tag{26}$$

where $SEF_{INCdioxin}$ is the specific emission factor of the INC; according to Ayodele et al. [7], this factor was taken as $3.31 \times 10^{-8}\ kg/tons$.

3. Results and discussion

This section presents the study's findings, discussing energy generation, demographic changes, MSW characterization, economic analysis and environmental effect analysis of AD and INC technologies in Lesotho.

3.1. Generation of electricity and population growth

The population under the study area is expected to grow from 1.3471 to 1.6359 million between 2021 and 2045. As a result, it is determined that the population is capable of producing up to 138.241 and 388.391 annual kilotons of MSW for INC and AD, respectively. Through INC and AD processes, 17.154 to 45.343 GWh and 0.336 to 0.887 GWh of electrical energy can be generated, respectively. This proves that the electricity of INC technology is higher for all the years followed by AD technology.

3.2. Economic assessment

3.2.1. Economic feasibility evaluation of INC technology

Economically, INC technology is viable for the country because it presents a positive NPV. Table 3 shows the outcome of the economic feasibility of INC.

Table 3. Economic metrics of AD and INC technologies.

AD		INC	
NPV (×10^3 USD)	LCOE (USD/kWh)	NPV (×10^6 USD)	LCOE (USD/kWh)
513.825	0.029	33.9645	0.0023

As reflected in Table 3, INC technology is the best WtE technology for the country, with a high NPV of USD 33.965 million. On the other hand, the LCOE of INC technology is expected to be 0.0023 USD/kWh. Again, the LCOE of INC technology is lower, making it the superior solution for Lesotho.

3.2.2. Economic feasibility evaluation of AD technology

The economic viability of AD technology for the nation is supported by a positive NPV. Table 3 depicts that AD technology is a secondary efficient WtE technology for the country, with an NPV of USD 513.825 × 10^3 and an LCOE of 0.029 USD/kWh. Again, the LCOE of AD technology is low, which makes it a viable option for Lesotho.

Evaluation of the environmental damage of AD and INC technologies

This section presents and discusses the results of the environmental impact of reusing MSW with AD and INC technologies. Lacking WtE technology, the atmosphere is exposed to a bigger quantity of GHG emissions, as depicted in Figure 4. The emission from 2021 to 2045 is expected to change from 760.613 $megatonsCO_2eq$ to 2.155 $gigatonsCO_2eq$. On the other hand, the emissions after engaging AD technology were estimated to be reduce by 1.601 $megatonsCO_2eq$ in 2021 and 4.537 $megatonCO_2eq$ in 2045. Again, it can clearly be seen from the results that WtE technology can introduce a safe living space that is not hazardous to the environment.

Furthermore, the study investigated the emissions that will arise from the INC procedure. Figure 5 presents the results of INC technology; it can be seen that GHG emissions range from 308.619 $megatonCO_2eq$ to 874.492 $megatonCO_2eq$ for the lifespan of the project. However, according to [59], the emissions can be suppressed by modifying the filtration system on the output side of the project.

Analysis of acidic rain for the period of the project was also considered in this study. Figure 6 depicts the acidification potential results considering that contributors of acidic rain are sulfur dioxide and hydrogen chloride gas. The emissions are expected to range from 61.5 $kilotonsSO_2eq$ to 493.79 $kilotonsSO_2eq$; as trash production continues to rise, it is evident that acidification is projected to increase over time.

