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Economic and Environmental Benefits of Energy Recovery from Municipal Solid Waste in Phnom Penh Municipality, Cambodia

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Abstract: This study assessed the energy potential, economic feasibility, and environmental performance of landfill gas (LFG) recovery, incineration, and anaerobic digestion (AD) technologies for Phnom Penh municipality in Cambodia, from 2023 to 2042. The economic analysis utilized the levelized cost of electricity (LCOE), payback period (PBP), and net present value (NPV) to evaluate the feasibility of each technology. Additionally, environmental performance was assessed following the IPCC 2006 guidelines. The results indicate that incineration produced the highest energy output, ranging from 793.13 to 1625.81 GWh/year, while the LFG and AD technologies yielded equivalent amounts of 115.44–271.81 GWh/year and 162.59–333.29 GWh/year, respectively. The economic analysis revealed an average LCOE of 0.070 USD/kWh for LFG, 0.053 USD/kWh for incineration, and 0.093 USD/kWh for AD. Incineration and LFG recovery were found to be economically feasible, with positive NPVs and a potential for profit within 8.36 years for incineration and 7.13 years for LFG. In contrast, AD technology had a negative NPV and required over 20 years to generate a return on investment. However, AD was the most promising technology regarding environmental performance, saving approximately 133,784 tCO_2-eq/year. This study provides valuable technical information for policymakers, development partners, and potential investors to use in order to optimize waste-to-energy investment in Cambodia.

Keywords: energy recovery; greenhouse gas; municipal solid waste; waste-to-energy; incineration; Phnom Penh

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1. Introduction

Globally, municipal solid waste (MSW) generation has increased significantly, from 1.3 billion tons in 2012 [1] to 2.7 billion tons in 2019 [2], with an average generation rate of 0.74 kg/capita/day [3]. It is estimated that by 2050, MSW generation will rise to 3.40 billion tons, with low- and middle-income countries contributing more than 40% of the total [3]. This trend is mainly attributed to population growth, economic development, urbanization, industrialization, and changes in consumption habits [4]. Unfortunately, approximately 75% of the world's MSW is sent to landfills and dumping sites without treatment [5], leading to the generation of landfill gas (LFG) through the biodegradation process, which has a significant impact on the environment and contributes to climate change.

Fossil-fuel-based electricity production significantly contributes to GHG emissions throughout its life cycle, from resource extraction to final consumption. This has led to a growing global focus on shifting from conventional electricity generation to greener energy sources. Waste-derived electric energy has been recognized as a sustainable solution for reducing the burden of waste, providing electricity, and mitigating GHG emissions [6–8].

Various waste-to-energy (WTE) technologies have been developed, including thermal treatment (incineration, gasification, pyrolysis, plasma arc) and biological treatment (anaerobic digestion and landfill gas recovery) [9]. As of 2018, there were over 2450 WTE plants operating globally, consuming approximately 368 M tons of waste yearly [10].

LFG typically consists of a mixture of methane (CH_4) (50–60%) [11], which can be extracted and used as a renewable energy source due to its high calorific value of 37.2 MJ/m^3 [12]. Several studies have used mathematical models to evaluate landfill CH_4 generation and its economic potential. For example, Escamilla-García et al. [13] evaluated the LFG generation, economic feasibility, and environmental benefits at a landfill site in southern Mexico using the LandGEM model (Version 3.02, US EPA, Washington, DC, USA). Their results showed that the CH_4 generation flow rate was 115.3 m^3/min, which could potentially produce about 32.396 GWh/year of electricity and 63.990 BTU/year of steam. The economic analysis demonstrated financial profitability with a positive net present value (NPV) over a 15-year project lifespan. Another study by Kumar and Shamar on the energy recovery potential (ERP) from three landfill sites in India also showed a positive NPV [14]. With a discount rate of 10%, the levelized cost of electricity (LCOE) was 0.12–0.17 USD/kWh, which was lower than that of solar power plants and offshore wind energy plants. In a separate study, Cudjoe, Han, and Chen estimated the ERP from LFG in three regions of China [15]. Using the LandGEM model to evaluate CH_4 generation potential based on 15 years of historical landfill data, the authors found that landfill sites could generate approximately 12,525 GWh of electricity. Their economic assessment also showed a positive cash flow.

MSW typically comprises organic fractions, which can be used for composting or in AD plants for energy production, recyclable materials which can potentially replace virgin materials when recycled, and nonrecyclables, which can be used as feedstock for incineration. Incineration and AD technologies have been used as alternatives to landfill. Incineration burns all input waste at a temperature of at least 900 °C [16], producing energy via a steam turbine, destroying hazardous organic substances, and minimizing toxic metals discard via a filter [6]. Meanwhile, AD typically handles only biodegradable organic waste to produce biogas as an output. Both technologies could prevent landfilling and contribute to a circular economy by utilizing organic waste and nonrecyclable materials to generate energy. This could reduce dependence on natural resources by converting waste into electricity and minimizing harmful risks to humans and the environment. In a circular economy, the focus is on minimizing waste generation and maximizing the value of resources by creating closed-loop systems where materials are continually reused, recycled, and recovered instead of being discarded as waste. However, increasing waste recycling may influence the availability of feedstock for WTE incineration. It is worth noting that not all recyclables can be recycled, which is particularly challenging in developing countries such as Cambodia, where comingled waste disposal without source segregation makes it difficult to separate or sort all recycling materials. As a result, recovered materials can be of low quality and damaged or contaminated, such as wet paper and mixed and soiled plastics. The contamination makes recyclables unappealing or challenging to process for recycling facilities, resulting in the need to discard them as trash. Additionally, some contaminated waste requires advanced recycling technologies to separate harmful compounds. Incineration is an effective method for reducing the mass and volume of waste being discarded, particularly that containing complex combinations of hazardous organic compounds. Furthermore, proper separation of MSW, particularly food waste, can increase the efficiency of an incinerator.

However, incineration potentially releases a variety of pollutants into the air, including carbon dioxide (CO_2), nitrogen oxides (N_2O), sulfur dioxide (SO_2), and particular matter. These pollutants can contribute to local air pollution, as well as global warming and climate change. Incineration can also release toxic emissions such as dioxins and furans [4,6], highly toxic chemicals that pose a risk to human health [17]. Many people oppose incineration facilities due to concerns about pollution, health risks, and potential negative impacts on local communities [18].

Developed countries have been using other thermal technologies, such as pyrolysis and gasification, which are equipped with more efficient equipment, such as combined cycle gas turbines [19]. Pyrolysis and gasification are considered promising technologies, but they require high capital and operating costs and have a greater degree of technology complexity [16]. One concern with these technologies is the limited range of feedstocks they can process, such as solid refuse fuels (SRFs), plastics, and rubber tires [19].

Cambodia has experienced a rapid increase in MSW generation over the last decade due to economic growth, population growth, improved living standards, and rapid urbanization [18]. In 2020, the country produced approximately 4.78 million tons, with an average per capita generation rate of 0.78 kg/day [18]. The current MSW management practice primarily relies on landfilling and burial at disposal sites, which poses environmental risks associated with GHG emissions and leachate generation. This presents a challenge for the government in choosing an effective alternative MSW management system. To address these issues and minimize environmental impacts, the government of Cambodia is considering WTE as an alternative approach. Currently, the country's electricity production mainly depends on hydropower (51.93%) and fossil-fired power plants (41.28%), such as those fueled by coal, diesel, heavy fuel oil, and light diesel oil [20]. Some electricity is imported from neighboring countries (Thailand, Vietnam, and Lao PDR), accounting for 26% [20]. However, the current electricity supply is insufficient for meeting consumer demand, especially during the dry season when the water resources used for hydropower plants are lessened. Therefore, introducing WTE technologies could help fill gaps in the electricity supply and mitigate GHG emissions from the waste sector. Therefore, studying the energy recovery potential of MSW is vital and can serve as a solid reference for decision making and developing an effective strategy.

