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Renewable Power for Sustainable Growth

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About this book

The proceedings is a collection of papers presented at International Conference on Renewal Power (ICRP 2023), held during 28 – 29 March 2023 in Mewat Engineering College, Nuh, India. The book covers different topics of renewal energy sources in modern power systems. The volume focusses on smart grid technologies and applications, renewable power systems including solar PV, solar thermal, wind, power generation, transmission and distribution, transportation electrification and automotive technologies, power electronics and applications in renewable power system, energy management and control system, energy storage in modern power system, active distribution network, artificial intelligence in renewable power systems, and cyber physical systems and internet of things in smart grid and renewable power.

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Hybrid Waste to Energy Electricity Generation and Battery Storage System: The Economics and Environmental Emission in a Low-Income Community

Ahmed Abubakar Elwan, Mohd Hafiz Habibuddin, Yanuar Z. Arief, Ahmad Safawi Bin Mokhtar, and Rasyidah Binti Mohamad Idris

Abstract Waste and population growth have increased significantly, even in low-income and developing countries. Gombe metropolitan is the largest local government area in Gombe state, which is located in northern Nigeria. Gombe, like any other city in Nigeria, has seen an increase in population growth and land occupation, which has resulted in an increase in waste generation and a reduction in nearby land for landfilling activities. Using HOMER Pro optimization software, this study assesses the economic, environmental, and technical impact of a waste-to-energy (WtE) hybrid plant with a storage device. The system's net present cost (NPC) is estimated to be \$112,633 with a levelized cost of energy (LCOE) of 0.283\$/kWh. The total energy generated is estimated to be 62,084 kWh/year, with an excess of 1049 kWh/year expected after consumption of 60,386 kWh/year. The simulation results show that the proposed system has a very significant impact on the environment, with very low emissions. The hybrid WtE/storage device system is not economically viable because the cost of electricity from the system is higher than the grid price, but the results show strong viability in terms of environmental impact.

Keywords Net present cost · Waste-to-energy · Environmental emission · Municipal solid waste · Electricity

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1 Introduction

The world produces 2.01 billion tons of municipal solid waste per year, and this figure is expected to rise to 3.4 billion by 2050 [1]. If there are no changes, solid waste-related emissions will rise to 2.38 billion tons of CO_2 equivalent annually by 2050 [2]. High-income countries are expected to grow by 19 percent per day per capita by 2050, while low- and middle-income countries are expected to grow by 40% [3]. Dry wastes, such as plastic, paper, cardboard, metal, and glass, account for 51% of total waste generated. Additionally, solid waste adds to the world's greenhouse gas emissions. In 2016, solid waste accounted for 5–6.4% of all greenhouse gas emissions in the world, or roughly 1.6 billion tons of carbon dioxide (CO_2) equivalent emissions [4]. The main factor causing emissions from solid waste is the manner of disposal, such as open dumps or landfills without mechanisms for collecting landfill gas [5].

An example of an integrated circular economy is waste-to-energy (WtE), which recovers energy from MSW. In addition to energy recovery, WtEs have other advantages, such as reducing the amount of waste transported to landfills, lowering air emissions typically experienced when open burning is used for waste disposal, increasing recycling rates, particularly during the preparatory stage of WtE, and, if harnessed, replacing fossil fuels in power generation, thus achieving the goal of environmentally friendly and sustainable energy generation. Reducing the amount of garbage that needs to be dumped, preventing water and air contamination, and replacing fossil fuels in the production of electricity are all advantages of hybrid waste management systems that incorporate energy recovery.

The majority of WTE feasibility studies fall into two broad categories: techno-economic and environmental analysis. The amount of heat or power recovered by WtEs was analyzed in terms of its relative environmental impact, as shown in [5–8]. Some of the most common elements used for economic analysis when performing feasibility studies are net present value, internal rate of return (IRR), and levelized cost of energy (LCOE) [9]. In feasibility studies, various combinations and architectures are developed using a variety of methods. Examples of such configurations include stand-alone, hybrid, stand-alone grid-connected, hybrid grid-connected, and so on, based on various renewable energy resources (PV, wind, and biomass), storage components (battery), and converters.