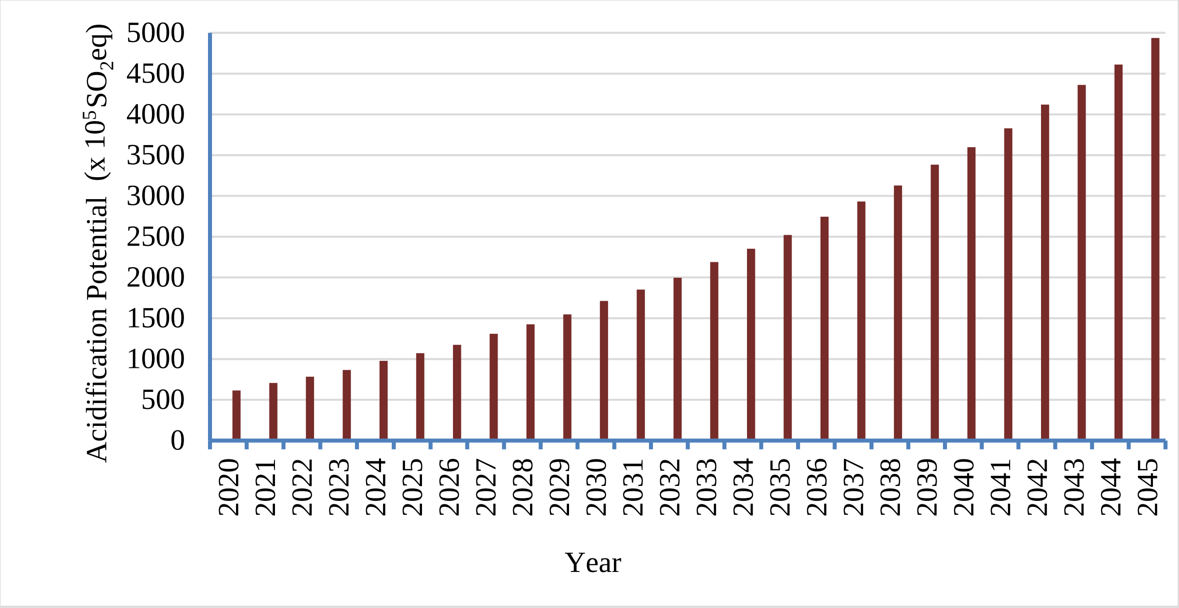

Figure 6. Potential of acidification resulting from incineration.

It is also found that exposure to dioxins can cause harm to humans; therefore, this study took a turn to research the dioxin potential that may result from INC technology [35,60,61] due to the incomplete combustion of the MSW inside the furnace [55,56,61]. Another study found that the presence of PVC as part of the MSW renders huge emission of dioxins during the combustion of waste. Figure 7 shows the increasing response of dioxin emission during the maturity of the project from the assessment.

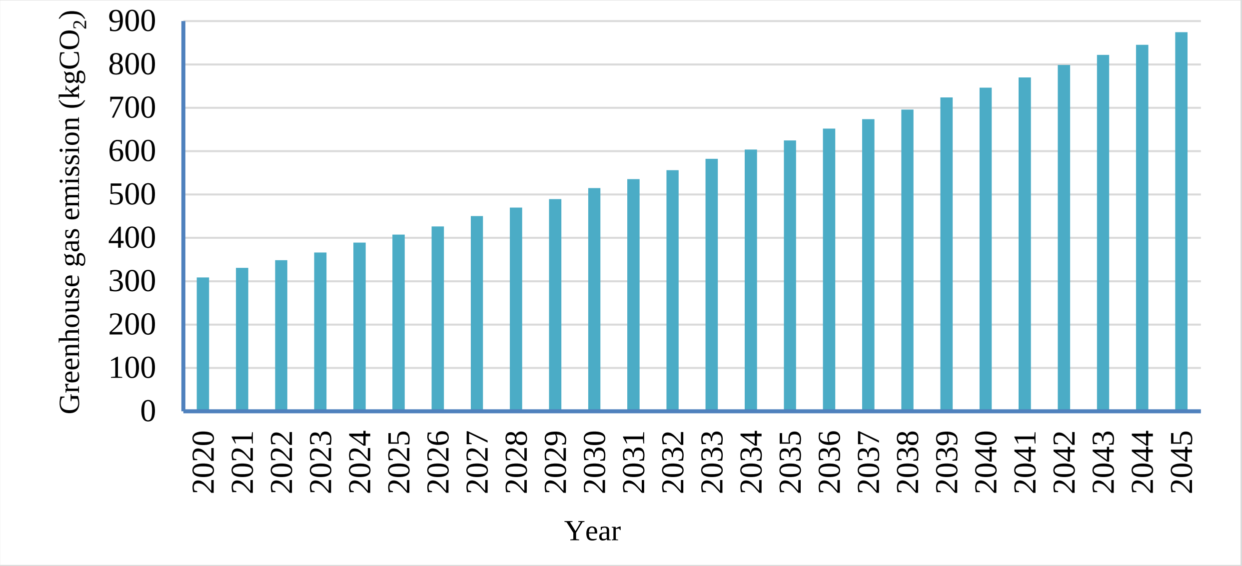

Figure 7. Dioxin potential due to incineration technology.

