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Techno-Economic Assessment of Different Waste-to-Energy Strategies for Charging Battery-Driven Auto Rickshaws: A Case Study in Bangladesh

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Abstract

Rapid growth demand for electricity makes it challenging for developing countries like Bangladesh to meet this huge electricity demand using conventional methods. Rajshahi City Corporation (RCC) of Bangladesh faces a huge challenge to avoid load-shedding, especially due to the extensive power requirements for battery-driven autorickshaws, which serve as a primary mode of transportation. This study aims to identify the most effective waste-to-energy conversion method—Anaerobic Digestion (AD), Incineration, or Landfill Gas Recovery (LGR)—for generating electricity in Rajshahi City, focusing on techno-economic feasibility and environmental sustainability.. In the analysis, Incineration offers the most viable solution, with a positive Net Present Value (NPV) of $65.82 million, a payback period of 7.04 years, and the lowest Global Warming Potential (GWP) at 0.88 million kg CO_2-equivalent. Although AD demonstrates high electricity generation potential, its negative NPV and long payback period of 23.65 years make it economically unfeasible for this context. LGR provides the shortest payback period of 4.23 years and a moderate NPV of $20.83 million but has a comparatively high GWP. The research highlights the significant potential of incineration in meeting the electricity demand for charging autorickshaws in Rajshahi City Corporation (RCC), fulfilling approximately 85% of the energy requirements for these vehicles with its positive Net Present Value (NPV) and shorter Payback Period (PB). The study concludes that incineration is the optimal WTE strategy for RCC. This approach offers a sustainable solution to address both waste management challenges and the increasing electricity demand from the transportation sector
Keywords: Incineration, Waste to Energy, Anaerobic Digestion

1. Introduction

Covering a land area of 2407 km^2, with 62 km^2 designated as river area, Rajshahi District (Zila) is positioned in the northwestern part of Bangladesh, sharing its southern border with India[1]. Established in 1987, Rajshahi City Corporation (RCC) covers an approximate area of 48 km^2, bordered to the east, north, and west by Paba Thana, while its southern part is bounded by the Padma River [2]. RCC is comprised of 12 Upazilas and is further divided into 30 wards. According to RCC's assessment in 2018, the city's population stood at 850,000 people [3]. This population generates an annual waste output of 146,000 tons [4]. 'Door to door waste collection' is available in less than 50% wards in RCC. The RCC is actively working to expand this service to encompass all the city's wards. [4]. An estimation indicates that by 2025, per capita waste generation is expected to reach 0.60 kg/day, resulting in a total municipal solid waste (MSW) generation of roughly 47,064 tons per day. In Nawdapara, there exists just one dumping site, which has a depth of 3.5 feet and spans 15.98 acres. [5]. These wastes can be converted to energy by some methods like Incineration, Landfill Gas Recovery (LGR) and Anaerobic Digestion (AD) as a source of renewable energy. Renewable energy is obtained from an endless source and has lesser negative impact on the environment. However, numerous industries globally continue to rely on fossil fuels to generate electricity, which is not a good source for a long run. That's why, industries need to shift to renewable sources as soon as possible [6]. Worldwide, the investment in power generation doubled from 2005 to 2015, reaching approximately 420 billion USD annually, with around 70% of this was invested towards renewable energy sources [7].So Converting waste into energy has a great significance as it addresses waste management challenges while simultaneously generating valuable power resource. One of the common transportation system in RCC is battery driven auto rickshaw, which needs to be charged 10 hours per day on average consuming 11.6 kWh of electricity per auto rickshaw [8]. This huge consumption of electricity causes power crisis in RCC. That's

