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City St George's, University of London
School of Science & Technology
Department of Engineering



PhD Thesis

**Sustainability Assessment of Biomass Utilisation
for Distributed Energy Systems in Nigeria.**

By: Stephen Majebi

Supervisor I: Dr. Jafar Al-Zaili
Supervisor II: Dr Tala El Samad

January 2026

Declaration

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any university or other institution. Where information has been derived from other sources, I confirm that this has been appropriately cited in the thesis.

Stephen Majebi

January 2026

Acknowledgments

I would like to express my deepest gratitude to my supervisor, Dr. Jafar Al-Zaili, for his invaluable guidance throughout this journey. His patience, honesty, and profound knowledge were not only a source of academic direction but a true pillar of support during the most challenging phases of this entire journey.

I also extend my sincere thanks to my co-supervisor, Dr. Tala El Samad, for her helpful insights and constructive feedback which greatly improved this work. Additionally, I am grateful to my former supervisor, Professor Abdalnaser Sayma, for his mentorship and for the foundation he helped me build during the earlier stages of my research.

My time as a doctoral researcher was made all the better by the camaraderie of my colleagues. A special thank you to Erika Rodriguez Aleman and Kirti Sharma for their friendship and solidarity. To my other colleagues in the department, thank you for providing such a collaborative environment.

Most importantly, this work is possible because of my family. To my parents, words cannot express my gratitude. You made the ultimate investment in my future by funding this research, and your unwavering belief in my potential is the reason I am here today. To my siblings and friends, thank you for keeping me grounded. Finally, to my partner, thank you for your patience, your understanding, and for standing by my side through the highs and lows of this chapter.

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Abstract

Nigeria faces concurrent challenges of energy poverty, inadequate waste management, and socio-economic instability. This research investigates the sustainable feasibility of utilising biomass, particularly municipal solid waste (MSW), as a resource for decentralised combined heat and power (CHP) generation. Three waste-to-energy (WtE) system configurations were conceptualised: System A (anaerobic digestion + gasification + Organic Rankine Cycle), System B (anaerobic digestion + gasification + agricultural drying and cooling), and System C (anaerobic digestion + gasification + greenhouse urban farming). A comprehensive Life Cycle Sustainability Assessment (LCSA) framework was applied, incorporating Environmental Life Cycle Assessment (E-LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA) methodologies.

Technical performance modelling assessed system efficiencies and energy outputs, while the E-LCA evaluated environmental impacts across global warming potential (GWP), acidification, eutrophication, particulate matter formation, and resource depletion categories. The LCC quantified capital expenditure (CAPEX), operating expenditure (OPEX), and levelised cost of energy (LCOE), and the S-LCA employed stakeholder-informed indicators across community, worker, and societal dimensions. Across the three configurations, System C (anaerobic digestion + gasification with greenhouse urban farming) consistently delivered the strongest overall performance. With efficient internal-combustion prime movers (e.g., Wärtsilä 9L34DF/12V34DF), System C achieved an overall CHP utilisation of approximately 80 percent (with heat used in the greenhouse) and produced about 1.376 MWh of electricity per tonne of MSW, while a 1,000 m² greenhouse demand was fully met and still left sizeable surpluses (1.24–4.66 GWh yr⁻¹ of usable heat and 177–240 GWh yr⁻¹ of electricity at the city-scale throughput). Economically, System C achieved the lowest life-cycle cost (LCC) more than 60% lower than the worst-case turbine configuration, for example the SGT-400 exceeded \$80 million in System C. It also achieved the most favourable Levelised Cost of Electricity (LCOE), reaching below \$0.05 kWh⁻¹ in the most favourable engine cases. For comparison, System A (with ORC) recorded \$0.46 kWh⁻¹ for the SGT-50 and \$0.31 USD kWh⁻¹ for the SGT-400, while System B (drying and cooling) remained below about \$0.08 USD per kWh with efficient engines. Socially, System C ranked highest on the weighted S-LCA (4.53 vs 4.07 for System B and 3.47 for System A), reflecting stronger community benefits, inclusion and job creation. Prime-mover choice was the single biggest driver of environmental and economic outcomes

across all systems. The study also identified key trade-offs, including between technological complexity and social inclusivity, and between environmental optimisation and financial viability. The findings underscore the necessity of designing multi-functional, socially integrated WtE systems to ensure sustainability in developing country contexts. Contributions to Sustainable Development Goals (SDGs), particularly SDGs 7, 11, 12, and 13, were demonstrated. This research advances methodological approaches for integrated LCSA in developing regions and offers practical policy and design recommendations for scaling sustainable waste-to-energy solutions in Nigeria and similar socio-economic contexts.

Nomenclature

Acronyms

AD — Anaerobic Digestion
BAU — Business As Usual
CAPEX — Capital Expenditure
CCE — Carbon Conversion Efficiency
CCHP — Combined Cooling, Heating, and Power
CHP — Combined Heat and Power
CGE — Cold Gas Efficiency
DG – Distributed Generation
E-LCA — Environmental Life Cycle Assessment
G – Gasification
GHG — Greenhouse Gas
ICE — Internal Combustion Engine
INC — Incineration
IRR — Internal Rate of Return
LCA — Life Cycle Assessment
LCI — Life Cycle Inventory
LCIA — Life Cycle Impact Assessment
LCC — Life Cycle Costing
LCSA — Life Cycle Sustainability Assessment
LCOE — Levelised Cost of Energy
LHV — Lower Heating Value
MGT — Micro Gas Turbine
Micro-CHP – Micro Combined Heat and Power
MSW — Municipal Solid Waste
NMVOC – Non-Methane Volatile Organic Compounds
NPV — Net Present Value
OPEX — Operating Expenditure
ORC — Organic Rankine Cycle
PBP – Payback Period
PPA – Power Purchase Agreement
PM — Particulate Matter

PMF – Particulate Matter Formation
POF — Photochemical Ozone Formation
PPP — Public-Private Partnership
PYRO – Pyrolysis
RDP – Resource Depletion Potential
SE — Stirling Engine
S-LCA — Social Life Cycle Assessment
SRF — Solid Recovered Fuel
SDGs — Sustainable Development Goals
TEA — Techno-Economic Assessment
TLCC – Total Life Cycle Cost
TRL – Technology Readiness Level
WtE — Waste to Energy

Symbols

a-e — Molar ratios of carbon, hydrogen, oxygen, nitrogen, sulphur in feedstock
 A_1 – A_5 — Stoichiometric coefficients in Buswell’s equation
 CH_4 — Methane
CO — Carbon Monoxide
 CO_2 — Carbon Dioxide
EP — Eutrophication Potential
AP — Acidification Potential
GWP — Global Warming Potential
LCV — Lower Calorific Value
 M_{CH_4} — Mass of methane
MF — Mass flow of waste or material fraction
N — Normalised environmental impact score
PMF — Particulate Matter Formation
 PO_4^{3-} — Phosphate ion (used in eutrophication calculation)
 $Q_{recoverable}$ — Recoverable heat energy
 η — Efficiency (e.g., electrical efficiency η_{el} , ORC efficiency η_{ORC})
 V_{CH_4} — Volume of methane
 M_{MSW} — Mass of Municipal Solid Waste
 $E_{biofuel}$ — Energy content of biofuel

$E_{\text{electricity}}$ — Electrical energy output
Nu — Number of prime mover units
TC — Total Carbon
THC — Total Hydrocarbons
 H_2 — Hydrogen
 N_2 — Nitrogen gas
MJ — Megajoule
kWh — Kilowatt hour
MW — Megawatt
tMSW/day — Tonnes of MSW per day
kgCO₂-eq — Kilograms of carbon dioxide equivalent
kgSO₂-eq — Kilograms of sulfur dioxide equivalent
kg PO₄³⁻-eq — Kilograms of phosphate equivalent
kg PM₁₀-eq — Kilograms of PM₁₀ equivalent
kg NMVOC-eq — Kilograms of Non-Methane Volatile Organic Compounds equivalent
MJ/tMSW — Megajoules per tonne of MSW

Key Technical Terms

Anaerobic Digestion (AD) — Biological process breaking down organic material without oxygen, producing biogas.