With the introduction of modern computer-based systems, the use of simulation tools has increased. Examples of such tools include MATLAB, PSIM, and HOMER. Hybrid Optimization Model for Electric Renewable (HOMER) software is widely used in determining likely configurations and implementation. The authors of [10] used HOMER to demonstrate the potential of optimized WtE technologies in conjunction with other renewable sources such as PV and wind in Bangladesh. Homer software was also used to assess the amount of electricity generated, as well as the economic and environmental impact on Hamadan [11]. HOMER was also used in hybrid off-grid feasibility studies in Australia, taking into account various climatic zones [11]. Liu et al. [12] used HOMER software to assess the feasibility of WtE in the Iraqi city of Najaf.

The authors of [13] use HOMER software to simulate the net present cost (NPC) and greenhouse gas emissions (GHG) of hybrid renewable energy systems. Heilig [14] investigated the techno-economics of replacing diesel generators and batteries in a hybrid with hydrogen. The results of the studies showed that it is technically possible to substitute; however, when economically evaluated, it shows that it has a high cost under current conditions; however, with advancements in hydrogen technologies, it is possible in the future. Heilig [14] used three (3) types of configuration to test the viability of options in off-grid rural electrification. According to the study's findings, PV is the most promising technology for rural electrification.

This paper presents a techno-economic and environmental assessment of a hybrid WtE and storage electricity generation plant to determine its viability as a grid electricity supply substitute for the selected community. The HOMER Pro software was used to model and simulate the hybrid system for feasibility analysis. The study area's estimated daily demand was used. An electricity generator was carefully chosen to match the amount of potential electricity available. For this study, gasification conversion technology was used for energy recovery.

2 Research Method

2.1 Study Area

The study area is a suburb of Gombe, the capital of Gombe state and one of the 11 LGA in Nigeria's northeastern region. When the insurgency was at its peak in 2014 and 2015, Gombe saw an influx of people from neighboring states [15]. Gombe, with an area of 52 km^2, is between latitude 10° 17′ 05.88″ N and longitude 11° 10′ 36.78″ E, as shown in Table 1. Gombe's population was 26,210 in 1950, and it has grown at a rate of 4.07% per year since then [15], with an estimated population of 529,283 in 2021. These estimates represent Gombe's urban agglomeration, which typically includes Gombe's population as well as adjacent suburban areas that are usually included due to the rapid rate of expansion witnessed [16] (Table 1).

Table 1 Gombe geographic information [20]

S. no.	Study area description (Gombe)		
	Item description	Unit	Value
1	Latitude	Degrees, minutes	10° 17′ N
2	Longitude	Degrees, minutes	11° 10′ E
3	Height above sea level	Meters	461 m
4	Population estimate (2021)	#	529,283

2.2 *Waste Management and Waste Specifications*

Gombe's solid waste management is not advanced and is frequently associated with data availability of the source, types of solid waste, composition, and generation rates. Gombe metropolis is the most advanced area of the state, but there is little record or knowledge of solid waste generated. For this study, we are using the most recent estimate from the state agency in charge of waste management in the city. According to estimates, the total amount of solid waste disposed of in open dump sites is around fifteen metric tons, which is equivalent to fifteen thousand kilograms (15,000 kg) daily in the Gombe metropolis [17]. Waste is generated in various parts of the Gombe metropolis, including residential households and other public areas such as shops, clinics, and schools. The community has a daily average waste generation capacity of 10 tons, which is disposed of in landfills or dumpsites for landfilling or open burning. The wastes can be classified as follows: Plastics, paper, wood, glass, polyethylene, organic waste/food, and others (uncategorizable waste) [18] as in Table 2.

3 Waste-to-Energy Conversion Technology

The selected conversion technology (gasification) and any other related parameters are based on the facility operating under all applicable regulations. The modular design technology approach was chosen. This concept will assist energy recovery systems in offsetting operating costs while also significantly lowering the capital costs of air pollution control equipment [19]. Figure 1 shows a typical gasification diagram. A modular gasification plant has two basic designs: a starved air combustor and an excess air combustor. The combustor is composed of two distinct combustion chambers known as the "primary" and "secondary" chambers. Waste enters the plant in batches via a hydraulically controlled ramrod from the primary chamber. When

Table 2 Waste distribution composition [17]

S. no.	Waste distribution and classification	
	Composition	Average (%)
1	Fabrics	3
2	Metals	0
3	Organic	9
4	Paper	19
5	Polyethylene	40
6	Plastics	18
7	Wood	3
8	Others	7