why the energy obtained from waste to energy (WTE) method can be used as a source to charging the batteries of these auto rickshaws. Hefa Cheng et al. 2007 described that Incineration method is considered for the purpose of producing electricity from MSW in the Changchun city of China. Consequently, around 1/6th of the total MSW generated led to the conservation of over 0. 2 Mm^3 of landfill space in the city and produced approximately 46.2 MWh of electricity. The overall efficiency of converting fuel to electricity stood at 14.6% [9]. In 2018, anaerobic digestion (AD) produced 0.7–2.0 kWh/m³ of energy [10], and in 2021, it generated 6000 MWh with 43.5% dry matter content [11]. Landfill gas recovery (LGR) in 2015 generated 5.66 MWh/ton of energy [12], while AD in 2011 produced 1–1.5 MW, though the process also generated toxic ash containing heavy metals [13]. Incineration in 2010 had an energy output of 622.5 MW but resulted in 76000 tons of CO_2-equivalent emissions per year [14]. By 2021, LGR produced 3003.3 GWh [15], and AD reached 4571.7 GWh [15]. Additionally, in 2018, AD produced 1170 kWh/ton [16], LGR generated 24.1 GWh/y at a cost of 69.9 USD/MWh, while AD yielded 68.4 GWh/y at 113.3 USD/MWh [17]. In 2021, LGR produced 11 billion kWh [18], while incineration, although less energy-efficient, produced 20.097 GWh/y, with a significantly higher cost of 2103.56 USD/MWh [17]. Rafaela Ediene dos Santos et al. estimated that the mean electricity usage per person in Brazilian households stands at 52,961 kWh over a certain period. Consequently, the energy produced at the landfill could fulfill the energy needs of an average of 38,000 residents (constituting 6.3% of the urban population under examination). If the incineration method were to be chosen then this figure might rise further, reaching up to 107,688 individuals (equivalent to 48.9% of the city's total population demand) [16]. Md. Ahasan Habib et al. 2021 has preferred AD, due to the predominantly food and vegetable composition of the municipal solid waste (MSW), was found to have an estimated energy potential of 3.85 MW. This has the potential to address the city's energy crisis [5] . From the literature review on Bangladesh, it is observed that no study has been conducted to determine the best method through a Techno-Economic Assessment for a specific city. This paper discusses different ways to turn waste into energy, like Landfill Gas Recovery, Anaerobic Digestion and Incineration. However, this work focuses on applying these methods to RCC and focuses on fulfilling the electricity demand to charge the batteries of battery driven auto rickshaws in RCC which is the novelty of this research as no such study has been found from the literature as per the authors' knowledge.

2. Research Methodology

The population of RCC is 962,000 [19] with an annual energy consumption of 449 MW [20].This huge consumption of power causes power crisis in the city corporation area. However, The number of battery driven auto rickshaws was found 24000 in 2020 [21] and per auto rickshaw consumed electricity about 4234 KW/h per year. In Bangladesh, the price of electricity per kWh is 0.068 dollars [22]. Different data for RCC used in this research are summarized in Table 1.

Table 1: Important data for RCC.

Population in RCC	962,000	[19]
Number of Auto rickshaws in Rajshahi city	24000	[21]
Electricity consumed (kW/h) / per year per capita	449	[20]
Electricity price per kWh ($)	0.068	[22]
Inflation rate in Bangladesh	9.24%	[23]
Electricity demand per auto rickshaw per day (kWh)	11.6	[8]

The study evaluated the feasibility of the three waste-to-energy methods by calculating four key parameters: Net Present Value (NPV), Payback Period (PB), Levelized Cost of Electricity (LCC), and Global Warming Potential (GWP)

2.1 Landfill Gas Recovery (LGR)

Anaerobic decomposition of waste in landfills leads to the production of landfill gas. This gas primarily comprises methane (CH_4) and carbon dioxide (CO_2), accompanied by traces of airborne pollutants and volatile acids [24]. The volume of methane generated (Q_{CH_4}) per year can be estimated from[25]:

$$Q_{CH_4} = \sum_{i=0}^{n} \sum_{i=0}^{n} KL_O \left(\frac{OFW_{LGR}}{10}\right) e^{-kt_{ij}} \quad (1)$$

In this context, the variable "i" denotes a one-year interval, "j" signifies a 0.1-year increment, "n" represents the overall number of years being considered, "k" stands for the annual rate at which methane is generated, "t_{ij}" denotes the waste age in the "j th" segment at year "i". Additionally, "L_O" represents the potential for methane

generation per unit mass in cubic meters per gram (m^3 /g), and "OFW_{CH_4}" represents the methane generation potential of the organic fraction.

2.2 Estimation of Electrical Energy

The methane produced by the landfill was utilized to approximate the overall generation of electrical power (kWh/yr) using the following equation no. (2) [25]

$$E_{P_LGR} = \frac{LHV_{CH_4} \times Q_{CH_4} \times \varphi_1}{\varphi_2} \quad (2)$$

Where, LHV_{CH_4} represents the lower heating value of methane that was taken as 37.2 MJ/m^3 [26], [27], φ_1 is the electrical conversion efficiency of the engine and was taken as 0.33[28] , and φ_2 represents the MJ to kWh conversion factor.