Gasification (G) — Thermochemical conversion of waste into syngas (CO, H₂, CH₄) under low oxygen.

Organic Rankine Cycle (ORC) — System recovering low-grade waste heat to generate electricity.

Prime Mover — Engine or turbine converting fuel energy into mechanical and electrical power.

Syngas — Synthetic gas containing CO, H₂, CH₄ and other components, used as fuel.

Digestate — Solid and liquid by-product from anaerobic digestion, often used as fertiliser.

Biochar — Carbon-rich solid residue from gasification, usable as a soil amendment or carbon sink.

Cold Gas Efficiency (CGE) — Efficiency of gasification process in converting feedstock into syngas energy.

Carbon Conversion Efficiency (CCE) — Percentage of carbon in feedstock converted to useful energy products.

Chapter 1

1. Project Background

1.1. Introduction

To create a balance between economic growth, environmental preservation, and social well-being, the United Nations (UN) introduced the idea of sustainable development back in 1972. This movement did not gain widespread traction until the 2010s, in particular with the introduction of the 2030 agenda for Sustainable Development Goals (SDGs). Sustainable development, according to the European Union (EU), focuses on improvement that satisfy current demands without jeopardising the ability of future generations to satisfy theirs [1]. All 17 SDGs serve as the movement's central focus and cover a wide range of topics, some are affordable and clean energy, decent work and economic growth, clean water and sanitation, responsible consumption and production, sustainable cities and communities, and industry, innovation, and infrastructure [2]. It is renowned that the Sub-Saharan African region are among the least deficient in achieving this goal but also stand at a vulnerable position to sustain the effects of climate change. Changes in agricultural productivity, extreme weather and desertification are some of the conditions expected to increase in occurrence within the region due to climate change [3], [4]. With a population projected to double by 2050, Nigeria holds the largest share of the current population within the region, about 20% [2]. However, the country is faced with difficulties that are quite distant from achieving all SDGs.

Energy is a key component for a nation's development. Modern forms of energy provide benefits of sanitation, healthcare, and clean water, efficient and reliable provision of cooking, heating, lighting, transport, and telecommunication services [5]. Within the mix of energy sources in Nigeria, biofuels and waste dominate with a total energy consumption in Nigeria amounting to about 80%, about 5×10^{15} KJ [6]. Energy poverty is one on the major setbacks in Nigeria. Out of the 206 million population, approximately 85 million are lacking access to electricity, this is a challenging factor when aiming to do business in Nigeria. A target of 60% and 75% national electrification by 2015 and 2025 was set by the Nigerian energy commission. In 2020, the national electrification rate was 55.4%, with the rural electrification rate at 25.55% [7]. For other developing countries that same year such as India, Ghana, South Africa, Pakistan, Egypt, and Indonesia, they had 90.4%, 71%, 85%, 75.4 and 99.6% national access respectively.

In 2019, Nigeria's total annual energy consumption was about 135.4×10^6 tonnes of oil equivalent (toe) [6]. However, this does not meet current energy demands, resulting in the use of self-power generation with petrol or diesel generators to meet citizens' basic energy needs [8]. Further actions were taken in the third quarter of 2018 by the Nigerian Government to meet energy demand. The current infrastructure state has become antiquated such that there is a dire need to overhaul the entire system. Previous maintenance has not yielded benefits resulting in about 3,000 MW loss since 2015 because of fuel shortages, frequency control issues, and other technical system problems [9]. Furthermore, finances within the sector are in distressing states as the distribution companies are not generating enough revenue to offset their full market costs. [9].

With commitments to the 2015 Paris agreement, countries within the SSA region find addressing climate change more challenging due to limited financial and technical resources, poor infrastructure and weak governance and institutions [10]. The goal of the region is to develop and grow to be able to experience without hardship however, being faced with demographic pressures from both urbanisation and a rapidly increasing working age population, requirements of improved infrastructure, jobs and conducive environment combine to make an overwhelming challenge. This critical infrastructure deficit is illustrated in Figure 1.1, which contrasts the projected exponential rise in municipal waste generation against the stagnant reliability of the local power grid, highlighting the diverging trajectory that this research aims to address. Most developing nations grew by jeopardising the environment. Large amounts of greenhouse gases and waste were produced to the environment to rapidly build infrastructure and provide energy to the high demand of it.

With understanding the repercussions of these actions, we cannot afford the welfare of our planet to develop such a large growing population in that manner. With the abundance of renewable energy sources, great potential to deliver economic growth and climate change mitigations fall in the energy sector. The transportation sector contributes about 60% of Nigeria's carbon dioxide (CO₂) emissions [11]. Compared to the likes of the United Kingdom with 35%, Brazil with 47% and the United States with 37% [6]. Biomass could present a sustainable solution for this and the electrification rate but also provide economic, social, and environmental enhancement capable of taking Nigeria a step closer to meeting the sustainable development goals and emission commitments [12]

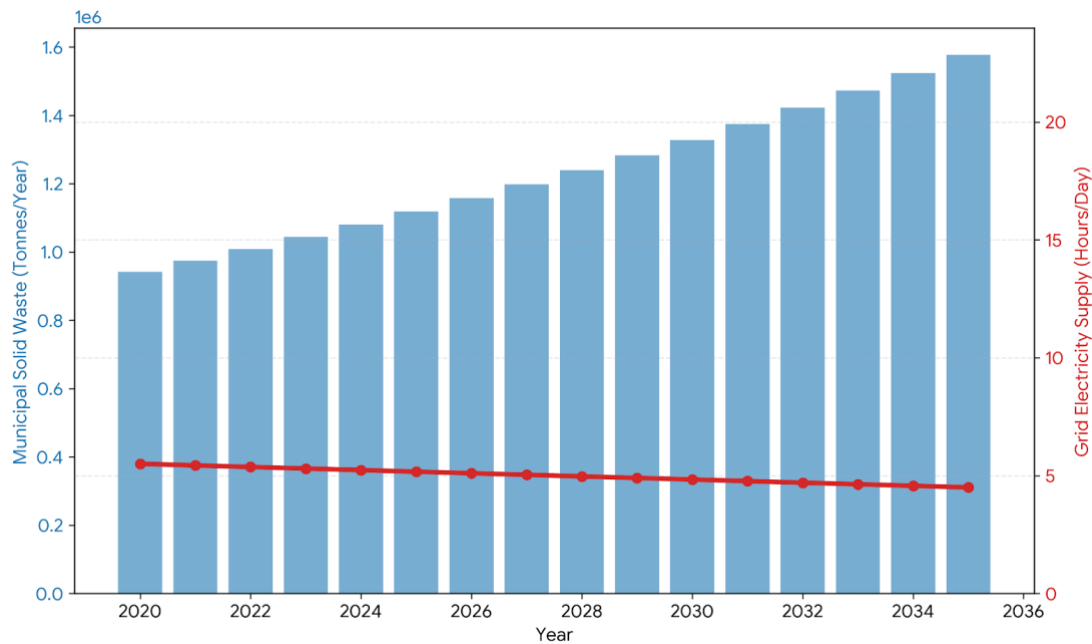


Figure 1-1: The diverging infrastructure challenge in Port Harcourt [2], [7], [13]

Biofuels have been globally accepted in the past because of their less harmful impact to the environment. The public acceptance for biofuels has recently increased due to the benefits gain from advanced utilisation such as electricity, heat, energy vectors, chemicals, and more. In Nigeria, the rural inhabitants are typically farmers, electric power supply by biomass can improve the income levels of local farmers and promote rural economies. It can also enhance the storage capacity and processing capability of agricultural produce, which can improve the market value of products. Nigeria is Energy security and other socio-economic factors can be improved through the application of biomass for power generation in rural areas to guarantee the continuous supply of energy. There is a high rate of rural–urban drift in Nigeria, which is steered by the search for paying jobs and comfortable lives that are rarely available in rural areas [12]. Biomass energy facilities are capable of stabilising local markets for biomass feedstock where they could also enhance local tax bases exclusive of extensive services from local communities. All these benefits are in addition to the production of clean energy, which attracts Kyoto incentives in the form of financial support mechanisms.