The present study aimed to (1) assess energy recovery potential, (2) analyze economic feasibility, and (3) evaluate environmental performance, considering the global warming potential (GWP) from the three WTE technologies: incineration, anaerobic digestion, and LFG recovery. Phnom Penh, the most populated city in Cambodia, was selected for this study. Figure 1 depicts the framework of the present study.

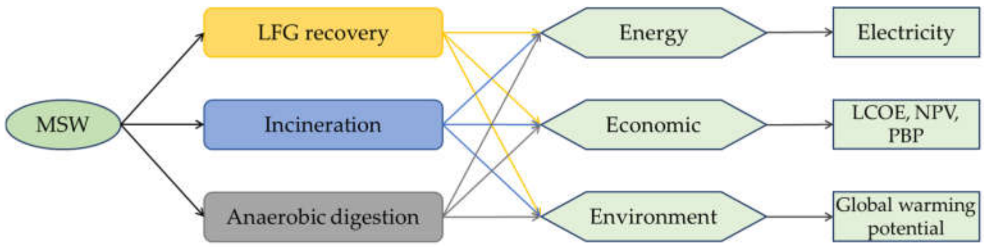

Figure 1. Assessment framework for WTE technologies.

2. Methodologies

2.1. Status of MSWM in Phnom Penh Municipality

Phnom Penh is the capital city of Cambodia, with a population of approximately 2,281,951 and a land area of 679 km^2 (a density of 3361 people/km^2), making it the most densely populated city in the country [21]. Between 2008 and 2019, the annual population growth in Phnom Penh municipality was 4.9%, which increased from 2.8% between 1998 and 2008 [21]. Therefore, MSW generated by the growing population coupled with limited land areas poses significant forthcoming problems in the city. In 2022, about 1.29 MtMSW were collected and disposed of at a landfill site without intermediate treatment. The existing landfill is operating without LFG collection and leachate treatment systems.

2.2. Waste Generation and Characteristics

This study evaluated the ERP from MSW over a 20-year period (2023–2042), based on waste characteristics presented in Table 1. The study considered a correlation between population and MSW generation and assumed a constant growth rate for MSW generation projection within the given period. The projection of MSW generation potential is given in Equations (1)–(3).

$$MSW_{gen(t)} = P_{(t)} \times W_{Gr} \times 365/1000 \quad (1)$$

$$P_{(t)} = P_{(0)} \times (1+r)^t \quad (2)$$

$$W_{Gr} = \frac{W_{collected}}{P_{(b)} \times R_{collection}} \times \frac{1000}{365} \quad (3)$$

where $MSW_{gen(t)}$ is the forecasted waste generation in year t; $P_{(t)}$ is the projected population over the years t, using geometrical increase method; W_{Gr} is the MSW generation per capita; P_0 is the initial population using the national census from 2019; r is the population growth rate; t is the number of years; $W_{collected}$ is the quantity of waste collected in 2022, which is taken as 1,288,223 tons; $P_{(b)}$ is the population in the base years of calculation; and $R_{collection}$ is the collection efficiency. This study used the average population growth rate in the last two decades (1998–2019) [21].

Table 1. MSW characteristics in Phnom Penh.

Composition	Waste Properties						Waste Treatment		
	Fraction (%) [a]	Moisture (%) [a]	*LHV* (MJ/kg) [a]	Carbon Content (%) [b]	Fossil Carbon (%) [b]	*DOC* (%) [b]	LFG (%)	Incineration (%)	AD (%)
Food waste	49.18	78.77	0.33	38.00	-	15	49.18	49.18	49.18
Wood and leaves	6.69	57.12	0.56	49.00	-	43	6.69	6.69	-
Mixed paper	6.54	63.61	4.04	46.00	1.00	40	6.54	6.54	-
Rubber and leather	0.87	18.09	22.37	67.00	20.00	39	0.87	0.87	-
Textiles	8.02	44.28	14.87	50.00	20.00	24	8.02	8.02	-
Nappies	2.91	58.29	4.49	70.00	10.00	24	2.91	2.91	-
Plastic	21.13	18.37	34.78	75.00	100.00	-	-	21.13	-
Glass	1.42	-	-	3.00	50.00	-	-	-	-
Metals	1.05	-	-	3.00	50.00	-	-	-	-
Others	2.21	22.73	3.84	3.00	50.00	-	-	-	-

[a] [22], [b] [11].

2.3. Estimation of Energy Recovery Potential

2.3.1. Energy Generation from LFG

The LFG generation was estimated using the LandGEM model (version 3.03) developed by the US EPA. The model is based on a first-order decay rate equation for quantifying emissions from landfilled waste [23]. The LFG generation and ERP are calculated following Equations (4)–(8).

$$Q_{CH_4(LFG)} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k \times L_0 \times (M_i/10) \times e^{-kt_{i,j}} \quad (4)$$

where $Q_{CH_4(LFG)}$ is the annual CH_4 generation in the year of calculation; i is the 1-year time increment; j is the 0.1-year time increment; n is the duration of waste acceptance at a landfill; M_i is the mass of waste disposed of in year i; and $t_{i,j}$ is the time in year j^{th} section of waste (M_i) accepted. CH_4 generation rate constant (k) and the potential CH_4 generation capacity (L_0) are calculated as follows:

$$k = \sum_{i=1} (k_i \times W_f) \tag{5}$$

$$L_0 = MCF \times DOC \times DOC_f \times F_{CH_4} \times 16/12 \tag{6}$$

where k_i is the degradation rate of decomposable waste composition i and taken from the IPCC 2006 guidelines for the moist and wet tropical climate region; W_f is the fraction of decomposable wastes; MCF is the CH_4 correction factor; DOC_f is the fraction of degradable organic carbon which decomposes; F_{CH_4} is the fraction of CH_4 in landfill gas; and 16/12 is the conversion factor from methane to carbon. DOC is the degradable organic yield on the CH_4 in landfill gas and can be estimated as

$$DOC = (0.4 \times A) + (0.17 \times B) + (0.15 \times C) + (0.30 \times D) \tag{7}$$

where A is paper and cardboard; B is wood and leaves; C is food waste; and D is textiles and nappies (see Table 1).

In general, landfill CH_4 collection cannot achieve 100% efficiency due to leakage of the gas collection system, bio-oxidation with covered soil, and improper cap [24]. According to Amini et al. [25], the average LFG collection efficiency ranges from 67% to 90%. In this study, the collection efficiency is taken as 75%, following [15]. The ERP for LFG recovery can be calculated following [8]:

$$ERP_{LFG} = (Q_{CH_4(LFG)} \times (1 - OF) \times LHV \times \eta \times \lambda \times CF)/3.6 \tag{8}$$

where OF is the oxidation factor in a landfill; LHV is the low heating value of CH_4; η is the electricity conversion efficiency for internal combustion; λ is the collection efficiency of methane from landfill; CF is the capacity factor of the plant over the year's operation (see Table 2); and 3.6 is the conversion factors from kJ to kWh.

Table 2. Parameters for calculating energy recovery potential from the three technologies.