2.3 Incineration

The heat quantity needed to produce steam is significantly influenced by the balance of mass and energy [29], [30]. The amount of heat that can be obtained from the incineration process was estimated using the following equation no. (3)

$$Q_{INC} = \frac{b \times HHV(100-e)}{100} \quad (3)$$

Here, Q_{INC} (measured in MJ) represents the thermal energy generated by the incineration procedure, while HHV (measured in MJ/kg) signifies the higher heating value of the dehydrated waste. Here, "b" (measured in kg) denotes the dry waste fed into the incineration facility, and "e" stands for the cumulative impact of all efficiency losses. The electricity generated from Incineration process (E_{P_INC}) can be estimated from equation no. (4):

$$E_{P_INC} = \frac{Q_{INC} \times \eta \times 8760}{3412.14} \quad (4)$$

Here, the efficiency of the steam turbine is represented by η and which is taken as 0.29 [27].

2.4 Anaerobic Digestion (AD)

Total methane generation in kg (M_{CH_4}) from AD was estimated using equation (5):

$$M_{CH_4} = \frac{16 \times D_3}{(M_C \times p)+(M_H \times q)+(M_O \times r)+ M_N \times 1000} \times 1000 \quad (5)$$

Here, M_C, M_H, M_O and M_N (gm) represent the molar masses of carbon, hydrogen, oxygen, and nitrogen, respectively. Total methane volume, $V_{CH_4}(m^3 /yr)$ was determined using equation no. (6):

$$V_{CH_4} = \frac{M_{CH4}}{\rho_{CH_4}} \times OFW_{AD} \quad (6)$$

Where, ρ_{CH_4} represents the methane density (0.717 kg/m^3) [47] and OFW_{AD} is the organic portion of waste. The amount of electrical energy (E_{AD}) that can be generated using the produced biogas from AD was calculated using equation no. (7):

$$E_{AD} = \frac{LHV \times V_{CH_4} \times 0.85 \times \eta_{generator}}{C} \quad (7)$$

Where, $\eta_{\text{generator}}$ represents the efficiency of the gas fired generator and is assumed to be 0.26 [27] , LHV is the lower heating value of methane which was taken as 37.2 $MJ/m^3$and C (=3.6) is the MJ to kWh conversion factor[27].

3. Economic Feasibility Analysis

The assessment of the economic feasibility of WTE systems must be conducted in conjunction with their energy potential to determine the optimal result. In this research, the economic viability of the three WTE systems has been assessed such as Net Present Value (NPV), Levelized Cost of Energy (LCOE), and Payback Period (PP).

3.1 Net Present Value (NPV)

NPV pertains to the accumulation of present values encompassing all the expenses that will arise during the entire lifespan of the facility[31]. It was determined using the following equation no. (8)

$$NPV = \sum_{n=0}^{N}\left(\frac{C_n}{1+r_n}\right) \quad (8)$$

Here, C_n denotes the cash flow rate, N denotes the total life cycle of the plant ($for\ curremt\ study\ we\ consider$, N = 20 yr) and r is the annual discount rate[28]. The total investment cost for LGR process was estimated according to the formulas[29] . The investment and operation cost of AD technology was calculated[32]. The investment and operation cost of Incineration technology was also determined according to the formulae provided in [32]

3.2 The Levelized Cost of Energy (LCOE)

The evaluation of a project's economic feasibility can be achieved by calculating the LCOE, which signifies the lowest cost in $/kWh of energy, indicating the point at which the system achieves financial equilibrium [25]. The LCOE of all the technologies was measured using the following equation no. (9)

$$LCOE = \frac{LCC}{E_P} \times R_f \quad (9)$$

LCC represents the Life Cycle Cost of the project and R_f is the capital recovery factor. E_P denotes the quantity of energy produced by each of the technologies in kilowatt-hours (kWh) [33]

3.3 Payback Period (PB)

PB indicates the time (in years) needed for the costs to become equal and reach a break-even point. Payback period of all the technologies was determined using equation no. (10) and (11)

$$PB = \frac{Inv - Rebates}{Annual\ Energy\ Savings\left(\frac{\$}{yr}\right)} \quad (10)$$

$$\text{Annual Energy Savings} = \text{Rev} - C_{OM} \quad (11)$$

Inv denotes investment, Rev and C_{OM} represent Revenue and operation and maintenance cost respectively.