1.1.1. Current energy structure in Nigeria

Nigeria’s energy sector has shifted towards the private sector involvement by targeting policies that govern the electricity market and its regulation. The underpinned actions are squarely aimed at addressing the structural challenges of poor service, low availability, and intermittent reliability. In 2005, the Energy Commission of Nigeria developed the Renewable Energy

Master Plan (REMP) that seeks to increase renewable electricity supply to 23% in 2025 and 36% by 2030. This followed with a suitable renewable energies plan target [14]:

- Small hydro: 600 MW in 2015 and 2, 000 MW by 2025
- Solar PV: 500 MW by 2025
- Biomass-based power plants: 50 MW in 2015 and 400 MW by 2025
- Wind: 40 MW for wind energy by 2025

In 2007, the NNPC in Nigeria released a biofuel policy and incentives plan which aimed to reduce the dependence on gasoline foreign supply and create a biofuel economy. A blend of gasoline with up to 10% bioethanol and diesel with up to 20% biodiesel forming E10 and E20 respectively, was mandated in the policy to the NNPC. This created a demand of 1.3 billion litres of bioethanol and 480 million litres of biodiesel. However, domestic production could not meet, and Nigeria turn to bioethanol importation [15]. A bioethanol blend solution to deviate from conventional fuel is currently produced in Nigeria by UNIKEM industries, established a distillery in Kogi State to produce 240,000 L bioethanol daily from biomass such as cassava and sugarcane [16]. However, there is little information on the progress of this plan. The conversion technology commonly used for biofuel production from biomass is anaerobic digestion and transesterification [17]. This is due to the high organic fraction of biomass available making this method most suitable. Currently there are scarce reports highlighting its contribution to the energy production mix in Nigeria.

The Nigerian Electricity Regulatory Commission (NERC) reported an installed power generation capacity of 13,435 MW of 28 grid-connected generating plants comprising thermal Simple Cycle Gas Turbine (SCGT), Combined Cycle Gas Turbine (CCGT) and Gas Fired Steam Turbine plants and hydropower plants in 2018. Though it has been reported that just about 5,160 GWh was distributed (2389 MW equivalent to 20% of installed generation capacity [9]). Worsened performance level in recent times, credited to the entire power system array being poorly maintained.

In Nigeria there are various waste biomass resources including crop and forest residues, food, industrial waste, animal waste, and municipal solid waste (MSW). The specific material composition of this waste stream is detailed in Figure 1.2, which demonstrates that over 90% of the aggregate MSW comprising organics, polythene, and paper possesses the necessary calorific and biological properties for hybrid energy conversion. Current waste generation is

about 0.51 kg/capita/day, but the waste collection rate is the lowest in Africa [13], [18]. Two or more of these classes of biomass can be utilised through combustion, gasification, pyrolysis and anaerobic digestion technologies [19]. These available biomasses also fall under the renewable carbon-based raw materials for biorefinery [20]. Fuelwood is the most regular form of biomass used in Nigeria, with utilisation methods for largely domestic cooking in rural areas via open burning, the lesser portion can be used for off-grid heating in small scale industries [21], [22], [23]. Modern use of waste is new in Nigeria. There are no large- or small-scale bioenergy facilities operating. Nonetheless, there are studies that assess the feasibility of bioenergy utilising waste. A study on dry MSW samples from a dumpsite in Ilorin metropolis, Nigeria concluded that out of 3072.21 kg of MSW that was generated in both seasons, 70% of the aggregate MSW and can be used as feedstock for energy conversion but also manage waste. [24]. An earlier report used the same prediction method and choice of case study to conclude that 584 tons of combustible municipal solid waste in Ilorin with a heating value of 21MJ/kg has the potential to produce 3.2 GWh of energy, 41 MW of electrical power and 27 MW of power to grid [25]. Though a high overall efficiency of 98% the study showed a beneficial outcome to the use of biomass.

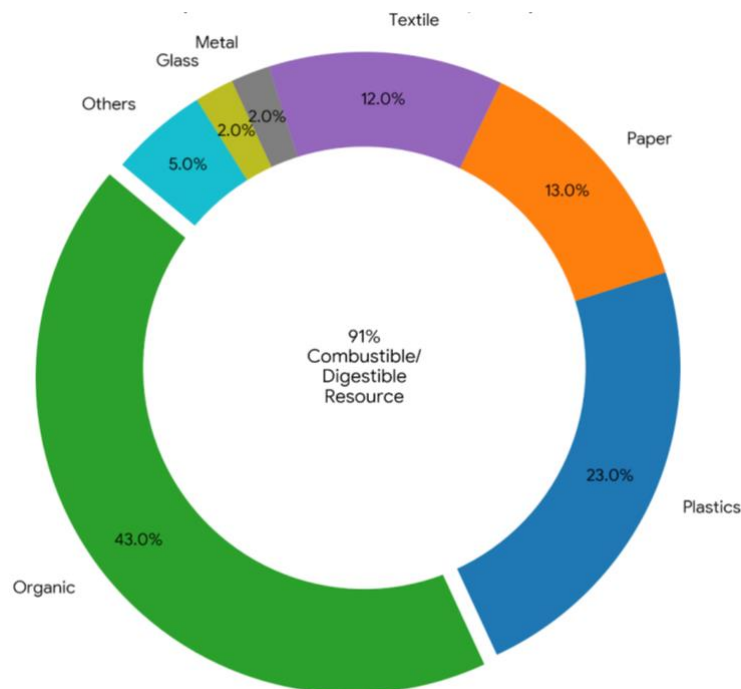


Figure 1-2: Material Composition of Lagos State MSW [26]

1.1.2. Sustainable development solutions

The primary force behind sustainable development is energy. The terminology "energy system" is frequently used to describe the energy chain, which can be thought of as an entity made up of energy generation, conversion, transmission, distribution, and consumption [27]. Distributed generation (DG) refers to the generation of energy using small, modular generation systems which are close to the point of consumption. The amount of the technology's power production as well as the device's location and use are some of its primary distinguishing features. Distributed systems can be autonomous and may act decentralised by having no interaction with other units. These systems have increased in popularity due to them being a solution to address multiple requirements such as conserving energy resources, ensuring homeowners' comfort, increasing total thermal efficiency, and limiting the emission of pollutants into the environment [28], [29]. A crucial strategy for extending the use of sustainable energy is to increase energy efficiency.

Cogeneration, sometimes referred to as combined heat and power (CHP) systems are a useful tool for achieving the goal of greenhouse gas reduction. A CHP system produces electricity while simultaneously capturing thermal energy from process waste heat [30]. The process is well known for its higher efficiency, enhancement of energy reliability, contribution to energy security and decentralisation of energy supply. It also can reduce the cost of energy for consumers and offers a possible avoidance of investment in transmission and distribution networks [31]. A simple configuration of a CHP system consists of a prime mover which converts energy into work, generator which generates electricity and heat recovery unit that captures the waste heat. There can be different technologies employed for the prime mover role; some are reciprocating engines, organic Rankine cycle, sterling engines, microturbines, steam engines, gas turbines and fuel cells. For domestic and small industrial applications, a smaller iteration of the CHP system, often known as micro combined heat and power (micro-CHP or mCHP). CHPs can serve as a base for building for further building out a sustainable energy generation system. This can be done is by introducing the system with renewable sources of energy and technologies, such as wind turbines, electrolysers, solar PV, absorption chillers, heat pumps, etc to further increase system efficiency or produce various energy vectors. Typical setups for biomass cogeneration systems are illustrated in Figure 1-1. While conventional systems often utilise steam turbines, modern distributed energy systems increasingly employ Internal Combustion Engines (Figure 1-2) or Micro Gas Turbines (Figure 1-3) to achieve higher electrical efficiencies and modular scalability.