4. Conclusions

The study assessed the economic viability and impact on the environment of producing power from MSW for the lowland districts of Lesotho (comprising Mafeteng, Maseru, Berea and Leribe) over 25 years (2021–2045). Based on the study's findings, the following can be concluded:

Between 2021 and 2045, it is anticipated that the population of the region under investigation will rise from about 1.35 million to 1.64 million people. Consequently, it has been determined that the population can generate up to 138.241 kilotons and 388.392 kilotons of MSW yearly for INC and AD technologies, respectively. Electrical energy may be created in the INC and AD processes, ranging from 17.155 GWh to 45.343 GWh and 0.336 to 0.887 GWh, respectively. This demonstrates that INC technology produces more power throughout the years, followed by AD technology. All of the technologies are economically feasible for the country since they have a positive NPV. With an NPV of USD 33.965 million, INC technology is the top WtE technology for the country, whereas AD has an NPV of USD 513.825 × 10^3. INC and AD, on the other hand, have LCOEs of 0.0023 and 0.029 USD/kWh, respectively. Again, it appears that INC technology is the preferred technology for Lesotho, as it has the smallest LCOE, followed by AD technology.

The results of the LandGEM program for the landfill site indicate an increase in GHG emissions from 2020 to 2045, after which the emissions is expected to begin to drop as waste is removed from the site. Regarding the deployment of AD technology, without energy recovery, 1.005 $gigatonsCO_2eq$ will be emitted into the atmosphere in 2025, whereas only 52.869 $megatonCO_2eq$ will be emitted into the atmosphere if the technology is applied. According to Yang et al., leaks can be avoided by utilizing contemporary construction techniques [61]. It is evident from this study's findings that the above-mentioned technologies are suitable for Lesotho. In addition, the environment will be preserved because the results indicate that only a small amount of LFG is released into the atmosphere when LFG is harvested using AD technology. Therefore, the adoption of AD or INC technology will create a sustainable environment and contribute to the economic prosperity of the nation by generating clean electricity from MSW. This document is essential for the government(s) or private sector(s) when choosing which WtE technology is most suited for the ecological zone of Lesotho's Lowlands or similar developing countries in the future.

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Conflict of interest

There are no conflicts of interest to declare by the authors.

References

1. Carlsson Reich M (2005) Economic assessment of municipal waste management systems—case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC). *J Cleaner Prod* 13: 253–263. https://doi.org/10.1016/j.jclepro.2004.02.015
2. Nguyen PH, Nguyen Cao QK, Bui LT (2022) Energy recovery from municipal solid waste landfill for a sustainable circular economy in Danang City, Vietnam. IOP Conference Series: *Earth Environ Sci* 964: 012015. https://doi.org/10.1088/1755-1315/964/1/012015
3. Cudjoe D, Han MS (2021) Economic feasibility and environmental impact analysis of landfill gas to energy technology in African urban areas. *J Cleaner Prod* 284: 125437. https://doi.org/10.1016/j.jclepro.2020.125437
4. Mvuma G (2010) Waste a necessary evil for economically impoverished communities in least developed countries (LCDc): a case study. Available from: https://researchspace.csir.co.za/dspace/handle/10204/4531.
5. Thamae M, Molapo K, Koaleli M, et al. (2006) The baseline assessment for the development of an Integrated Solid Waste Management System (ISWMS) for Maseru City. Lesotho2006. Available from: https://info.undp.org/docs/pdc/Documents/LSO/00058398_PPP-ISWM%20Prodoc.pdf.
6. Hoornweg D, Bhada-Tata P (2012) What a waste: a global review of solid waste management. Available from: https://openknowledge.worldbank.org/handle/10986/17388.
7. Ayodele TR, Ogunjuyigbe ASO, Alao MA (2017) Life cycle assessment of waste-to-energy (WtE) technologies for electricity generation using municipal solid waste in Nigeria. *Appl Energy* 201: 200–218. https://doi.org/10.1016/j.apenergy.2017.05.097
8. Independent Group of Scientists (2019) The Future is Now: Science for Achieving Sustainable Development. New York: United Nations. Available from: https://sustainabledevelopment.un.org/content/documents/24797GSDR_report_2019.pdf.
9. Johari A, Ahmed SI, Hashim H, et al. (2012) Economic and environmental benefits of landfill gas from municipal solid waste in Malaysia. *Renewable Sustainable Energy Rev* 16: 2907–2912. https://doi.org/10.1016/j.rser.2012.02.005
10. Shin HC, Park JW, Kim HS, et al. (2005) Environmental and economic assessment of landfill gas electricity generation in Korea using LEAP model. *Energy Policy* 33: 1261–1270. https://doi.org/10.1016/j.enpol.2003.12.002
11. Sechoala TD, Popoola OM, Ayodele TR (2019) A review of waste-to-energy recovery pathway for feasible electricity generation in lowland cities of Lesotho. *IEEE,* 1–5. https://doi.org/10.1109/AFRICON46755.2019.9133756
12. Scarlat N, Motola V, Dallemand JF, et al. (2015) Evaluation of energy potential of municipal solid waste from African urban areas. *Renewable Sustainable Energy Rev* 50: 1269–1286. https://doi.org/10.1016/j.rser.2015.05.067
13. Cudjoe D, Acquah PM (2021) Environmental impact analysis of municipal solid waste incineration in African countries. *Chemosphere* 265: 129186. https://doi.org/10.1016/j.chemosphere.2020.129186
14. Silva LJ de VB da, dos Santos IFS, Mensah JHR, et al. (2020) Incineration of municipal solid waste in Brazil: An analysis of the economically viable energy potential. *Renewable Energy* 149: 1386–1394. https://doi.org/10.1016/j.renene.2019.10.134

