

Lecture Notes in Electrical Engineering 1086

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Y. R. Sood · Atif Iqbal ·
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Renewable Power for Sustainable Growth

Proceedings of ICRP 2023



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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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-

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Table of contents (68 papers)

Front Matter

Pages i-xix

Editorial: Renewable Power for Sustainable Growth

- Hasmat Malik, Sukumar Mishra, Y. R. Sood, Atif Iqbal, Taha Selim Ustun
-

Pages 1-29

An Efficient Algorithm for Energy Management in Smart Grid for Various Improvements

- Deepa Kumari, Ashish Sharma
-

Pages 31-43

Investigations and Validation of PV-Powered Unified Power Quality Conditioner for Electric Vehicle Smart Charger in Standard AC/DC Hybrid Microgrid Test System

- S. Sumana, R. Dhanalakshmi
-

Pages 45-60

Short-Term Electricity Load Forecasting Using Modified Hidden Markov Model

- Poras Khetarpal, Neelu Nagpal, Mahesh Kumar, D. Lakshmi, Neelam Kassarwani
-

Pages 61-74

Microgrid Systems with Classical Primary Control Techniques—A Review

- Sujit Kumar, H. K. Yashaswini, Naveen Sharma, Mohit Bajaj
-

Pages 75-83

Green Energy Solutions for Indoor Air Quality Improvement

- Saad Javed, Safdar Tanweer, Syed Sibtain Khalid, Naseem Rao, Jawed Ahmad, Bhavya Alankar
-

Pages 85-97

Data Resource Library for Renewable Energy Prediction/Forecasting

-
- Subeyr Bashir Ahmed, Hasmat Malik, Shahrin Md Ayob, Nik Rumzi Nik Idris, Awang Jusoh, Fausto Pedro García Márquez

Pages 99-164

Solar Rooftop On-Grid Connected Net Metering System

-
- Sarfraz, Anju Gupta, Rashmi Agarwal

Pages 165-176

Contemporary Maximum Power Point Tracking Methods of Solar Photovoltaic Modules

-
- Jyothi Tompala, Sravana Kumar Bali

Pages 177-192

Performance Analysis of Perturb & Observe and Incremental Conductance Method of Maximum Power Point Tracking in Solar PV-Based Power Generation

-
- Avdhesh Kumar

Pages 193-204

The Airfoil Design for Small-Scale Wind Turbines in Maximizing Renewable Wind Energy

-
- S. A. H. Roslan, N. Umar, Z. A. Rasid, A. K. Arifin

Pages 205-216

Comparative Study on Solar PV Module Performance with Sun Irradiance Trapping Mechanism: Power Generation Forecasting Using Machine Learning

-
- Rupendra Kumar Pachauri, Ashutosh Shukla, Ahmad Faiz Minai, Aryadhara Pradhan, Vinay Gupta, Mohit Kumar et al.

Pages 217-228

The Geometric Modelling and Linearization of Small-Scale Wind Turbine Blades for Optimized Renewable Energy

-
- S. A. H. Roslan, N. Umar, Z. A. Rasid, A. K. Arifin

Pages 229-243

Performance Analysis of H-Type Vertical Axis Wind Turbine by Using Novelty Numerical Simulink Method

- Muhammad Radhiva, Muhammad Hasya Abdillah, Geordiano Devanaldy Khresna Putra, Muhammad Raihan Wajdi, Putri Wulandari, Wahyu Caesarendra et al.

Pages 245-257

Energy Production from Various Bio-wastes Under Different Electrode and Temperature Conditions: Experimental Study

- Rahul Anand, Rupendra Kumar Pachauri, Ahmad Faiz Minai, Akhlaque Ahmad Khan, Rajesh Singh, Shashikant

Pages 259-270

Simulation and Prototype Design of Hybrid Renewable Energy Harvesting System

- Yanuar Z. Arief, Muhammad Syukri Nurulhak, Hamzah Eteruddin

Pages 271-288

Design and Development of an Inexpensive Intelligent Device for Sag Measurement for Overhead Transmission Lines

- Manoj Kumar, Aman Kumar, Tushar Tomar, Anuj Dixit, Divya Asija, R. K. Viral

Pages 289-303

Gradient Descent Back-Propagation Through Momentum (GDBPM) Endorsed \diamond cos \diamond Control Technique-Based DSTATCOM Intended for Shunt Indemnification