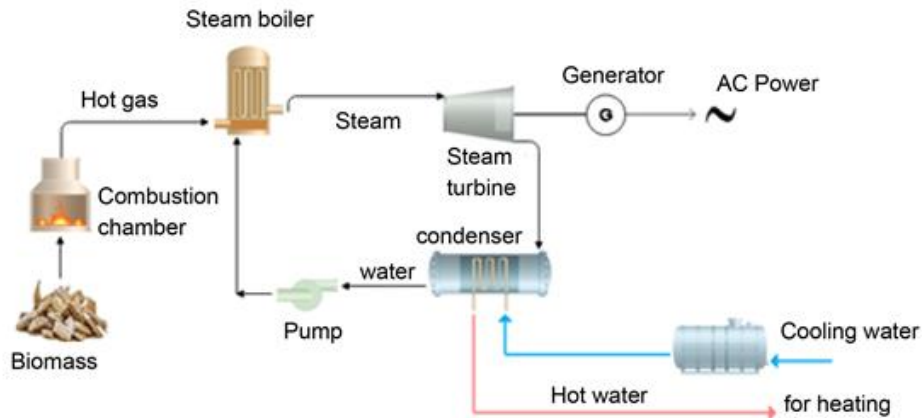


Figure 1-3: An example of a biomass cogeneration system that uses a steam turbine.

Systems for biomass-based CHP can be used as a dispatchable source of power and are growing in popularity within academia and industry [32], [33], [34], [35], [36]. Case study focused studies on biomass use are also becoming more common in the field. For example, the energy potential of municipal solid waste in Nigeria was studied in 4 scenarios being landfill with no gas recovery, landfill gas to energy technology, hybrid incineration with anaerobic digestion, and hybrid incineration with landfill gas technology [37]. Both developed and developing countries have adopted these systems to meet their energy needs. A comparative study for small industries Brazil assessed the energetic and economic performance of natural gas or biogas in a compact cogeneration system and found both to have similar energy performances but biogas to be more profitable [38]. By the end of 2020, there were 2659 installed CHP systems in the UK with a capacity total of 7.7% electricity generation. Five other countries have successfully expanded the uses of CHP with unique approaches to about 30-50% of total power generation: Denmark, Finland, Russia, Latvia and the Netherlands [39].

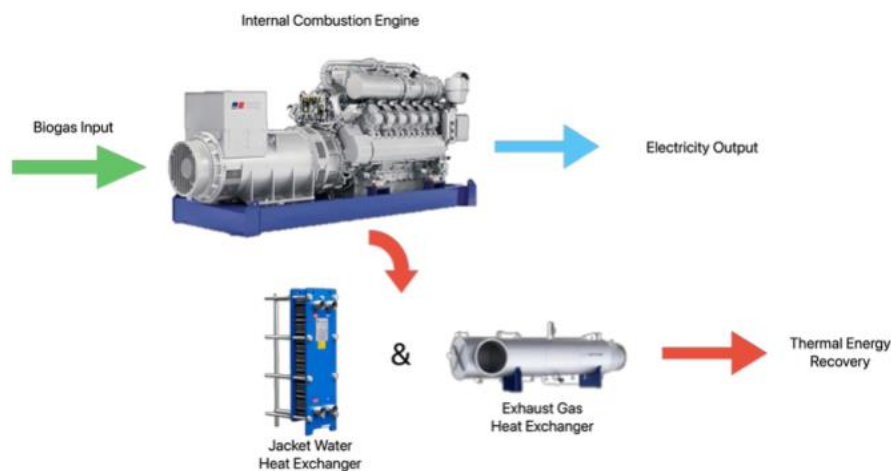


Figure 1-4: Internal Combustion Engine (ICE) CHP Schematic

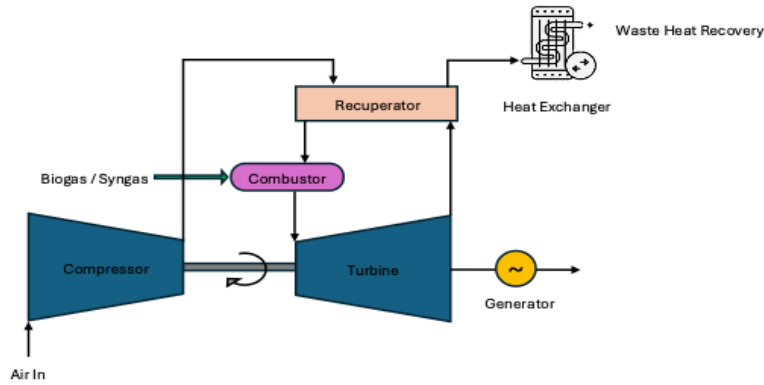


Figure 1-5: Schematic of a Micro Gas Turbine (MGT) CHP System

A fundamental advantage of Distributed Energy Systems (DES) over centralised power generation lies in the mitigation of Transmission and Distribution (T&D) losses. In centralised networks, particularly in developing infrastructures like Nigeria's, T&D losses can frequently exceed 15-20% of generated power due to long-distance transport resistances, transformer inefficiencies, and aging grid infrastructure. Conversely, distributed cogeneration systems operate at the point of demand, effectively reducing these losses to negligible levels (<2%). Furthermore, while centralised plants typically vent waste heat (resulting in overall efficiencies of ~35-40%), distributed CHP systems recover this thermal energy for local applications, boosting total system efficiency to upwards of 85-90%, as illustrated in Figure 1-4.

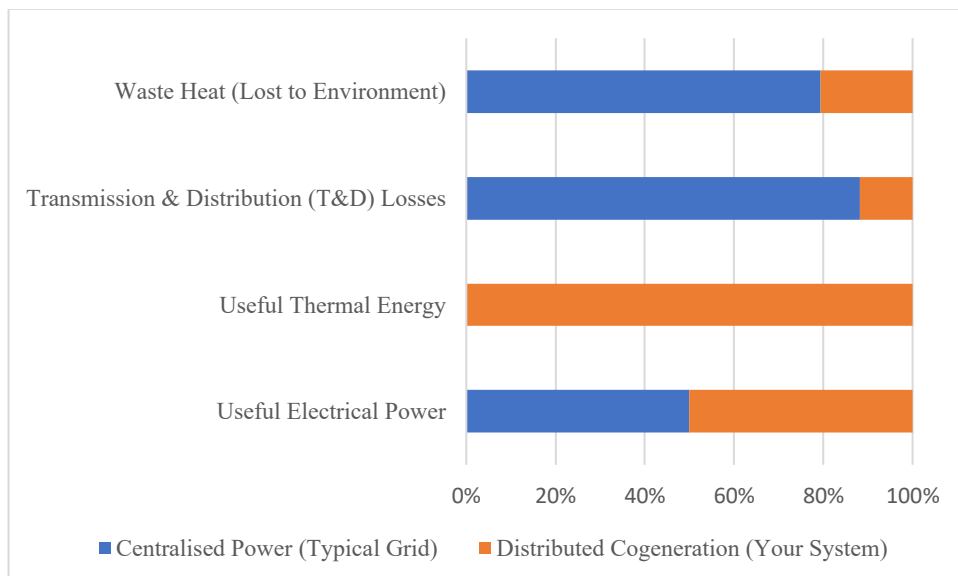


Figure 1-6: Efficiency Comparison between conventional centralised generation and distributed cogeneration.

1.2. Research aims and objectives

Mitigating global climate change and promoting sustainable development requires significant efforts. Considering the growing population, energy poverty levels and poor socio-economic indices, Nigeria could adopt biomass energy to accomplish its sustainability commitments and develop its economy. It will be important to know if this is the right step for rural communities and understand how an environmentally friendly energy source can sustainably provide similar communities, energy that enhances their current available source whilst growing their socio-economic status and improving the environment. This study will aim to offer a systematic approach to determine the most suitable biomass-based polygeneration energy pathway for distributed systems that fosters growth aligned with the United Nation's sustainable development goals. This is achieved by identifying and examining the sustainability of different biomass-to-energy technology configurations in different scenarios within Nigeria.