15. China Statistical Yearbook (2015) China Statistical Yearbook 2014. NBSC Beijing. Available from: http://www.stats.gov.cn/sj/ndsj/2014/indexeh.htm.
16. Damgaard A, Riber C, Fruergaard T, et al. (2010) Life-cycle-assessment of the historical development of air pollution control and energy recovery in waste incineration. *Waste Manage* 30: 1244–1250. https://doi.org/10.1016/j.wasman.2010.03.025
17. de Souza Ribeiro N, Barros RM, dos Santos IFS, et al. (2021) Electric energy generation from biogas derived from municipal solid waste using two systems: Landfills and anaerobic digesters in the states of Sao Paulo and Minas Gerais, Brazil. *Sustainable Energy Technol Assess* 48: 101552. https://doi.org/10.1016/j.seta.2021.101552
18. El Ibrahimi M, Khay I, El Maakoul A, et al. (2021) Techno-economic and environmental assessment of anaerobic co-digestion plants under different energy scenarios: A case study in Morocco. *Energy Convers Manage* 245: 114553. https://doi.org/10.1016/j.enconman.2021.114553
19. Cudjoe D, Han MS, Nandiwardhana AP (2020) Electricity generation using biogas from organic fraction of municipal solid waste generated in provinces of China: Techno-economic and environmental impact analysis. *Fuel Process Technol* 203: 106381. https://doi.org/10.1016/j.fuproc.2020.106381
20. Tyagi VK, Fdez-Güelfo LA, Zhou Y, et al. (2018) Anaerobic co-digestion of organic fraction of municipal solid waste (OFMSW): Progress and challenges. *Renewable Sustainable Energy Rev*. https://doi.org/10.1016/j.rser.2018.05.051
21. Hapazari I, Ntuli V, Taele B (2015) Waste generation and management in lesotho and waste to clay brick recycling a review. *Curr J Appl Sci Technol* 8: 148–161. https://doi.org/10.9734/BJAST/2015/11224
22. Sechoala TD, Popoola OM, Ayodele TR (2020) Projection of electricity potential through exploitation of methane gas from landfilled MSW of Lesotho. *IEEE*, 1–5. https://doi.org/10.1109/PowerAfrica49420.2020.9219870
23. Sechoala TD, Popoola OM, Ayodele TR (2021) Potential of electricity generation through anaerobic digestion and incineration technology for selected districts in Lesotho. *IEEE*, 1–7. https://doi.org/10.1109/SAUPEC/RobMech/PRASA52254.2021.9377211
24. Adenuga OT, Mpofu K, Modise KR (2020) An approach for enhancing optimal resource recovery from different classes of waste in South Africa: Selection of appropriate waste to energy technology. *Sustainable Futures* 2: 100033. https://doi.org/10.1016/j.sftr.2020.100033
25. Ayodele TR, Alao MA, Ogunjuyigbe ASO (2020) Effect of collection efficiency and oxidation factor on greenhouse gas emission and life cycle cost of landfill distributed energy generation. *Sustainable Cities Soc* 52: 101821. https://doi.org/10.1016/j.scs.2019.101821
26. Ayodele TR, Ogunjuyigbe ASO, Amusan TO (2018) Techno-economic analysis of utilizing wind energy for water pumping in some selected communities of Oyo State, Nigeria. *Renewable Sustainable Energy Rev* 91: 335–343. https://doi.org/10.1016/j.rser.2018.03.026
27. Ayodele TR, Alao MA, Ogunjuyigbe ASO (2018) Recyclable resources from municipal solid waste: Assessment of its energy, economic and environmental benefits in Nigeria. *Resour, Conserv Recycl* 134: 165–173. https://doi.org/10.1016/j.resconrec.2018.03.017
28. Bureau of Statistics (2016) 2016 Lesotho Population Census. Maseru Lesotho: Ministry of Development Planning. Available from: https://searchworks.stanford.edu/view/13170410.