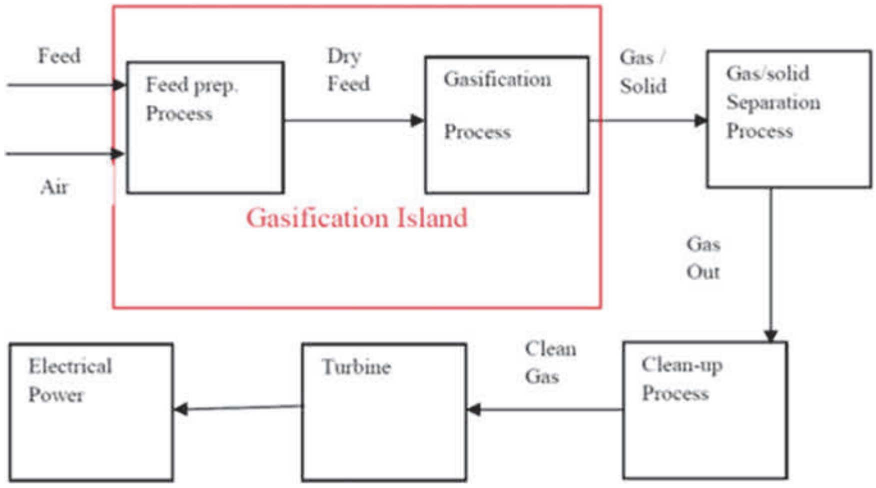

Fig. 1 Typical gasification diagram

waste is introduced into the primary chamber, it undergoes a retention period of up to 12 h.

4 Simulation and Modeling

4.1 Financial Modeling

HOMER uses (1–3) for financial analysis. The entire cost of plant components and installation costs is used to compute the capital cost of the WTE facility. For a small capacity, a gasification WTE facility can cost anywhere between $15 and $25 million on average [20]. Net present cost (NPC) and localized cost of electricity (LCOE) of the system are the financial parameters expected. Emission reduction and renewable fractions are employed in HOMER to assess environmental factors [21].

$$\text{NPC} = \text{TAC}/\text{CRF} \tag{1}$$

where

TAC = total annualized cost
CRF = capital recovery factor

$$\text{LCOE} = C_{\text{ann,tot}}/E \tag{2}$$

where

$C_{\text{ann, tot}}$ = annual cost in \$
E = total electricity consumption in kWh/year

$$f_{\text{WtE}} = E_{\text{WtE}}/E_{\text{ann,tot}} \quad (3)$$

where

$E_{\text{ann, tot}}$ = annual total energy generation of the system
E_{WtE} = electricity generation from the generator

4.2 Assumption for Simulation

Some basic assumptions must be made for HOMER simulations to be effective, as shown in Table 3.

Energy density refers to the amount of energy that can be stored in a single system per unit volume or weight. Battery efficiency is expressed as a percentage of charge and discharge efficiency (4) is used in sizing the number of batteries required.

$$\text{BC} = f_g * G * f \quad (4)$$

where

BC = BESS capacity in MW
f_g = frequency gain
G = governor drop
f = system frequency in Hz.

Electrical energy recovered from the combustion of waste can be determined from (5).

Table 3 Assumption parameters [17]

S. no.	Assumed parameters		
	Parameter	Unit	Value
1	Capacity factor	%	80
2	Carbon content at gasification	%	100
3	Gasification ratio	–	0.2
4	Grid unit price	$/kWh	0.06
5	Hours of service	Hours	6970
6	Low heating value	MJ/kg	23
7	Moisture	%	15
8	Number of starts	Start/year	400
9	Operational life Genset	Year	20
10	Operational life storage	Year	4.21

$$\text{Electrical energy} = \frac{hv * \left[\frac{2000ib}{\text{ton}}\right]}{\text{heat rate}} \quad (5)$$

where

hv = heating value of waste component *i*
heat rate = a measure of the efficiency of the plant, the number of Btu's fuel needed to generate one kWh (Btu/kWh).

5 Results and Discussion

Based on impact categories, the simulation results from HOMER were presented and analyzed. Three impact levels, namely technical, economic, and environmental impact, were created from these categories. The subcategories for environmental are emissions, which are largely greenhouse gases (GHG). NPV, annualized costs, and LCOE were discussed at the economic impact level. Last but not least, the technical impact was reviewed concerning the contribution of electricity generation and consumption, excess electricity produced, and associated conclusions. Under each category, the results were displayed in figures and tables.