The objectives set out for this study are:

- To identify the social implications and environmental impacts of utilising biomass for CHP applications in Nigeria.
- To develop a framework to assess the sustainability of particular technologies for various evaluated scenarios in Nigeria.
- To evaluate sustainable utilisation of biofuel for decentralised/distributed energy systems in Nigeria.

The expected outcomes are to show the connection through literature between utilising biomass and economic improvement, environmental enhancement, and social development. It also presents that a decentralised distributed generation of energy would be a better solution to decrease energy poverty. This work critiques existing literature of some proposed solutions and the continued investment in centralised generation by the government.

1.3. State of the art, Gaps and Contributions

Nigeria and Port Harcourt face concurrent shortfalls in reliable electricity supply and modern waste management. Collection coverage is incomplete and open dumping remains common, while daily grid supply can be limited in urban areas, creating a strong case for distributed waste-to-energy solutions tailored to local conditions. The MSW stream in Port Harcourt is dominated by organics, which supports biogas pathways, but institutional capacity and policy enforcement are uneven. These conditions shape the feasible technology space and the priorities for impact evaluation.

1.3.1. Gaps

Prior Nigerian studies tend to evaluate single technologies or electricity-only options and rarely quantify the co-use of heat, the choice of prime mover, or the combined environmental–economic–social trade-offs in one framework. There is also limited scenario work that couples anaerobic digestion with gasification and then routes useful heat into productive services such as drying, cooling, or greenhouse farming. Finally, few studies benchmark complete systems with Nigeria-specific inventories and policy context for Port Harcourt.

1.3.2. Thesis Contributions

Scientific & Methodological Contributions:

- **Integrated TEA and LCSA Framework:** The thesis establishes a unified framework coupling Techno-Economic Assessment (TEA) with Life Cycle Sustainability Assessment (LCSA). This contributes to the field by validating a methodology for data-scarce regions that gives equal weight to social indicators (e.g., NIMBYism, informal sector integration) alongside standard economic and environmental metrics.
- **System Architecture Analysis:** The research defines and benchmarks the performance of hybrid Anaerobic Digestion and Gasification configurations, providing novel thermodynamic data on the trade-offs between "Exergy-optimised" (System A) and "Energy-optimised" (System C) designs for biomass valorisation.

Practical & Policy Contributions:

- **Dual-Path MSW Utilisation:** The study demonstrates a technical solution for the high-moisture/high-plastic waste stream typical of West Africa, validating a single platform that increases feedstock coverage beyond what simple incineration or digestion alone can achieve.
- **Policy and Deployment Guidance:** The findings translate complex multi-criteria results into actionable deployment guidance for the Niger Delta, including specific LCOE ranges, public-private partnership models, and policy recommendations for decentralised energy planning.

1.4. Research Roadmap and Thesis Structure

To achieve the aim and objectives outlined in Section 1.3, the research is structured into four logical phases. This structure ensures a coherent progression from problem definition to policy recommendation:

- Phase 1: Definition & Context (Chapters 1–2): This phase establishes the research boundary. Chapter 1 defines the specific challenges of the Port Harcourt case study, while Chapter 2 critically reviews the state-of-the-art in biomass technologies, identifying the lack of holistic sustainability assessments for Nigerian contexts as the primary knowledge gap.
- Phase 2: Framework & Design (Chapters 3–4): This phase focuses on methodology. Chapter 3 develops the integrated Life Cycle Sustainability Assessment (LCSA) framework. Chapter 4 subsequently applies this framework to engineer three specific system configurations (Systems A, B, and C), generating the mass-and-energy balance data required for assessment.
- Phase 3: Multi-Dimensional Assessment (Chapters 5–7): This phase rigorously tests the proposed systems against the three pillars of sustainability:
 - Environmental: Chapter 5 (Life Cycle Assessment) quantifies ecological impacts such as Global Warming Potential.
 - Economic: Chapter 6 (Life Cycle Costing) evaluates financial viability and investment risk.
 - Social: Chapter 7 (Social Life Cycle Assessment) assesses stakeholder impacts and community acceptance.
- Phase 4: Synthesis (Chapter 8): The final phase integrates these diverse metrics to rank the systems. It synthesises the findings to provide evidence-based policy recommendations for energy planning in the Niger Delta region.

Chapter 2

2. Literature Review

This chapter's first two sections state types of sustainable energy generation systems which use biomass as their fuel source. Then identifies what contributions and challenges such system has on a developing country by drawing on relevant research. 2.3. discuss on sustainable technologies within the energy generation system that are suit for structure of Nigeria. The next two sections discuss on the studies around design models of energy generation systems and a review of sustainability assessment methods. The last section of the report presents concluding remarks on the literature review and identifies the gaps in the literature.

2.1. Sustainable energy systems for distributed energy generation

Expanding on cogeneration system for sustainable generation, a trigeneration system or also known as Combined Cooling Heating and Power (CCHP) involves combining cogeneration technologies with various thermally fed systems, such as absorption chillers or heat pumps. This system simultaneously produces power heating and cooling by using one source of primary energy [39]. Lastly is a system centred on the creation of multi-generation or polygeneration energy solutions are made conceivable by the potential benefits of the combined production of several energy vectors such as electricity, heat, cooling, hydrogen, water, fuels, or other chemical products [40]. As the benefits of these various systems are evident, it is important to know the sustainability of each to model a system that best suits a developing nation. Below will uncover the scientific literature for each system type to lead our understanding of modelling a sustainable energy system.

2.1.1. Trigeneration systems

Biomass trigeneration, sometimes referred to as combined heat, power, and cooling (CHPC), is a sustainable energy system that uses biomass as the fuel source to produce electricity, heating, and cooling all at once. The sustainability of the energy systems in developing nations might be greatly enhanced by this technology. The primary elements regulating the overall performance are correct design and prime mover choices [41]. A study reviewed various systems and concluded that while gas turbines and ICEs are the most often utilised technology for producing heat and electricity, Rankine cycles and fuel cells are promising technologies that still require further study [42]. A trigeneration system was simulated and technically and financially evaluated to satisfy the energy needs of commercial buildings and district

heating/cooling typical applications where commercial building's energy demand profile was considered [43]. The authors established that the trigeneration system's process efficiency is significantly higher than it would be if it simply used the generated power, but that it is lower than it would be if it also used the generated heat. Nonetheless, the trigeneration option still has a considerable reduction in CO₂ emissions over the power generation option. There are various studies available in the literature that show the feasibility of using biomass in a trigeneration energy system with different prime movers [44], [45], [46]. It has also been noted that trigeneration systems are implemented around central facilities for consumers due to the losses involved when transferring energy over long distances [27].

2.1.2. Polygeneration (Multigeneration) systems

A sustainable polygeneration energy system plays a significant role in meeting a developing country's energy needs. The ability to utilise local available biomass resources which includes biodegradable waste such as wood, crops, and agricultural waste [47]. It can be used to meet multiple objectives such as producing energy vectors (electricity, heat, and cooling), solid, liquid, or gaseous biofuels, water and fertiliser as shown in Figure 2-1. Polygeneration systems can also be aimed to meet more objectives such as job creation, environmental improvement, and economic development. An analysis of a polygenerational systems stated these systems provide effective process integration with several inputs and outputs and they can be a sustainable energy solution with improved efficiency and optimal resource usage [48].



Figure 2-1: Schematic diagram of the biomass-based polygeneration system [49]

By the integration of numerous sub-systems and use of low-grade heat, energy can be supplied at a lower cost, losses can be minimised, efficiency increased and negative impacts on the environment reduced considerably [50]. A study showed that it is feasible to generate power, fresh water, heat, and hydrogen based on biomass anaerobic digestion polygeneration system that uses sewage sludge [51]. Another showed the use of local agricultural waste to deliver power, chilling for cold storage, heating, and fresh water through desalination for rural coastal areas in India [52]. It has been asserted that by 2030 multigenerational systems can cut annual CO₂ emissions by 950 Mton.[29]. Different configurations of polygeneration plants using biomass have been examined in several studies within the literature [53], [54], [55], [56], [57].