29. Alao MA, Popoola OM, Ayodele TR (2021) Selection of waste-to-energy technology for distributed generation using IDOCRIW-Weighted TOPSIS method: A case study of the City of Johannesburg, South Africa. *Renewable Energy* 178: 162–183. https://doi.org/10.1016/j.renene.2021.06.031
30. Ryu C (2010) Potential of municipal solid waste for renewable energy production and reduction of greenhouse gas emissions in South Korea. *J Air Waste Manage Assoc* 60: 176–183. https://doi.org/10.3155/1047-3289.60.2.176
31. Ogunjuyigbe A, Ayodele T, Alao M (2017) Electricity generation from municipal solid waste in some selected cities of Nigeria: An assessment of feasibility, potential and technologies. *Renewable Sustainable Energy Rev* 80: 149–162. https://doi.org/10.1016/j.rser.2017.05.177
32. Moeketsi M (2019) 2018 Annual Report by Central Bank of Lesotho. Lesotho: Mininstry of Finance. Available from: https://www.centralbank.org.ls/images/Publications/ANNUAL_REPORTS/2019_CBL_Annual_Report_-_07.09.2020.pdf.
33. Seleteng M (2010) Inflation and Economic Growth: An estimate of an optimal level of inflation in Lesotho. Maseru Lesotho: Central Bank of Lesotho. 16. Available from: https://www.centralbank.org.ls/images/Publications/Research/Papers/Working/Inflation__Econo_Growth.pdf.
34. Gonzalez R, Daystar J, Jett M, et al. (2012) Economics of cellulosic ethanol production in a thermochemical pathway for softwood, hardwood, corn stover and switchgrass. *Fuel Process Technol* 94: 113–122. https://doi.org/10.1016/j.fuproc.2011.10.003
35. Fernández-González JM, Grindlay AL, Serrano-Bernardo F, et al. (2017) Economic and environmental review of Waste-to-Energy systems for municipal solid waste management in medium and small municipalities. *Waste Manage* 67: 360–374. https://doi.org/10.1016/j.wasman.2017.05.003
36. Ayodele TR, Ogunjuyigbe ASO, Alao MA (2018) Economic and environmental assessment of electricity generation using biogas from organic fraction of municipal solid waste for the city of Ibadan, Nigeria. *J Cleaner Prod* 203: 718–735. https://doi.org/10.1016/j.jclepro.2018.08.282
37. Short W, Packey DJ, Holt T (1995) A manual for the economic evaluation of energy efficiency and renewable energy technologies. *National Renewable Energy Lab.(NREL), Golden, CO (United States)*. https://doi.org/10.2172/35391
38. Cudjoe D, Han MS (2020) Economic and environmental assessment of landfill gas electricity generation in urban districts of Beijing municipality. *Sustainable Prod Consumption* 23: 128–137. https://doi.org/10.1016/j.spc.2020.04.010
39. Leme MMV, Rocha MH, Lora EES, et al. (2014) Techno-economic analysis and environmental impact assessment of energy recovery from Municipal Solid Waste (MSW) in Brazil. *Resour, Conserv Recycl* 87: 8–20. https://doi.org/10.1016/j.resconrec.2014.03.003
40. Dong J, Tang Y, Nzihou A, et al. (2018) Life cycle assessment of pyrolysis, gasification and incineration waste-to-energy technologies: Theoretical analysis and case study of commercial plants. *Sci Total Environ* 626: 744–753. https://doi.org/10.1016/j.scitotenv.2018.01.151
41. Shabib A, Abdallah M (2020) Life cycle analysis of waste power plants: systematic framework. *Int J Environ Stud* 77: 786–806. https://doi.org/10.1080/00207233.2019.1708146
42. Selibe Mochoboroane (2015) Lesotho Energy Policy. Maseru Lesotho: Ministry of Energy and Meteorology. Available from: https://worldcat.org/title/1033543233.