Plant Type	*OF* (%)	*LHV* (MJ/m^3)	η (%)	λ (%)	*CF* (%)
LFG	10 [a]	37.2 [b]	30 [c]	75 [d]	85 [e]
AD	-	37.2 [b]	30 [c]	95 [a]	85 [e]
Incineration	-	(see Table 1)	25 [c]	-	80 [c]

[a] [11], [b] [26], [c] [17], [d] [15], [e] [5].

2.3.2. Energy Generation from Incineration

The data in Tables 1 and 2 are used for estimating ERP from incineration using moving grate system, following Equation (9) [17].

$$ERP_{inc} = (MSW_i \times LHV_i \times \eta \times CF)/3.6 \tag{9}$$

where ERP_{inc} is the energy recovery potential from waste incineration; and LHV_i is the low heating value of waste fraction i.

2.3.3. Energy Generation from AD

Food waste is considered as a potential feedstock for the digestion plant to produce electricity potential. According to Al-Wahaibi et al. [27], the biogas yield derived from experiments was 1550 L/kg of mixed food waste with a CH_4 content of 30%. Therefore, the amount of CH_4 that can be derived from the AD plant can be calculated as follows:

$$Q_{CH_4(AD)} = (M_{food\ waste} \times dm \times Yield_{biogas} \times F_{CH_4})/1000 \tag{10}$$

where $Q_{CH_4(AD)}$ is the methane generation from AD; $M_{food\ waste}$ is the mass of input waste; dm is the dry matter content of food waste, taken as 21.23% [22]; $Yield_{biogas}$ is biogas yield; and F_{CH_4} is the methane content in biogas. The ERP from AD technology and the plant capacity can be calculated as follows [8]:

$$ERP_{AD} = (Q_{CH_4(AD)} \times LHV \times \eta \times \lambda \times CF)/3.6 \quad (11)$$

where ERP_{AD} is the energy recovery potential from AD technology; the values of LHV of CH_4, η, λ, and CF are shown in Table 2.

In this study, WTE plants are assumed to operate throughout the year. Therefore, the plant capacity LFG recovery, incineration, and AD technologies are determined as follows:

$$G_{P(i)} = ERP_i/24 \times 365 \quad (12)$$

where $G_{P(i)}$ is the plant capacity (kW) for WTE technology i.

2.4. Economic Feasibility Analysis

The economic assessment is performed based on the LCOE, NPV, and payback period (PBP) for technology comparison.

2.4.1. Net Present Value (NPV)

NPV is the sum of annual cash flow based on the discount rate over the project's lifetime. The project is considered economically viable when the NPV is positive, and it can be calculated as follows [28]:

$$NPV = \sum_{n=0}^{y} \frac{P_n}{(1+\alpha)^n} = P_0 + \frac{P_1}{(1+\alpha)^1} + \cdots + \frac{P_y}{(1+\alpha)^y} \quad (13)$$

where P_n is the net cash flow rate; α is the annual discount rate taken as 10%; [8] y is the economic period of the project; and P_0 is the initial investment cost. P_n can be determined as

$$P_n = Rev - OPEX - P_{tax} - INVEST_{cost} \quad (14)$$

$$Rev = ERP \times FIT + Fee_{gate} \times MSW \quad (15)$$

$$P_{tax} = Profit \times R_{tax} \quad (16)$$

$$Profit = Rev - O\&M_{cost} \quad (17)$$

where Rev is the revenue from the WTE plant; $OPEX$ is the operation and maintenance cost; P_{tax} is the tax paid on the profit made from the WTE plant; $Invest_{cost}$ is the initial investment cost; FIT is the feed-in tariff; Fee_{gate} is the gate fee for waste disposal; $Profit$ is the accrued profit from the plant; and R_{tax} is the annual marginal tax rate of Cambodia (20%). The purchasing cost of electricity for a biomass-fired plant in Cambodia was from 0.095 to 0.120 USD/kWh [29]; hence, the feed-in tariff was taken as 0.095 USD/kWh as shown in Table 3.

2.4.2. Payback Period (PBP)

PBP is the time at which the project can recover the amount invested. It is the maximum period of the year in which a project starts to have a return on investment, and it can be calculated as follows [15]:

$$PBP = \frac{TLCC}{Proft} \quad (18)$$

$$TLCC = INVEST_{cost} + \sum_{n=1}^{y} \frac{O\&M_{cost}}{(1+\alpha)^{y}} \quad (19)$$

where $TLCC$ is the total life cycle cost of the WTE project.

2.4.3. Levelized Cost of Electricity (LCOE)

LCOE is the minimum cost of the electricity generated (in USD/kWh) at which the system breaks even [26]. LCOE serves as a vital economic indicator to measure the economic viability of a project, and it can be calculated as follows [26]:

$$LCOE = (\frac{TLCC}{ERP_i}) \times (\frac{\alpha(1+\alpha)^{y}}{(1+\alpha)^{y}-1}) \quad (20)$$

2.4.4. Capital Investment and Operating Expenditure

Investment and Operating Cost for LFG Recovery

This study considered the internal combustion engine (ICE), commonly used for electricity generation from LFG recovery and AD plants, because of its low cost and high efficiency. The investment cost of the LFG recovery ($CAPEX_{LFG}$) can be calculated as follows [26,28]:

$$CAPEX_{LFG} = C_{(v)} + C_{(w)} + C_{(k)} + C_{(e)} + C_{(ICE)} \quad (21)$$

where $C_{(v)}$ is the installation cost of the vertical gas extraction wells; $C_{(w)}$ is the cost of installing wellheads and pipe gathering; $C_{(k)}$ is the cost for installation of the knockout, blower, and flare system; $C_{(e)}$ is the cost of engineering, permitting, and surveying; and $C_{(ICE)}$ is the cost of installing reciprocating internal combustion engine. These costs can be calculated as follows:

$$C_{(v)} = 85 \times W_n \times (D_{well} - 10) \quad (22)$$

$$C_{(w)} = W_n \times 17,000 \quad (23)$$

$$C_{(k)} = (FR_{CH_4})^{0.6} \times 4600 \quad (24)$$

$$C_{(e)} = W_n \times 700 \quad (25)$$

$$C_{(ICE)} = (1300 \times G_{P(LFG)}) + 1,100,000 \quad (26)$$

where W_n is the number of wells dug at the site; FR_{CH_4} is the methane flow rate; and D_{well} is the depth of the well, assumed to be 15 m.

The operating and maintenance expenditure for LFG recovery ($OPEX_{LFG}$) is the sum of fixed operation and maintenance of the landfill site cost ($O\&M_{fixed}$) and the variable operation and maintenance cost ($O\&M_{variable}$). The calculation of costs associated with operation and maintenance is as follows [8]:

$$OPEX_{LFG} = O\&M_{fixed} + O\&M_{Variable} \quad (27)$$

$$O\&M_{fixed} = O\&M_{cost(LF)} + O\&M_{cost(ICE)} \quad (28)$$

$$O\&M_{cost(LF)} = 2600 \times W_n + 5100 \quad (29)$$

$$O\&M_{cost(ICE)} = 0.025 \times ERP_{LFG} \quad (30)$$

$$O\&M_{variable} = ERP_{LFG} \times 4.4/1000 \quad (31)$$

where $O\&M_{cost(LF)}$ and $O\&M_{cost(ICE)}$ are the costs for scheduled operation and maintenance of the landfill and the IEC, respectively, and 4.4 is the cost for unscheduled expenditure and maintenance of the system [5].