5.1 Economic Impact Assessment

Tables 4 and 5 show the cost impact results from the simulation. In Table 4, the generator has a capital cost of $12,500, an operating cost of $40,944, a replacement cost of $42,156, and a salvage value of $−283. Using net present cost indices, the total cost of the Genset is $95,367. Table 5 shows the optimized cost on an annualized basis. The annualized capital costs for the generator are $1594 as a capital cost, $5375 as a replacement cost after its lifetime, and $5227 to keep the generator in good working order. The highest cost is the replacement, followed by operation and capital costs.

The system converter is an exception to the preceding; it has no operating costs, low replacement costs, and a capital cost that is higher than its operating cost.

Table 4 Economic simulation results (NPC)

S. no.	Net present cost ($)					
	Parameter	Capital	Operating	Replacement	Salvage	Total
1	1 kWh lead acid	600	1725	7850	−17	16,159
2	25 kW capacity Genset	1.250	40,994	42,156	−283.1	95,367
3	Converter	952.4	0	174.01	−18.68	1108
4	Total	20,052	42,720	50,180	−318.8	112,634

Table 5 Economic simulation results (annualized)

S. no.	Annualized cost ($)					
	Parameter	Capital	Operating	Replacement	Salvage	Total
1	1 kWh lead acid	841.5	220	1001	−2.17	2060
2	25 kW capacity Genset	1.594	5,227	5375	−36.09	12,159
3	Converter	121.4	0	22.19	−2.38	141.24
4	Total	2557	5447	6398	−40.64	14,361

Table 6 Environmental impact analysis

S. no.	Electrical production and consumption		
	Parameter	Unit	Value
1	Carbon dioxide	kg/year	119
2	Carbon monoxide	kg/year	0.54
3	Unburned hydrocarbon	kg/year	0.024
4	Particulate matter	kg/year	0.003
5	Sulfur dioxide	kg/year	0
6	Nitrogen dioxide	kg/year	0.52

According to the tables, the overall cost of replacement is high, accounting for the majority of the costs. The simulation's NPC is $112,630, and the LCOE is $0.238/kWh.

5.2 Environmental Impact Analysis

The environmental impact of HOMER simulation for the WtE/storage hybrid system is shown in Table 6. Greenhouse gases (GHG) from the system total 120 kg/year and are composed of carbon dioxide, carbon monoxide, sulfur dioxide, and nitrogen dioxide. Unburned hydrocarbon emissions are as low as 0.024 kg/year, and particulate matter emissions are as low as 0.0032 kg/year. This demonstrates that hybrid WtE/storage can reduce GHG emissions as well as air emissions when compared to open burning or landfilling.

5.3 Technical Impact Analysis

Table 7 summarizes the system generation versus the required demand; the system is expected to generate a total of 62,084 kWh per year, with an annual load to serve of 60,386 kWh, and an excess of 1049 kWh per year, representing 1.6% of the total energy generated. There will be no capacity shortages or unmet loads from the system

Table 7 Technical impact analysis

S. no.	Electrical production and consumption		
	Parameter	Unit	Value
1	Excess electricity	kWh/year	1049
2	Unmet electric load	kWh/year	0
3	Genset generation	kWh/year	62,084
4	Load consumption	kWh/year	60,386
5	Effective battery energy	kWh/year	3744
6	Battery losses	kWh/year	936
7	Converter maximum output	kW	2.88
8	Converter losses	kWh/year	187
9	Converter hours of operation	hrs	1791

because 100% of the energy demand is expected to be met. Because the system is a stand-alone hybrid system, excess energy can only be stored and not sold back to the grid.

When demand is low, the batteries are charged, and when demand exceeds generation, the batteries are discharged to power up the load. According to Table 7, the batteries have total energy supplied out that is 3744 kWh and a loss of approximately 936 kWh. Battery output is typically in DC form and cannot be used to power AC equipment, which is the most common load in every home. A system converter is used to convert the battery output back to alternating current (AC) for consumption. Table 7 shows that the converter loses 187 kWh/year, which is 5% of the total input energy (3744 kWh/year). The converter has a maximum output of 2.88 kW and a mean output of 0.41 kW.

6 Conclusion

This research is a techno-economic and environmental assessment of a hybrid WtE/storage system to supply a load demand from a Gombe metropolis suburb in Gombe state, Nigeria. The study concludes that:

(1) While the amount of waste generated for this study is adequate for the purpose, the quality of the waste does not have the required heat value, affecting the overall optimization of the system.
(2) Adopting WtE for suburban settlements in Northern Nigeria will help improve energy access to the population without electricity and waste management.
(3) The cost of WtE energy is higher than the cost of energy from the government-owned grid. This is the case.

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