2.2. Impacts of biofuel utilisation in developing countries

Bioenergy plays a crucial role in many scenarios for achieving the Paris goals of limiting climate change to well under 2 degrees Celsius [58] and there many creative ways of utilising biomass. There are a few examples in parts of the world, particularly in Europe where biomass has successfully been used to manage waste and/or produce energy. This section of the literature will highlight ways in which biomass has been utilised and how it one or more of the pillars of sustainability.

2.2.1. Social Impacts

Social acceptance and participation are key factor for the effectiveness and sustainability of a biomass energy system [59]. It has been shown that social acceptance increases when WTE systems are perceived to promote climate change mitigation and address local deficiencies such as energy supply, service provision, and employment. As important as economic and environmental factors are, the quality-of-life of surrounding communities, education and information dissemination can enhance the impact of WTE. The 'Not-In-My-Backyard' (NIMBY) syndrome where residents oppose local infrastructure due to perceived risks despite broader benefits is another critical indicator to be considered. It serves as a gauge for social acceptance, ensuring that technical development is matched by community engagement strategies. This encompasses factors such as safety, method of handling, and land space requirement [60]. There have been ways shown where legislation can support social involvement, a known example was in Japan where the Food Recycling Law requires food waste emitters to report the amount of food waste recycled [61].

Preliminary results from a study within the literature show approximately one-third of the study's participants were willing to purchase the stove at or above the minimum price of N15,000, which is approximately USD \$42. Furthermore, they have demonstrated the acceptability of the blended ethanol-methanol fuel and the willingness of the participants to purchase it from gas stations that are within 2 km of their homes. Households purchased an average of 2.3 canisters per month, which is approximately 25% of the estimate monthly need for a typical Lagos household. The canister sales data suggests sustained, but not exclusive, use of the Clean Cook stove, and further detailed analysis of the stove use monitoring data and household surveys will allow more complete investigation of adoption patterns [16]. A social life cycle assessment was conducted to assess the social impacts that develop from generating electricity from municipal solid waste in Nigeria through focus groups [62]. Assessed in line with United Nation Environment Programme (UNEP) guidelines, the study found improved electricity supply, employment, contribution to economic development, public acceptance, and improved sanitation as the highest positive social impact of waste to energy adoption respectively. The results did not show any negative impact of waste to energy adoption however, public awareness, health and safety, education and training, and income scored the lowest respectively which was categorised as a neutral social impact by the author. Using the perspective of this study, future waste to energy projects in Nigeria may have a higher social impact if these factors are largely considered.

2.2.2. Environmental Impacts

The utilisation of biomass for energy has had polarised views regarding the impact it has on the environment. Using a life cycle assessment to examine the environmental impacts on a Glasgow township, a report studied the environmental impact an anaerobic digestion and gasification system [63]. With global warming potential (GWP), eutrophication potential, and acidification impact as indicators, the results showed it was possible to avoid over 300 kg of CO₂ per tonne of municipal solid waste treated when biogenic carbon is excluded. Chang et al, [64] study detailed the environmental impact and sustainability of biofuel blends for transportation use, showing various blends of biofuel from the right source can reduce fossil fuel usage and minimise GHG emissions. A life cycle assessment was used within a study covering the environmental impacts (global warming, acidification, and dioxin/furan emission potentials) of a waste to energy treatment plant in 12 cities Nigeria. Finding a hybrid of as the incineration and anaerobic digestion to have the lowest global warming and acidification potential [65].

However, this study excluded gasification and pyrolysis which are emerging technologies with lesser impacts on the environment.

Aberilla et al, [66] conducted a detailed environmental sustainability assessment of power generation technologies using biomass. The study was aimed at agricultural communities in developing countries and compared their performance to a traditional diesel generator method. The authors found that anaerobic digestion is the best option for most environmental impacts due to the systems additional functions. For environmental indicators such as global warming potential (GWP), photochemical oxidants formation (POFP) and particulate matter formation potentials (PMFP), gasification is the recommended substitute. Except for the case of terrestrial ecotoxicity potentials (TETP), all power generation technologies using biomass have a considerably lesser impact on the environment compared to diesel power generation. This may be due to the source of biomass having to be produced from agriculture. Nonetheless, this shows why biomass energy generation is a formidable solution for developing countries.

Particulate matter (PM) and local emission are important factors to consider when utilising biomass. In a study on the female rural dwellings in Southern Nigeria, the relationship between nonusers and user fuelwood combustion with their carotid intima media thickness (CIMT) levels and blood pressure (BP) [67]. Users of fuelwood showed higher levels of PM 2.5 - a hazardous level of airborne particles compared to non- fuelwood users. A way to tackle this problem is by introducing a more environmentally friendly method of utilising biomass such as gasification. From the introduction of more efficient biomass conversion technologies, there have also been concerns about the negative impact residue ash from thermochemical conversion processes have on the environment. However, Chuang et al., [68] study shows it is possible to use ash residue from the incineration of municipal solid waste to produce of light weight aggregate material. This can further be incorporated in asphalt mixtures for paving material and in cement composites [69].

2.2.3. Economic impacts

The economical probability of an energy generation system using biomass is dynamic. Some factors that largely affect key indicators of net present value (NPV), internal rate of return (IRR), Levelised cost of energy (LCOE) and payback period are the number of products the plant can generate, the minimum unit cost of each product and the regional or global demand the markets of these products offer. Profitability of investments of a diversified biomass energy

generation portfolio has been seen in developing countries. Provided a strong IRR is achieved, a robust biofuel production project can still be possible even in unfavourable economic circumstances such as high inflation and interest rates [70], [71].

Various studies have assessed the economic performance of biomass conversion systems for developing countries. Transport, storage, and loading/unloading and some of the logistics of biomass which can be a large determinant of the economic feasibility. A study by Tauro et al, [72] for Mexico showed the logistics costs of sawdust pellets had a significant impact on its competitiveness for energy use compared to coal, coke, and natural gas. Ayodele et al., [73] investigated the power production and economic performance of MSW used in anaerobic digestion and landfill gas in Nigeria. The economic viability of the study was successful and found that though AD is a better energy generator, it performs worse in IRR, total life cycle cost and NPV but performs better in payback period and LCOE. Huang and Fooladi's [74] study for a use case in China supports the economic performance of AD and Landfill gas. Abdelhady et al. [75] investigation on rice straw use in a combustion energy system for Egypt found that LCOE is highly sensitive to the price of feedstock and discount rate.

2.3. Technologies for a sustainable energy system in Nigeria

Conditional to the sustainable objectives of a distributed energy system, technologies comprised within can includes a conversion technology, a prime mover, an electric generator, thermally activated equipment, and a heat recovery unit.

2.3.1. Conversion technologies for fuel and chemical production

The processes for fuel production from biomass are physiochemical, biochemical, and thermochemical processes. Physicochemical technologies include transterification which convert organic wastes to liquid fuels such as biodiesel by aid of chemical agents. Technologies for biochemical process are anaerobic digestion, fermentation, landfill gas recovery and microbial fuel cell which produces methane, ethanol, biodiesel along with fertilisers as a by-product. Thermochemical technologies are the most widespread. They include pyrolysis, gasification, and incineration. With biochar and slag often as a by-product, fuel and chemical products include hydrogen, alcohols, methane, ammonia, methanol and Fischer-Tropsch (FT) liquids (e.g., biodiesel, biokerosene, biopetrol). The following technologies discussed are the most relevant for the case study.

Anaerobic Digestion (AD)

Anaerobic Digestion also known as biomethanation, is a versatile technology that involves microbial degradation of organic biodegradable matter in the absence of oxygen which produces heat, biogas, and enriched compost, thereby significantly reducing the cost of treating wastes and pollution. The enriched compost produced could be used in agriculture both as a nutrient fertiliser or as an organic modification [76]. The anaerobic digestion processes are mainly of two types, “dry” (24–40% of dry matter content) and “wet” (10–15% of dry matter content) processes [77].