- Mrutyunjaya Mangaraj, Kampara Ravisankar, Majji Satish, Kantubhukta Dinesh, A. Praveena

Pages 305-317

Improvement in Voltage Stability of the System Due to Increased Penetration of Electric Vehicles Using Distributed Solar Photovoltaic Sources

- Sheetal Deshmukh, Shirazul Islam, Atif Iqbal, Md Fahim Ansari

Pages 319-338

An Intelligent System for Furfural Estimation in the Power Transformers

- Md. Manzar Nezami, Hythem Hashem, Md. Danish Equbal, Mohammad Junaid Khan, Md. Fahim Ansari, Elfatih Elmubarak Mustafa

Pages 339-345

Design of PID-Tuned Controller for Automatic Voltage Regulator for Frequency Stability in Thermal Power Plant

- Md. Fahim Ansari, Atif Iqbal, Md. Manzar Nezami

Pages 347-354

Optimization of Distributed Generators in a Virtual Power Plan Using Mixed Integer Linear Programming Method

- Ahmed Abubakar Elwan, Mohd Hafiz Habibuddin, Yanuar Z. Arief, Siti Nur Aisyah Mohd Sharan, Ahmad Safawi Bin Mokhtar, Rasyidah Binti Mohamad Idris

Pages 355-365

Solving Unit Commitment Problem Using Mixed Integer Linear Programming for Demand Side Management

- Ahmed Abubakar Elwan, Mohd Hafiz Habibuddin, Yanuar Z. Arief

Pages 367-375

Deployment of Renewable Embedded Generation and Unified Power Quality Conditioner in Distribution System using Firefly Algorithm

- Musa Mustapha, Madihah Binti Md. Rasid, Jasrul Jamani Bin Jamian, Ganiyu Ayinde Bakare, Yau Shuaibu Haruna

Pages 377-389

Application of Wind Power in Backwashing Filter Media

- Deepak Juneja, Sushindra Kumar Gupta, Aditya Rana

Pages 391-401

Mixed Reality Accelerates the Designing Process in Automotive Industry

- Mohamad Yahya Fekri Aladin, Ajune Wanis Ismail, Fazliaty Edora Fadzli

Pages 403-415

Design and Implementation of Solar Charging Electric Vehicle

-
- Rahil Imtiyaz, Aman Kumar, Gitanjali Mehta, Ruqaiya Khanam

Pages 417-429

Modelling and Analysis of a Permanent Magnet DC Motor Fed Electric Vehicle Drive System

-
- K. Subbaramaiah, Ravisankar Kampara, Majji Satish, Kantubhukta Dinesh, Karthik Tamvada

Pages 431-440

An Overview of Electric and Hybrid Vehicle Technology

-
- V. S. Vishwanath Nagarajan, Vinay Kumar Jadoun, N. S. Jayalakshmi, Anubhav Kumar Pandey

Pages 441-456

Performance Analysis of Classical Converter Using Different Control Strategies for Switched Reluctance Motor with Dynamic Loading

-
- Ritika Asati, Deepak S. Bankar

Pages 457-467

Design and Development Gear-Electric Bike and Performance Testing for Indian Road Conditions

-
- Vinay Gupta, Jitesh Kumawat, Rupendra Kumar Pachauri, Shashikant

Pages 469-479

Design and Development of a Solar-Based Wireless Electric Vehicle Charging System

-
- Sanyam Jain, Samyak Jain, Sanjay Kumar, Harsh Kaushik, Neelu Nagpal, Ravi Sharma

Pages 481-494

Design, Optimization, and Performance Enhancement of Switched Reluctance Motor for Pollution-Free Electric Vehicle Application

-
- Kesar Ali, Arbaz Sher Khan Shaikh, Kirti Govind, Javid Navaj Shaikh, Yogesh B. Mandake, Deepak S. Bankar

Pages 495-512

Using Linear Regression Model to Predict the Wholesale of the Electric Car in Indonesia: What Can Be Learned from the Model?