Investment and Operating Cost for Incineration

The models for estimating the capital expenditure ($CAPEX_{inc}$) and the fixed operating expenditure ($Fixed\ OPEX_{inc}$) of an incinerator were adopted from Alzate-Arias et al. [30], as given in Equations (32) and (33). The calculation of variable operating cost for incineration follows Equation (31).

$$CAPEX_{inc} = 16,587 \times G_{P(inc)}{}^{0.82} \quad (32)$$

$$Fixed\ OPEX_{inc} = CAPEX_{inc} \times 4\% \quad (33)$$

Investment and Operating Cost for AD

The CAPEX and fixed OPEX were calculated for AD technology as shown in Equations (34) and (35) [5,28]. The calculation of the variable operating cost of the AD plant follows Equation (32).

$$CAPEX_{AD} = Cost_{Install} \times G_P \quad (34)$$

$$O\&M_{fixed} = CAPEX_{AD} \times 3\% \quad (35)$$

where $Cost_{Install}$ is the installation cost of the AD plant, which is taken as 4339 USD/kW [28].

Table 3. Input parameters for economic analysis.

Parameter	Value
Electricity price (USD/kWh)	0.095 [a]
Discount rate (%)	10 [b]
Gate fee (USD/ton)	1.00
Internal use of electricity (%)	20 [c]
Marginal tax rate (%)	20
Variable OPEX for LFG and AD (%)	4.40 [d]
Variable OPEX for incineration (%)	4.00 [d]
General inflation rate (%)	5.48

[a] [29], [b] [8], [c] [31], [d] [5].

2.5. Environmental Performance Evaluation

An environmental assessment was performed considering the impact on GWP. The calculation of GWP is considered using (1) the direct emissions because of fugitive emissions from LFG and AD technologies and stack emissions from an incinerator and (2) the emission avoidance from electricity replacement. It is important to note that 36% of electricity production in Cambodia is generated from coal-fired power plants; hence, the present study considered replacing electricity generated from this conventional source. The GHG emissions were quantified following the IPCC 2006 guidelines with the 100-year GWPs of 1, 25, and 298 for CO_2, CH_4, and N_2O, respectively [11].

2.5.1. Direct GHG Emissions

Fugitive CH_4 emissions from the LFG recovery and AD significantly contribute to GWP. CO_2 released from the landfill and biogas plants is of biogenic origin; hence, it is not included in the calculation of GWP. GHG emissions from the two technologies are calculated below:

$$GHG_{LFG} = Q_{CH_4(LFG)} \times (1 - OF) \times (1 - \lambda) \times \rho_{CH_4} \times GWP_{CH_4} \quad (36)$$

$$GHG_{AD} = Q_{CH_4(AD)} \times (1 - \lambda) \times \rho_{CH_4} \times GWP_{CH_4} \quad (37)$$

where GHG_{LFG} and GHG_{AD} are the direct GHG emissions from landfill and AD plants, respectively; ρ_{CH_4} is the density of CH_4 in standard temperature (6.67×10^{-4} t/m^3); and GWP_{CH_4} is the global warming potential for CH_4.

The direct emissions from waste combustion in an incinerator are calculated following Equations (38)–(40).

$$GHG_{inc} = E_{CO_2} + E_{N_2O} \times GWP_{N_2O} \quad (38)$$

$$E_{CO_2} = MSW \times \sum (W_i \times dm_i \times CF_i \times FCF_i \times OF \times 44/12) \quad (39)$$

$$E_{N_2O} = \sum (W_i \times EF_{N_2O})/1000 \quad (40)$$

where GHG_{inc} is the direct GHG emissions from incineration; GWP_{N_2O} is the global warming potential for N_2O; E_{CO_2} and E_{N_2O} are the emissions of CO_2 and N_2O from incinerator, respectively; W_i is the fraction of waste in MSW, dm_i, CF_i, and FCF_i are the dry matter content, total carbon content, and fossil carbon fraction of waste constituent i, respectively; OF is the oxidation factor, taken as 100% [11]; 44/12 represents the molecular weight ratio of CO_2 to carbon; and EF_{N_2O} is the emission factor for N_2O, taken as 50 gN_2O/t [11].

2.5.2. GHG Emission Avoidance

Energy generation from WTE technologies is used to offset the electricity generated from coal-based power plants. The emission factor for the coal power plant was taken from an average of coal-fired power plant technologies in Cambodia, which is taken as 0.919 kgCO_2-eq/kWh [32]. The emission avoidance due to the implementation of WTE technologies is calculated as shown below:

$$GHG_{avoided} = ERP_i \times EF_{coal-fired\ plant} \quad (41)$$

where $GHG_{avoided}$ is the avoided emission of GHGs from electricity replacement, and ERP_i is the energy recovery potential of each WTE technology.

2.6. Sensitivity Analysis

Electricity generation and the economic viability of WTE technologies are influenced by the input parameters, such as the electricity conversion efficiency and the discount rate. In this study, a sensitivity analysis was performed to observe these parameters' influence on the economic viability of the three technologies.

3. Results and Discussion

3.1. MSW Generation Projection

The MSW generation was projected from 2023 to 2042 using population data obtained from the general population census report [21], waste disposal data obtained from the Dangkao landfill office, and waste collection efficiency data taken from the local government's report [33]. The per capita generation of MSW was calculated at 1.50 kg/day, which is an increase from the 2016 rate of 1.32 kg/capita/day [33]. The United States of America and Abu Dhabi, an emirate of the United Arab Emirates, have recorded higher MSW generation rates, amounting to 2.03 and 2.1 kg/capita/day, respectively [18,34]. Nevertheless, Thailand and Vietnam have lower generation rates at 1.14 and 0.80 kg/capita/day, respectively [18]. As shown in Figure 2, the MSW generation in Phnom Penh is expected to be about 1,454,152 tons in 2023 and would exponentially increase to 2,980,801 tons in 2042. With 92% collection efficiency, an average of 1,961,167 tMSW is expected to be collected and disposed of at the landfill annually between 2023 and 2042, and this was used in the model calculation. The energy recovery potential of incineration is considered for a moving grate-firing incineration system, which utilizes only burnable waste. Therefore, the incineration capacity is 5122 tMSW/day.

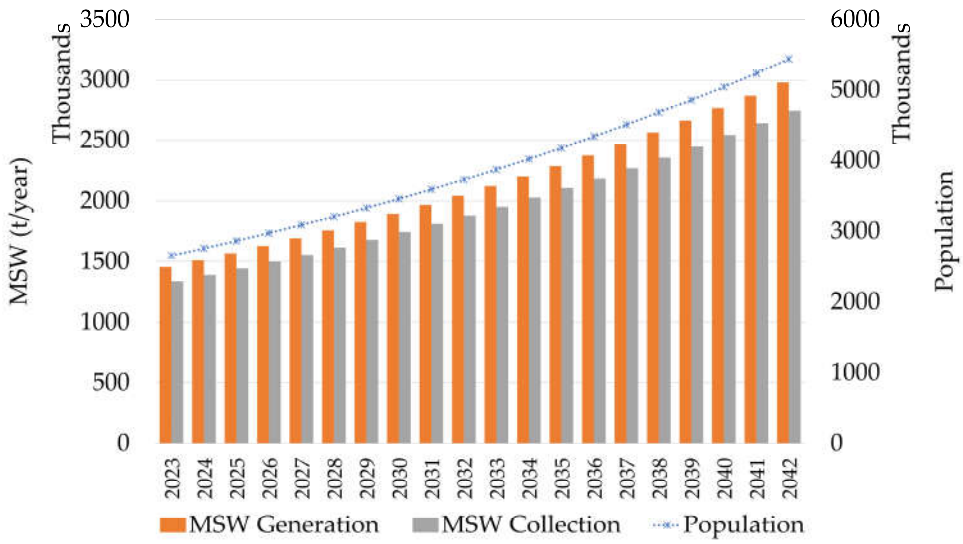

Figure 2. MSW projection for Phnom Penh municipality from 2023 to 2042.