The feasibility of the anaerobic digestion process depends on operating parameters, design of the reactor and quality of feedstock input (proteins, minerals, and vitamins content of waste) which will determine the quality of output product and amount of gas yield (enriched solid compost and biogas) [78]. Domestic sewage, agricultural waste, organic waste, and animal manure treatment were the main feedstock for the early anaerobic digestion process but now it is widely used for energy recovery from high moisture content municipal solid waste especially in the developing countries [79]. With a low to medium pollution control requirement, anaerobic digestion is reported to reduce the volume fraction of waste by 45 – 50% [80]. The biogas produced can be used after cleaning up in prime movers or can be upgraded to biomethane for distribution.

Anaerobic digestion process comes with some drawback consisting of long retention times, low overall degradation efficiency of biomass, low methane yield, instability of digester system and 16 complex compositions of product [81], [82]. These often lead to low energy production, high maintenance, and operating costs. AD technology has been applied on a limited scale in Europe on mixed MSW and on a larger scale on source separated organics (SSO) or agricultural-based processes. There are several smaller demonstration facilities in America and North America operating on either mixed MSW, SSO, or in some cases co-digested with biosolids [82], [83].

Studies have highlighted this method as most favourable to deal with waste in Nigeria. Alao et al., [84] compared AD to Landfill gas recovery, Incineration and Pyrolysis, for the least investment cost, operation and maintenance cost as well as lowest cost of energy. The researcher concluded gives the best option with the values 3.914 million USD, 57.51 million

USD and 0.0581 USD/kWh, respectively. But also identifies pyrolysis having the least cost of energy of 0.0318 USD/kWh and anaerobic digestion as the best option for environmental impact with the least CO₂ equivalent emission of 2842.9 ktCO₂ eq emission. Ayodele et al, [65] reported that a hybrid incineration and anaerobic digestion scenario (INC/AD) has the best electricity generation compared with various technologies and hybrid scenarios, based on different kinds of waste generated. Port Harcourt city in the south-south region of Nigeria reported to be the highest electricity generation potential of 267.24 GWh/yr. The study also mentioned the INC/AD scenario can reduce its global warming potential (GWP) of 91.53 ktonCO₂ eq in Port Harcourt by 75.7-93.3%.

Gasification (G)

An appealing technology, with only a few demonstration-scale projects in the world. Gasification is a partial oxidation at elevated temperatures.

There aren't many large-scale demonstration projects worldwide, despite the fact that gasification of MSW is a very attractive technology [16].

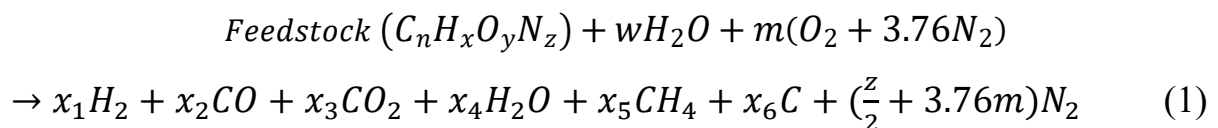
A partial oxidation process called gasification, which occurs at temperatures between 600 and 1700 C, transforms organic compounds into a Synthesis Gas (syngas), which is primarily composed of CO, H₂, a trace amount of CH₄, and small amounts of various hydrocarbons (tars), as well as particulates and inorganic impurities like H₂S, HCl, NH₃, HCN, HF, and alkalis [17]. Air, oxygen, steam, CO₂, or a combination of these can all be used as gasification fluids in a gasifier. A syngas produced by air gasification has a minor Lower Heating Value (LHV) of 4.0 to 6.0 MJ/Nm³, whereas a syngas produced by O₂ gasification has a medium LHV of 10.0 to 20.0 MJ/Nm³.

a solid fuel producing synthesis gas which can be used for electricity generation or in the synthesis of fuels or chemicals [85]. The result gas contains large amounts of not completely oxidised products holding great value, which can be employed energetically to applications such as lime and brick kilns, metallurgical furnaces, dryers, steam-raising boilers, gas engines and turbines, fuel cells etc. Furthermore, carbon monoxide and hydrogen raw materials can be used as the basic building blocks for producing valuable highly efficient products [86]. Over the last twenty years, significant advances have been made in the field of gasification, which has enabled the technology to represent itself as an attractive alternative to the well-established

conversion methods for treating agricultural waste, sewage sludge, wood waste, commercial and industrial wastes, and plastics [87].

Withdrawing from the high costs, high dioxin and furans related to traditional incineration and pyrolysis technologies; the gasification process achieves a higher energy recovery and heat capacity during the conversion process [88]. The gasification technology aims at improving environmental compliance of waste to energy technologies by its pre-mixed flame and vitrifying solid residues thus saving disposal costs and raising additional revenue [89], [90]. Biomass gasification is at fairly early stages of industrial commercialisation however, extensive practices are in place to build confidence in this technology particularly, in tar reduction, ash behaviour, gas cleaning, gas usage in different prime movers, efficient behaviour of the reactor regarding the nature of biomass, etc. The further paragraphs outline how waste is turned into gas and what changes are being made to commercialise the technology. Mohammed, Y.S., et al., [21], pointed out advantages and stated gasification power plants have been used for rural electrification in developing countries and are usually located close to rural electricity consumers. This supports Demirbas' [91] point on when biomass is focused on biofuel production, many benefits for the environment, economy and user follow. Plasma Arc is a novel method of gasification that create an electric arc and produce a plasma gas with very high temperature of up to 20000 °C or more. Though high investment cost is required to procure, it produces the about 816 kWh/ton MSW [92]. This is higher compared to conventional Gasification (685 kWh/ton MSW), pyrolysis (571 kWh/ton MSW), and incineration (544 kWh/ton MSW) [92].

In order to gasify the waste, the downdraft reactors under consideration in this work will run at atmospheric pressure, with air serving as the gasification agent, The reactants and products involved are summarised in the general chemical equation that follows.



The equation 1 suggests, in the presence of air, the feedstock (any organic substances in the MSW) is transformed into six main products. Those products include two energy carriers (H_2 and CH_4), pollutants (CO and CO_2), water vapor (H_2O), free carbon (C) and nitrogen gas (N_2).

The amount of carbon in the feedstock that is still unconverted during the gasification process is represented as free carbon. The feedstock's chemical composition and operating conditions affect the proportion. In this model, it is expected that nitrogen gas (N_2), which is 3.76 times more prevalent in air than oxygen, will not undergo any reaction.

Where $C_nH_xO_yN_z$ is the chemical formula of the dry ash and free biomass, $x_1 - x_6$ (mol/mol_{bio}) are the specific molar amount of the constituents of syngas. w (mol/mol_{bio}) is the specific molar amount of the biomass moisture, m (mol/mol_{bio}) is the specific molar amount of air.

Pyrolysis (PYR)

Ayodele and Dawodu [93] were successful in yielding biodiesel using *Calophyllum inophyllum* - an agricultural crop through pyrolysis and esterification. Other studies showed it is also possible to produce biodiesel with palm oil, obtained from palm which is a widely available agricultural crop in Nigeria [94]. There have also been studies that have used crop residues to produce biofuel. A study by Okeh et al., [95] showed using 50 g of rice husk feed is able to produce 382ml of biogas daily. Forage grasses and shrubs used to produce 200 million tons of dry biomass, which give up to 2.28×10^6 MJ of energy [96].