4. Result and Discussion

This study aimed to identify the most effective waste-to-energy (WTE) method for Rajshahi City by evaluating electricity generation, economic feasibility, and environmental impact of Anaerobic Digestion (AD), Incineration, and Landfill Gas Recovery (LGR). Figure 1(a) illustrates the electricity generation of the three methods, where AD and incineration performed well, while LGR produced comparatively less electricity. However, the highest LCOE was observed for AD, as shown in Figure 1(b). Table 2 presents the results of NPV, PB, LCC, and GWP for each method. Results indicate that LGR has the shortest payback period (4.23 years), a positive net present value (NPV) of $20.83 million but a relatively high global warming potential (GWP) of 43.15 million kg CO_2-eq. Although AD has the potential to generate significant electricity, its economic limitations, such as a negative NPV (-$19.73 million) and the longest payback period (23.65 years), outweigh its moderate environmental benefit of a lower GWP (35.81 million kg CO_2-eq) making it unsuitable for practical implementation. Incineration demonstrated a strong economic and environmental profile, with a moderate NPV of $65.82 million, a payback period of 7.04 years, and the lowest GWP (0.88 million kg CO_2-eq), making it the most balanced and viable option among the assessed methods. Its shorter PB demonstrates that the initial investment could be recovered in just 7 years. Considering both economic and environmental factors, incineration is clearly the most suitable waste-to-energy method for Rajshahi City. Table 2 also reveals that GWP is significantly lower for incineration, making it a more environmentally friendly option. Numerous research findings indicate that incineration stands out as a more favorable technology for both energy generation and waste reduction [33]. Other research also shows that incineration yields the most significant net profit while offering greater energy potential and a notable reduction in net greenhouse gas emissions [34]. Electricity generation for LGR and incineration was found to be 35.29 GWh/y and 85.5 GWh/y, respectively. A similar result was observed in another study, where electricity generation was 24.1 GWh/y for LGR and 68.4 GWh/y for incineration [17]. The total electricity generation by incineration was 85,808.615 MWh/y, while the electricity demand for all the auto-rickshaws in RCC is 101,616 MWh/y. Therefore, electricity generation by the incineration method meets nearly 85% of the energy demand for charging auto-rickshaws in RCC.

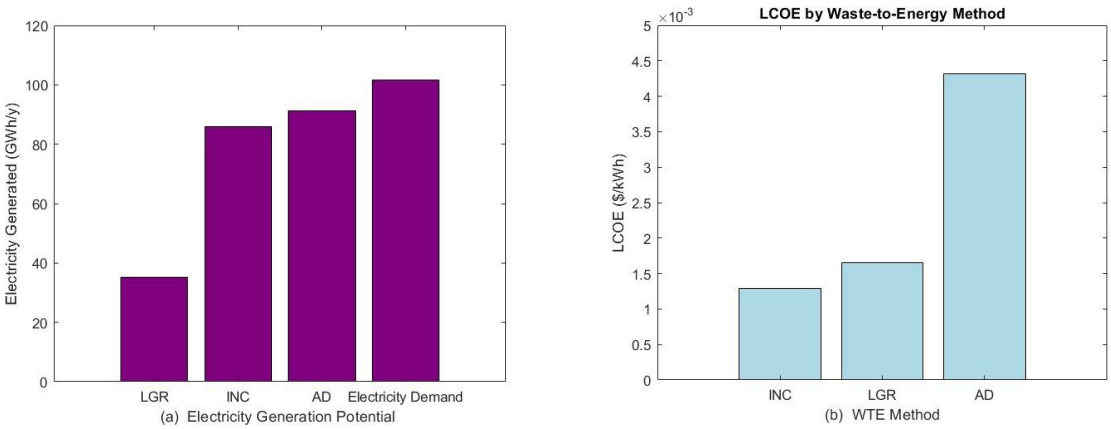


Fig.1: a) Electricity generation potential and (b) LCOE of the selected WTE technologies.

Table 2: Summary of the results calculated in this study

Factors	LGR	AD	Incineration
NPV ($)	20828815	-19729357	65824631
Payback Period (yr)	4.23	23.65	7.04
LCC ($)	21785510.33	146770835.1	41084655.91
GWP (kg CO_2-eq)	43146562.5	35814091.4	881424.5835

5. Conclusions

This work investigates the feasibility of implementing three of the most prominent waste-to-energy conversion techniques, i.e., AD, incineration, and landfill gas recovery (LGR), to meet the additional electricity demand imposed by electric auto rickshaws in Rajshahi City Corporation (RCC), Bangladesh. The techno-economic analysis shows that while AD has the potential to generate the most electricity annually but its negative NPV (-$19.73 million) and long payback period (23.65 years) makes it impractical for real world implementation. Incineration, with a moderate NPV of $65.82 million, a payback period of 7.04 years, and the lowest GWP (0.88 million kg CO_2-eq), stands as the most viable option. LGR with an NPV of $20.83 million and the shortest payback period (4.23 years), has a significantly higher GWP (43.15 million kg CO_2-eq) than Incineration. Consequently, incineration is identified as the optimal WTE solution for RCC, capable of meeting approximately 85% of the annual electricity demand for auto rickshaws, while offering a sustainable balance between economic returns and environmental impact.

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