3.2. Energy Recovery Potential

The input parameters for the LandGEM model were calculated under Equations (5)–(7) and values recommended in the IPCC 2006 guidelines, as shown in Table 4. The value of k was estimated at 0.21, which is consistent with field measurement and laboratory tests for tropical landfills [35], and falls within the range of rapidly degrading waste in moist and wet tropical regions with annual precipitation of 1000 mm or more, as suggested by the IPCC [11]. The L_0 was determined to be 90 m^3/t, slightly lower than that of the wet landfill in the LandGEM model [23]. Only the biodegradable waste types listed in Table 1 were considered for LFG simulation in the LandGEM model. As shown in Figure 3, CH_4 generation is zero in 2023 (the initial year of waste acceptance) and will exponentially increase from 2024 to 2043 as the waste accumulates in the landfill. CH_4 generation begins to decline drastically after one year of landfill closure, which could impact the economic viability of LFG recovery. Therefore, from an economic perspective, this study considered the utilization of CH_4 for electricity generation for 15 years [36,37], from 2028 to 2042.

Table 4. Key parameters for the LandGEM model.

Parameters	Unit	Value
Landfill open	year	2023
Landfill closure year (with 80-year limit)	year	2042
Annual precipitation	mm	1550
Methane generation rate constant, k	$Year^{-1}$	0.213 [a]
Potential methane generation capacity, L_0	m^3/ton	90 [a]
Nonmethane organic carbon concentration (NMOC)	ppmv as hexane	600
Fraction of methane (F)	% by volume	50 [b]
MCF for unmanaged landfill–deep (>5 m waste)		0.8 [b]
Degradable organic carbon (DOC)		0.15 [a]
Fraction of degradable organic carbon (DOC_f)		0.77 [c]

[a] Calculated from Equations (5)–(7), [b] [11], [c] [38].

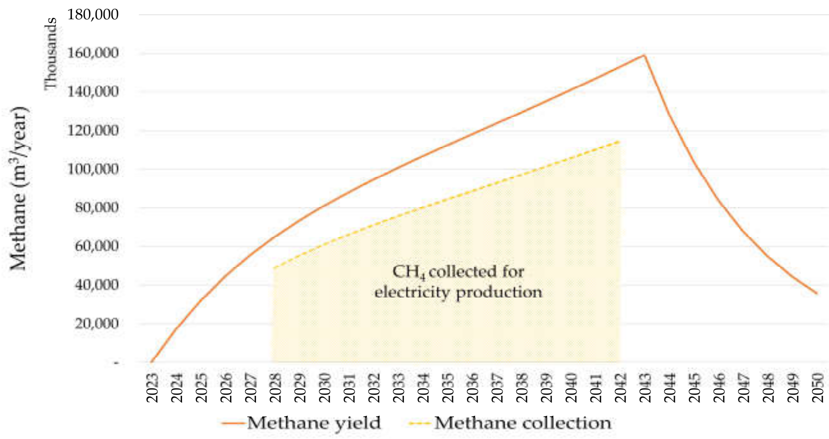

Figure 3. Annual landfill methane generation and collection.

Within this period, the average annual CH_4 yield was estimated at 111 million m^3 with an average flow rate of 212 m^3/min, comparable to a study in Taiwan [39]. In this study, a 75% CH_4 collection efficiency is considered, which is in line with other researchers [8,26,36].

The annual ERP from the LFG recovery ranges between 120.38 and 320.52 GWh over a project lifespan (2028–2042), as shown in Table 5. This value is consistent with a report by Ogunjuyigbe et al. [26] when applying a similar electricity conversion efficiency. The average ERP was 220.96 GWh/year with an installed capacity of 23 MW (see Table 6), 2.5-fold greater than the ERP from the rice-straw-fired plant in Cambodia, which was estimated to be about 10 MW [29].

Table 5. ERP over the lifetime of WTE technologies.

Year	LFG (GWh)	Incineration (GWh)	AD (GWh)	Year	LFG (GWh)	Incineration (GWh)	AD (GWh)
2023		660.94	162.59	2033	179.24	964.34	237.22
2024		686.39	168.85	2034	189.80	1001.47	246.36
2025		712.82	175.35	2035	200.06	1040.02	255.84
2026		740.26	182.10	2036	210.16	1080.06	265.69
2027		768.76	189.11	2037	220.18	1121.65	275.92
2028	115.44	798.36	196.39	2038	230.22	1164.83	286.54
2029	130.50	829.09	203.95	2039	240.34	1209.68	297.58
2030	144.11	861.01	211.81	2040	250.62	1256.25	309.03
2031	156.60	894.16	219.96	2041	261.09	1304.61	320.93
2032	168.23	928.59	228.43	2042	271.81	1354.84	333.29

Table 6. Energy and power production.

WTE Plant Characteristics	Unit	LFG	Incineration	AD
Mass of input waste	Ton	1,454,989 *	1,869,482	964,502
Operating time	h/year	8760	8760	8760
Lifespan of the WTE projects	Year	15 [a]	20 [b]	20 [b,c]
Average electricity production within 2023–2042	GWh/year	197.89	968.91	238.35
Plant capacity	MW	23	111	27

* Only biodegradable waste fractions are included in the LandGEM model. [a] [36,37], [b] [26], [c] [8].

For the incineration technology, only organic and burnable wastes are considered. The ERP from incineration technology is much greater than that of LFG technology, with annual production ranging between 660.94 and 1354.84 GWh/year. In Mexico, the ERP was estimated at 537.71 GWh from the combustion of 708,900 tons of MSW [36], which is higher than the value in this study due to a higher LHV.

The CH_4 generated from AD technology was estimated at 98.72 m^3/t of food waste. This value is within the range of other studies that used the same technology [27,40–42]. Alzate et al. [42] reported 71 m^3 of CH_4 generated from AD plants, while Bicks [40] presented a lower CH_4 yield at 50 m^3/t of food waste. Notably, Al-Wahaibi et al. [27] and Chowdhury [41] found a higher CH_4 generation rate at 123 and 200 m^3/t of food waste, respectively. The present study estimated the ERP from AD technology at about 238.35 GWh/year, which is greater than that generated from LFG but lower than incineration.

As shown in Table 6, a comparison of the three technologies reveals that incineration produces outstanding electricity and has the potential to contribute significantly to the national electricity supply, accounting for 23.63% of imported electricity. According to a report by the Electricity Authority of Cambodia, 11,092 GWh of energy were sold to 3,244,209 consumers in 2021, averaging to 3,357 kWh/consumer/year [20]. Based on this, electricity generated from incineration could potentially supply approximately 238,220 consumers.

3.3. Economic Feasibility Assessment

In the economic analysis, the plant's internal use accounts for 20% of electricity generation, so only 80% of electricity is sold to the national grid to generate income. As shown in Table 7, the initial investment cost of LFG recovery is USD 31,716,738, lower than the capital cost of the AD plant (USD 101,373,259). The incineration technology uses a moving grate system, resulting in a higher capital investment cost of USD 227,474,483. Both LFG recovery and incineration technologies are economically feasible, with a positive NPV, while AD technology results in a negative NPV, indicating that it is not favorable from an economic perspective. The PBPs for LFG and incineration technologies are 7.13 and 8.36 years, respectively. Ogunjuyi et al. [26] evaluated the economic feasibility of LFG, incineration, and AD technologies in various cities in Nigeria. Their study revealed that the PBPs for LFG and AD technologies ranged from 4.9 to 7.8 years and from 1.2 to 18.6 years, respectively, but incineration had a higher PBP, exceeding 20 years in all cities.