43. International Renewable Energy Agency (2012) Biomass for power generation. IRENA Abu Dhabi, UAE. Available from: https://www.irena.org/publications/2012/Jun/Renewable-Energy-Cost-Analysis---Biomass-for-Power-Generation.
44. Cudjoe D, Nketiah E, Obuobi B, et al. (2021) Forecasting the potential and economic feasibility of power generation using biogas from food waste in Ghana: Evidence from Accra and Kumasi. *Energy* 226: 120342. https://doi.org/10.1016/j.energy.2021.120342
45. Suryati I, Farindah A, Indrawan I (2021) Study to reduce greenhouse gas emissions at waste landfill in Medan City. *IOP Conference Series: Earth Environ Sci* 894: 012005. https://doi.org/10.1088/1755-1315/894/1/012005
46. Mohareb AK, Warith MA, Diaz R (2008) Modelling greenhouse gas emissions for municipal solid waste management strategies in Ottawa, Ontario, Canada. *Resour, Conserv Recycl* 52: 1241–1251. https://doi.org/10.1016/j.resconrec.2008.06.006
47. Change I (2006) 2006 IPCC guidelines for national greenhouse gas inventories. Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan.
48. Assamoi B, Lawryshyn Y (2012) The environmental comparison of landfilling vs. incineration of MSW accounting for waste diversion. *Waste Manage* 32: 1019–1030. https://doi.org/10.1016/j.wasman.2011.10.023
49. Moberg Å, Finnveden G, Johansson J, et al. (2005) Life cycle assessment of energy from solid waste—part 2: landfilling compared to other treatment methods. *J Cleaner Prod* 13: 231–240. https://doi.org/10.1016/j.jclepro.2004.02.025
50. Finnveden G, Johansson J, Lind P, et al. (2005) Life cycle assessment of energy from solid waste—part 1: general methodology and results. *J Cleaner Prod* 13: 213–229. https://doi.org/10.1016/j.jclepro.2004.02.023
51. Finnveden G, Moberg Å (2005) Environmental systems analysis tools–an overview. *J Cleaner Prod* 13: 1165–1173. https://doi.org/10.1016/j.jclepro.2004.06.004
52. Guendehou S, Koch M, Hockstad L, et al. (2006) Incineration and Open Burning of Waste. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Japan: Institute for Global Environmental Strategies (IGES). Available from: https://nswmc.emb.gov.ph/wp-content/uploads/2022/08/2006-IPCC-Guidelines-for-National-Greenhouse-Gas-Inventories.pdf.
53. EPA U (2018) Emission factors for greenhouse gas inventories Stationary combustion emission factors. Go to reference in article. Available from: https://www.epa.gov/sites/default/files/2018-03/documents/emission-factors_mar_2018_0.pdf.
54. Kweku DW, Bismark O, Maxwell A, et al. (2018) Greenhouse effect: greenhouse gases and their impact on global warming. *J Sci Res Rep* 17: 1–9. https://doi.org/10.9734/JSRR/2017/39630
55. Guo Y, Glad T, Zhong Z, et al. (2018) Environmental life-cycle assessment of municipal solid waste incineration stocks in Chinese industrial parks. Resources, Conservation and Recycling 139: 387–395. https://doi.org/10.1016/j.resconrec.2018.05.018
56. Yao X, Guo Z, Liu Y, et al. (2019) Reduction potential of GHG emissions from municipal solid waste incineration for power generation in Beijing. *J Cleaner Prod* 241: 118283. https://doi.org/10.1016/j.jclepro.2019.118283
57. EPA U (1996) Solid Waste Disposal. Refuse Combustion 42. Available from: https://www3.epa.gov/ttnchie1/ap42/ch02/.

58. Kumar A, Sharma M (2014) Estimation of GHG emission and energy recovery potential from MSW landfill sites. *Sustainable Energy Technol Assess* 5: 50–61. https://doi.org/10.1016/j.seta.2013.11.004
59. Kale C, Gökçek M (2020) A techno-economic assessment of landfill gas emissions and energy recovery potential of different landfill areas in Turkey. *J Cleaner Prod* 275: 122946. https://doi.org/10.1016/j.jclepro.2020.122946
60. Shunda l, Jiang X, Zhao Y, et al. (2022) Disposal technology and new progress for dioxins and heavy metals in fly ash from municipal solid waste incineration: A critical review. *Environ Pollut* 311: 119878. https://doi.org/10.1016/j.envpol.2022.119878
61. Yang L, Liu G, Zhu Q, et al. (2019) Small-scale waste incinerators in rural China: Potential risks of dioxin and polychlorinated naphthalene emissions. *Emerging Contam* 5: 31–34. https://doi.org/10.1016/j.emcon.2019.01.001