- Rosyid R. Al-Hakim, Nur F. Soelaiman, Sri Riani, Yanuar Z. Arief

Pages 513-519

Comparison of Thermoelectric Generator with Boost Converter and Single-Ended Primary-Inductance Converter

- Megat Azri Irfan Adzmi, Mohd Zaki Daud, Shahrin Md Ayob, Razman Ayop

Pages 521-533

A Hybrid Maximum Power Point Tracking (MPPT) for Thermoelectric Generator (TEG) System

- Naseem Mohd Arshad, Mohd Zaki Daud, Shahrin Md Ayob, Razman Ayop

Pages 535-551

Thermoelectric Generator (TEG) by Using Indirect Maximum Power Point (MPP) Algorithm

- Ardrine Justin, Mohd Zaki Daud, Shahrin Md Ayob, Razman Ayop

Pages 553-568

Comprehensive Review on AC-DC, DC-DC, DC-AC-DC Converters Used for Electric Vehicles and Charging Stations

- Utkarsh Shukla, Shekhar Yadav, Nitesh Tiwari, Aayushi Priyadarshini

Pages 569-588

Control and Performance Analysis for Active Islanding Detection Using q-Axis Control in Renewable Energy Sources Based Microgrid: A Review

- Avdhesh Kumar

Pages 589-599

Harmonics Analysis of Triple-Phase Induction Motor Drive

- Mohd. Rizwan Khan, Md. Nasim Akhter, Mohd. Sartaj

Pages 601-618

Development of Witricity Based Wireless Power Transmission System

- Kanhaiya Mishra, Arjun Kushawaha, Neetigya Chaurasia, Sudhanshu Kumar, Gautam Kr. Singh, Mohammad Shahid

Pages 619-634

Analysis of Three-Winding Transformer Configurations for Energy Storageless Dynamic Voltage Restorer

- Muhammad M. Roomi, S. M. Suhail Hussain, Mohd Tariq, Taha Selim Ustun

Pages 635-648

Data Reliability Analysis for Early Fault Diagnosis of Air Handling Unit (AHU)

- Hasmat Malik, Shahrin Md Ayob, Nik Rumzi Nik Idris, Awang Jusoh, Fausto Pedro García Márquez, Abdulaziz Almutairi

Pages 649-674

Use of Solar Energy in Treatment of Pulp and Paper Industry Effluent with Hemp: An Experimental Study

- Ambika Thakur, Deepak Juneja, Yogyendra Narayan

Pages 675-687

Design of Radar-Based Portable System for Monitoring of Human Vital Signs with Renewable Energy Resources

- Pushparaj, Amod Kumar, Garima Saini

Pages 689-716

Controlling Methods of Brushless DC Motor in Electrical Vehicle Drives

- Megha Sharma, Shailly Sharma, Jayashri Vajpai

Pages 717-726

Effect of Number of Poles on IPMSM Performance for Electric Vehicle Drivetrain

- Vinod Kumar Kuttey, Sravana Kumar Bali

Pages 727-736

Offline Power Quality Management and Control Using Neural Networks

- Papia Ray, Surender Reddy Salkuti, R. Aditya Kumar

Pages 737-749

Optimized Integral Sliding Mode Load Frequency Control of an Isolated Power System

- Neelam Kassarwani, Neelu Nagpal, Jagrat Sehgal, Pierluigi Siano

Pages 751-762

Implementation of Supercapacitor-Battery-Based Energy Storage System in Hybrid Power System Incorporating Renewable Energy Resources

- Jahid, Manauallah, Sheeraz Kirmani

Pages 763-772

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, Rasyidah Binti Mohamad Idris

Pages 773-783

Application of Solar Power in the Loopholes and Coverages of Buses in the Bus Rapid Transit System in Bhopal

- Rajeev Kumar, Deepak Juneja, Yogendra Narayan

Pages 785-797

Forecasting of Carbon Emissions in India Using (ARIMA) Time Series Predicting Approach

- Somesh Sharma, Amit Mittal, Manmohan Bansal, Bhagawati Prasad Joshi, Ashish Rayal

Pages 799-811

Peak Shaving Through Battery Storage for Photovoltaic Integrated Building Considering the Time of Day Pricing

- A. Sharma, P. Mahajan, R. Garg

Pages 813-825

Economic Analysis of Renewable Energy Systems for Rural Electrification

- Nikita Yadav, Rahul Sharma, Yashwant Sawle

Pages 827-836

Improved Voltage Regulation in Hybrid Photovoltaic/Wind Using Modified Dynamic Voltage Restorer with Hybrid Control Scheme