Table 7. Summary of economic feasibility assessment of the WTE technologies.

Financial Indicators	Unit	LFG	Incineration	AD
Cost				
Initial investment cost	USD	31,716,738	227,474,483	101,373,259
Fixed O&M cost	USD/year	7,426,072	15,829,524	3,041,198
Variable O&M cost	USD/year	916,590	4,080,768	1,048,728
Total life cycle cost	USD	95,232,512	387,186,003	152,593,851
Depreciation cost	USD/year	2,114,449	11,373,724	5,802,066
Tax	USD/year	1,343,205	8,423,313	1,405,515
Benefit				
Net present value (NPV)	USD	25,472,926	169,858,819	−5,556,540
Payback period (PBP)	Year	7.13	8.36	>20
Levelized cost of electricity (LCOE)	USD/kWh	0.070	0.053	0.093
Internal rate of return	%	18.53	16.94	8.08
Net cash flow	USD	5,037,019	33,693,254	6,484,177

Though AD technology may be less commercialized, it is possible to increase its profitability by optimizing income from selling digestate for agricultural purposes due to its nutrient richness [43]. Tan et al. [44], reported that approximately 30% of digestate is produced in proportion to the waste input volume. In this study, the methane content in biogas was set at a low value of 30%. However, Holden et al. [45] reported that the CH_4 content in biogas can be as high as 70%, depending on the substrate and the operational conditions of the AD plant. Therefore, increasing the methane content by 10% could make AD technology economically feasible and reduce the PBP to 15 years.

The LCOEs of the LFG, incineration, and AD technologies were found to be 0.070, 0.053, and 0.093 USD/kWh, respectively, which is lower than the current feed-in tariff for biomass power plants in the country. The PBPs and IRRs of the incineration and LFG technologies were competitive. Incineration had a PBP of 8.36 years and an IRR of 16.94%, while LFG recovery could have breakeven within 7.13 years and had an investment return of 18.53%. These results are comparable to those of other projects with similar power capacities. For example, Ayodele et al. [8] reported an LCOE of 0.067 USD/kWh for LFG technology in Nigeria, while Emilio et al. [36] and Xin-Gang et al. [46] obtained very close IRRs for incineration plants in Mexico and China at 17% and 18%, respectively. Nubi et al. [28] found that incineration is the most promising technology, with an LCOE ranging from 0.046 to 0.062 USD/kWh and the highest IRR (45–63%). In contrast, AD technology had an IRR of 8.83%, which is less than the discount rate and confirms its financial infeasibility. This result is consistent with another study that found an IRR of 6.90% for the same technology [43]. However, Ayodele et al. [8] obtained better economic feasibility for AD technology with an IRR of 19.3%. On the other hand, Ogunjuyigbe et al. [26] found financial infeasibility for incineration technology, with the LCOE ranging from 0.2033 to 0.4585 USD/kWh, which contrasts with the findings of this study.

3.4. Environmental Performance

As shown in Table 8, incineration yields the highest GWP among the three technologies, accounting for 975,554 tCO_2-eq/year in proportion to a large quantity of waste incinerated. In incineration technology, stack emission is the main contributor to the GWP [47]. Furthermore, the environmental performance of incineration depends mainly on electricity generation efficiency, with higher generation efficiency meaning better emission saving. For example, with 25% electricity generation efficiency, approximately 1.007 kgCO_2-eq/kWh of GHGs is produced from an incineration plant. By increasing the plant efficiency by 5%, the GHG emissions would reduce by 17%. Another key contributor to the high emissions from incineration technology is the properties of feedstock. More than 20% of incoming waste is plastic waste, which has the most significant impact on GWP owing to the fossil carbon fraction, carbon content, and dry matter content. In addition, the current MSW disposal is commingled without source segregation, resulting in high moisture content. To obtain better economic benefits and minimize the GHG emissions from WTE technologies, Tan et al. [48] suggested having a pretreatment of input waste.

Table 8. GHG emissions and emission saving from WTE technologies (tCO_2-eq/year).

Technology	Direct Emissions	Emission Avoidance	Net Emissions
LFG	417,533	181,930	235,603
Incineration	975,554	890,750	84,803
AD	79,386	219,121	−139,735

LFG is the second-largest emission source contributing to GWP impact, mainly from uncollected CH_4 (25%), accounting for 417,533 tCO_2-eq/year of GHGs. At the same time, AD emits the fewest GHGs since the collection efficiency of CH_4 can be achieved at 95%, resulting in only 5% of CH_4 being released into the atmosphere [11].

Figure 4 presents the environmental performance of WTE technologies by offsetting conventional coal-based electricity. The results of the study show that LFG recovery has the highest net GWP, equivalent to 137,439–323,604 tCO_2-eq/year of GHGs. Incineration has a lower GWP, ranging between 57,849 and 118,582 tCO_2-eq/year. However, while incineration generates a high amount of GHG, the benefits of electricity generation could offset its global warming impacts. AD technology has significantly contributed to reducing GWP impact, with 95,321–195,395 tCO_2-eq/year of GHGs avoided. Therefore, from an environmental point of view, AD technology would be the best option due to its emission-saving benefits.

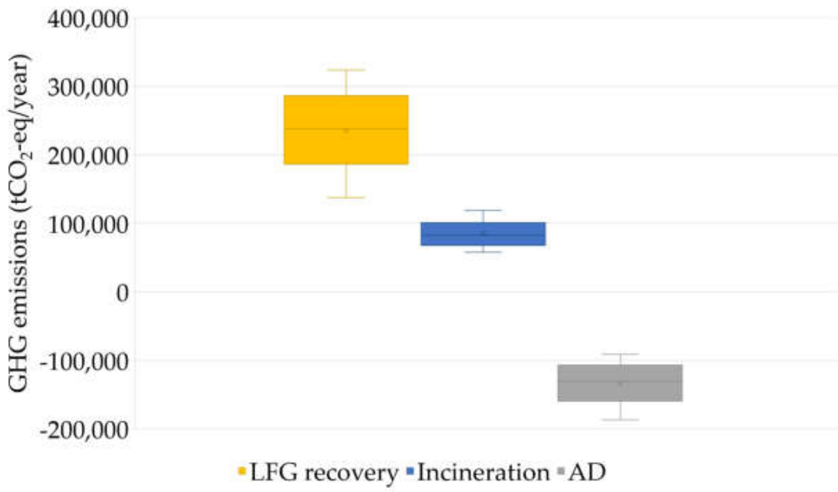

Figure 4. Net GHG emissions of WTE technologies.

3.5. Sensitivity Analysis

To gain insight into the economic feasibility of WTE technologies, a sensitivity analysis was performed to examine the influence of the discount rate and electricity generation efficiency. Figure 5 shows how economic parameters (NPV, LCOE, PBP, and TLCC) vary with changes in electricity generation efficiency. The results indicate that improving efficiency from 15% to 40% leads to a significant reduction in LCOE for LFG, incineration, and AD technologies, with values ranging from 0.071 to 0.069 USD/kWh, from 0.057 to 0.049 USD/kWh, and from 0.180 to 0.071 USD/kWh, respectively. Notably, increasing the energy generation efficiency of AD to 32% results in a positive NPV and a reduced PBP of 19.22 years. This suggests that a minimum energy generation efficiency of 32% is needed to make AD technology economically viable. Additionally, the NPV for incineration technology shows a definite upward trend as the plant's efficiency increases. All WTE technologies have higher TLCC values as plant efficiency improves. Thus, energy conversion efficiency is a critical factor affecting the economic viability of all WTE technologies.

Figure 6 provides additional insights into the importance of the discount rate when comparing WTE technologies. The figure shows that the NPV and TLCC decrease consistently as the discount rate increases. For AD technology, the NPV is positive when the discount rate is less than 10%. However, as the discount rate goes beyond 10%, the PBP of the AD plant increases to more than 20 years. The LCOEs and PBPs for all technologies increase substantially as the discount rate increases. This suggests that lower discount rates in economic analysis would make WTE technologies more competitive and appealing for electricity generation.

To improve the attractiveness of WTE technologies and reduce the PBP, it is essential to increase profits by raising the feed-in tariff and tipping fee and reducing internal energy consumption. Table 9 illustrates the impact of fluctuations in the feed-in tariff (±0–30%) on the IRRs and NPVs of WTE technologies. The results indicate that changes in electricity prices have a significant effect on both IRR and NPV. Specifically, a 30% decrease in electricity prices resulted in a negative NPV for LFG recovery and AD technologies. Additionally, the IRRs for all three technologies declined by less than 10%. However, increasing the feed-in tariff by a minimum of 10% would turn the negative NPV value of AD technology into a positive one.

The current tipping fee in Cambodia is insufficient compared with those of other countries. In the Philippines, the tipping fee for waste disposal is 15 USD/t [49], while the United Arab Emirates charges 14 USD/t for waste disposal in waste treatment facilities [43]. In addition to raising the tipping fee, Dong et al. [47] suggested reducing internal electricity consumption as much as possible to achieve effective energy recovery.

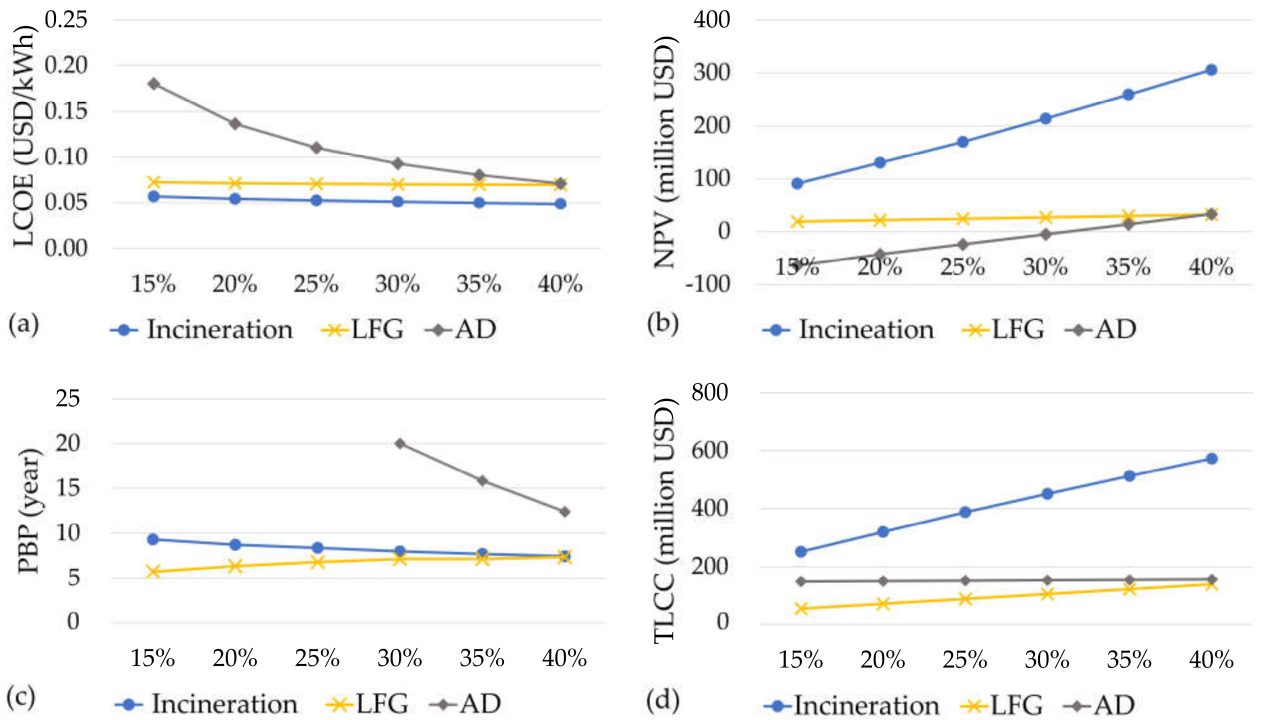

Figure 5. Influence of electricity generation efficiency on (**a**) LCOE, (**b**) NPV, (**c**) PBP, and (**d**) TLCC.

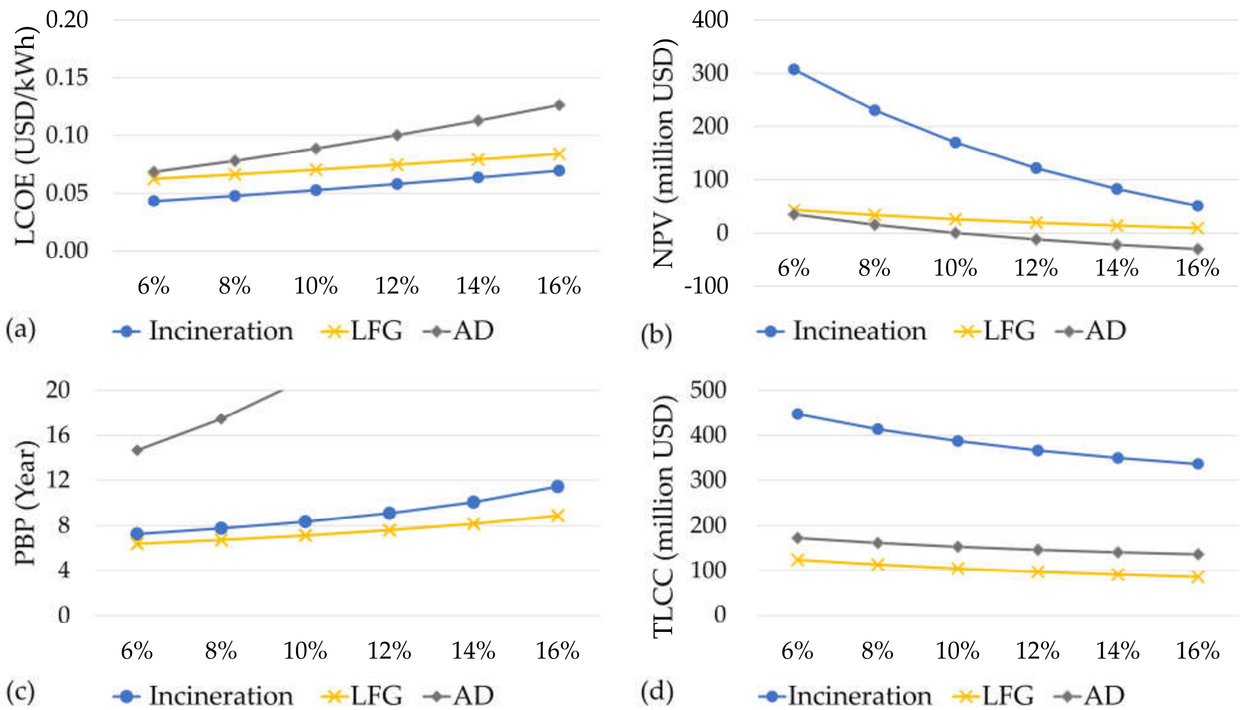

Figure 6. Influence of discount rate on (**a**) LCOE, (**b**) NPV, (**c**) PBP, and (**d**) TLCC.