- Preeti Rani, Ved Parkash, Naveen Kumar Sharma

Pages 837-852

Contingency Analysis for a Solar Energy Generation System Using Real-Time Data Analysis

- Vishal V. Mehtre, Shivani Jitendra Khare, Swapnil Namekar, D. S. Bankar

Pages 853-866

Digital Twin in Extended Reality Applications for Industry 4.0

- Ajune Wanis Ismail, Mohamad Yahya Fekri Aladin, Nur Ameerah Abdul Halim

Pages 867-880

Deep Image Coding in the Fractional Wavelet Transform Domain based on High-Frequency Sub-bands Prediction

- Nadeem Ahmad, Zainul Abdin Jaffery, Irshad, Shaheen Khan

Pages 881-898

QIVIFS: Quaternion Approach of Interval-Valued Intuitionistic Fuzzy Sets with Applications in Renewable Energy System

- Bhagawati Prasad Joshi, Madan Mohan Sati, Sanjay Oli, Deepak Kumar, Ashish Rayal, Abhay Kumar

Pages 899-910

Feminine Protection Wearable System Based on IoT

- Shubham Kumar Verma, Udai Raj Tiwari, Utkarsh Rau, Khadim Moin Siddiqui, Sandhya Srivastava, Jayati Vaish

Pages 911-922

Marine Predictors Algorithm Optimization Technique to Estimate GMPP of PV Array Under Partial Shadowing Conditions

- Rupendra Kumar Pachauri, Rajesh Singh, Ahmad Faiz Minai, Shashikant

Pages 923-932

Artificial Intelligence-Based Bearing Fault Diagnosis of Rotating Machine to Improve the Safety of Power System

-
- Mohmad Iqbal, A. K. Madan

Pages 933-942

Stability Enhancement of AC Microgrid Using Discrete Mode Controllers with Optimum Sampling Frequency

-
- Amit Arora, Mahendra Bhadu, Arvind Kumar

Pages 943-962

Performance Analysis of Grid-Integrated Solar System Through Interlinking Converter with Control Schemes

-
- Preeti Rani, Ved Parkash, Naveen Kumar Sharma

Pages 963-980

Towards Achieving Net Zero Emissions in India by 2070

-
- Akash Midha, Anuradha Tomar

Pages 981-991

IOT-Based Monitoring and Controlling of Substation Parameters

-
- P. Sai Kiran, B. Venkateswara Rao, G. Satyamohan Sarveswar, P. Manikanta

Pages 993-1002

Effectiveness of Resilience Index in Assessing Power System Performance

-
- Hasna Satya Dini, Jasrul Jamani Jamian

Pages 1003-1019

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 land-filling 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 CO₂ 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 (CO₂) 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 km², 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 |

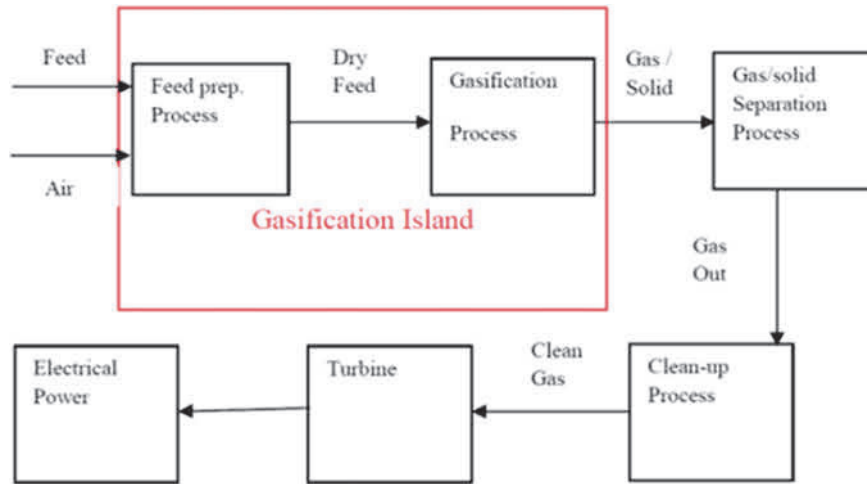


Fig. 1 Typical gasification diagram

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].

$$\text{NPC} = \text{TAC}/\text{CRF} \quad (1)$$

where

TAC = total annualized cost
CRF = capital recovery factor

$$\text{LCOE} = C_{\text{ann,tot}}/E \quad (2)$$

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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