WTE technologies offer significant environmental benefits by saving an abundance of carbon. In addition to this, additional income can be generated through carbon credits for carbon avoidance and by selling by-products such as digestate, which should be included in the economic analysis. According to Tan et al. [44], the financial benefit from carbon credit is approximately 15.38 USD/tCO_2 and selling one ton of digestion can yield around USD 100. The development of financial and regulatory policies, such as carbon trading, renewable power credits, and renewable power production tax credits, could encourage more investment in energy recovery from waste [25]. Such incentives would help to further draw attention to the economic benefits of WTE technologies.

Table 9. Influence of feed-in tariff on NPV, PBP, and IRR.

Economic Parameter	Technology	−30%	−20%	−10%	0%	+10%	+20%	+30%
NPV	Incineration	22,461,015	71,593,616	120,726,218	169,858,819	218,991,420	268,124,021	317,256,622
	LFG	−1,856,129	7,253,556	16,363,241	25,472,926	34,582,611	43,692,296	52,801,980
	AD	−41,815,814	−29,729,389	−17,642,965	−5,556,540	6,529,884	18,616,309	30,702,733
PBP	Incineration	16.63	12.38	9.95	8.36	7.22	6.36	5.69
	LFG	>20	11.16	8.65	7.13	6.10	5.34	4.75
	AD	>20	>20	>20	>20	17.68	14.68	12.62
IRR	Incineration	9.98%	12.46%	14.77%	16.94%	19.03%	21.05%	23.02%
	LFG	7.7%	11.73%	15.29%	18.53%	21.56%	24.44%	27.2%
	AD	2.78%	4.73%	6.48%	8.08%	9.57%	10.98%	12.32%

4. Conclusions

This study evaluated the energy recovery potential, economic feasibility, and GHG emission saving of LFG recovery, incineration, and AD technologies for a case study in Phnom Penh, Cambodia. The results revealed that incineration is the most promising technology in terms of energy generation and financial profitability with a low LCOE, high NPV, and possibility of breakeven in 8.36 years. Incineration can provide superior MSW management by accepting abundant organic and inorganic feedstocks, yielding a large amount of power that could replace electricity and save GHG emitted by coal-based power plants, equivalent to 968.91 GWh/year and 890,750 tCO_2-eq/year, respectively. On the other hand, LFG recovery demonstrated an attractive investment with a PBP of 7.13 years and a higher IRR of 18.53%. However, LFG recovery technology emitted the highest amount of GHGs, and the system has a limited lifespan, while the GHG generation at the landfill site can persist for up to 100 years. AD is the most appropriate technology for handling organic waste and can substantially reduce overall GHG emissions. However, based on an economic performance evaluation, AD technology is deemed economically infeasible. Improving energy conversion efficiency and reducing the discount rate could increase investment interest in all of these technologies.

Incineration technology demonstrated outstanding profitability; however, there are growing concerns regarding stack emissions and bottom ash management. Furthermore, incineration is becoming increasingly less desirable due to difficulties in gaining public acceptance, as it poses a potential risk of disasters and occasional pollution. Compliance with air emission standards and proper management of bottom ash are crucial in order to mitigate potential health risks. In developed countries, bottom ash is treated and used as a construction material instead of being disposed of at landfills. The present study focused solely on the impact of WTE technologies on GWP. However, other hydrocarbon emissions resulting from complete and incomplete combustions of incineration, such as dioxins, furans, and benzene, need to be comprehensively examined in further studies. In particular, the associations between these emitted hydrocarbons and human health, ecosystems, and natural resources should be evaluated through life cycle assessment. In Cambodia, the government has recently put more effort into encouraging investment in WTE. However, the adoption and implementation of WTE technologies require clearer guidelines. Regulations and incentive policies including investment subsidies, tax exemptions, carbon credits, etc., should be implemented to make the WTE project more attractive in commercial schemes. This analysis will serve as the foremost fundamental information for developing sustainable MSW management through WTE technology in Phnom Penh, Cambodia.

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Abbreviations

AD	Anaerobic digestion
CAPEX	Capital expenditure
CH_4	Methane
CO_2	Carbon dioxide
ERP	Energy recovery potential
GHGs	Greenhouse gases
GWP	Global warming potential
ICE	Internal combustion engine
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal rate of return
LandGEM	Landfill Gas Emissions Model
LCC	Life cycle costing
LCOE	Levelized cost of electricity
LFG	Landfill gas
LHV	Low heating value
OPEX	Operation expenditure
MSW	Municipal solid waste
NPV	Net present value
N_2O	Nitrous oxide
PBP	Payback period
SRF	Solid refuse fuels
WTE	Waste-to-energy

Symbols

$C_{(v)}$	Vertical gas extraction well cost, USD
$C_{(w)}$	Wellhead and pipe installation cost, USD
$C_{(k)}$	Knockout installation cost, USD
$C_{(e)}$	Engineering cost, USD
$C_{(ICE)}$	Internal combustion engine installation cost, USD
CF	Capacity factor, %
D_{well}	Depth of the well, m
DOC	Degradable organic carbon, %
DOC_f	Fraction of degradable organic carbon, %
dm	Dry matter, %
E_{AD}	Emission from anaerobic digestion
E_{CO_2}	Emissions of CO_2
E_{N_2O}	Emissions of N_2O
$EF_{coal\text{-}fired\ plant}$	Emission factor for coal power plant
EF_{N_2O}	Emission factor for N_2O
FCF	Fossil carbon fraction of waste, %
FIT	Feed-in tariff, USD/tMSW
F_{CH_4}	Fraction of methane, %
Fee_{gate}	Waste disposal fee at disposal site, USD/tMSW
FR_{CH_4}	Methane flow rate, m^3/min
$G_{P(i)}$	Plant capacity of technology i, kW
k	Methane generation constant rate, per year
L_0	Potential methane generation capacity
OF	Oxidation factor, %
P_0	Initial investment cost, USD
P_n	Net cash flow, USD
P_{tax}	Tax paid on the profit, USD
$P_{(t)}$	Projected population
$P_{(0)}$	Population in the initial year of projection
MCF	Methane correction factor, %
M_i	Mass of waste, t
$O\&M_{cost}$	Operation and maintenance cost, USD
$O\&M_{fixed}$	Fixed operation and maintenance cost, USD
$O\&M_{variable}$	Variable operation and maintenance cost, USD
$Q_{CH_4(LFG)}$	Methane generation from landfill, m^3
$Q_{CH_4(AD)}$	Methane generation from anaerobic digestion, m^3
r	Population growth rate, %
$R_{collection}$	Waste collection rate, %
Rev	Revenue, USD
R_{tax}	Annual marginal tax rate, %
$TLCC$	Total life cycle cost, USD
$W_{collected}$	Waste collected, t/day
W_f	Waste fraction, %
W_{Gr}	Waste generation per capita, kg/capita/day
W_n	Number of wells dug
$Yield_{biogas}$	Biogas yield, m^3
λ	Methane collection efficiency, %
η	Electricity conversion efficiency, %
ρ_{CH_4}	Methane density, kg/m^3
α	Annual real discount rate, %

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