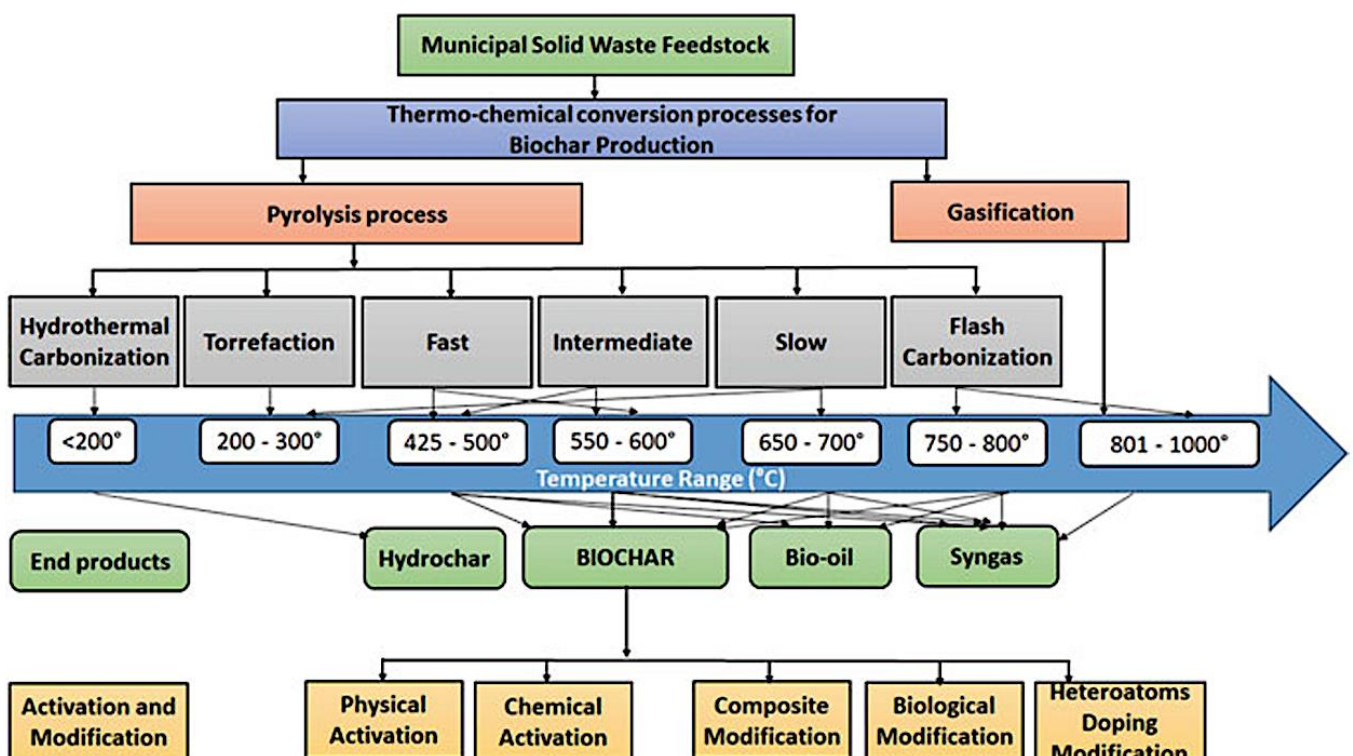


Figure 2-2: MSW Biochar production methods [97]

During Pyrolysis, thermal decomposition takes place in the absence of oxygen at different temperature gradients which define the method of pyrolysis. As seen in Figure 2-2, the methods available are conversional, fast and flash pyrolysis, and operating at 200 – 425 °C, 425 – 500°C and 750 – 800°C respectively [91]. The pyrolysis method has been widely used due to its ability to convert solid biomass and wastes into solid, liquid, and gaseous products such as crude bio-oil, char, chemicals for commercial opportunity, electricity production or fuel in an engine or turbine without the need for extensive upgrading [98], [99]. A plant of 110 tonnes per day capacity in Burgau, Germany has been successfully generating electricity through MSW pyrolysis since 1987 [100]. Advantages of this process include the significant reduction of the volume of waste to about (<50-90%), using waste feedstock input which produces gaseous, liquid, solid fuels and consequently, renewable source of energy. In comparison to the incineration process, capital cost is lower. Nevertheless, there are disadvantages such as high viscosity of pyrolysis and high operating, maintenance, and capital cost.

Combustion or incineration (INC)

Incineration is a well-known technique used to convert waste to energy by degradation and combustion organic elements of MSW with the presence of oxygen to decrease solid waste's volume by 90% and mass by 70% converting the feedstock into heat and energy whilst recovering energy from waste to generate electricity. Unlike fossil-fired power plants, a net power cycle efficiency of 13% to 25% can be achieved with incineration [101]. A study done by Murphy and McKeogh [102] stated incineration to have the highest gate fee and the greatest capital cost when compared to other thermal processing methods. Incineration requires supplementary fuels to achieve high combustion temperatures therefore higher emissions of greenhouse gases (GHGs) per kWh of converted waste to energy are produced. Not all waste is combustible, and some may give rise to harmful emissions. There is difficulty dealing with metal emissions in inorganic waste containing heavy metals as they can cause severe respiratory problems [103]. In addition, leftover ash contains leachable inorganic pollutants which need a better disposal procedure rather than landfilling furthermore, air pollution control systems for treating emissions and pre-drying of feedstock all increase the operational cost of the incineration process [104]. A tonne of MSW incinerated generates 544 kWh of energy and 180 kg of solid residue per tonne [105]. Ibikunle et al., [24] suggested WTE via incineration is recommended as the best option of MSW management method for Ilorin, because the

percentage of the combustible waste fractions to the aggregate of waste generated is about 71%, with HV ≥ 26 MJ/kg and generation rate of ≥ 0.15 kg/capita/ person.

2.3.2. Prime mover technologies for power generation

The central component of an energy system is a prime mover, often an engine or turbine, which converts energy from thermal, electrical, or pressure form to mechanical form. The output is a rotary motion hence they are normally coupled to electricity generators. Thermal activated technologies can also be coupled to prime movers to utilise the waste heat and further increase system efficiency. The efficiency, performance, configuration, and sustainable benefits of co-, tri- or poly-generation systems depends on the prime mover employed. The various technologies available include reciprocating internal combustion engine (ICE), gas turbine (GT), micro gas-turbine (MGT), fuel cells (FCs), steam turbines (ST) and Stirling engine. The assessment of the most suitable given prime mover for this study is discussed below.

Micro gas turbine (MGT)

Micro turbines are a popular technology for distributed energy system because of their high rotational speed, low emission, small size, low noise levels and reject high temperature exhaust gases with high quality heat. They can range from 30 to 500kW but require high quality fuel when used in a biofueled based energy system [106]. MGT comes in two configurations: single shaft and double shaft. Operating MGT with biofuel is novel within the literature and requires modification to the fuelling system and combustor. Bruno et al. [107] conducted a techno-economic evaluation of the performance of several hybrid configurations that included an MGT powered by a specific biogas and absorption cooling methods. The drawbacks of MGTs are the high capital cost when compared to reciprocating engines, low electrical efficiency and sensitivity of efficiency to changes in ambient condition [108]. Nonetheless MGT proven to be feasible for distributed energy systems.

Internal combustion engine (ICE)

A very mature technology that ranges from 3kW to 23 MW power generation [109]. They are coupled with generators and heat exchangers to produce electricity and recover the heat of the exhaust gases. It has a short payback period due to its low cost as assessed within Yin et al. [110] study on a waste cassava starch plant. This is a significant finding as it could be system fit for Nigeria who is largest producer of cassava starch plants in the world, the waste from

producing this crop has a high potential for biogas production. Wu and Wang, [111] highlighted in detail the benefits and drawbacks of ICE within CCHP. A study by Ogunjuyigbe et al., [37] utilised a 33% electrical efficient ICE to assess the feasibility of generating electricity from MSW across cities in Nigeria, coupling it LFGTE, INC, or AD.

Fuel cell (FC)

Similar to main batteries, fuel cells are electrochemical energy converters except they produce water as a by-product [112]. Fuel cells achieve high electrical and overall efficiency, high reliability, silent operation, cheap maintenance, low emissions, good match with household thermal-to-power ratio and good part load behaviour but its cons are high fuel purity requirement levels, short life membrane and high capital cost [113], [114]. There are several different types of fuel cells available on the market today, but SOFC is the most used [115]. Bang-Møller et al., [116] studied a decentralised system on gasification and SOFC with 45.3% electrical efficiency was able to achieve over 1.4MWe with from a bio-fuelled CCHP system. Additionally, fuel cells (FCs) may have a promising for the future due, in large part, to their potential for exceptionally high electrical efficiency, as well as their possible connection with turbine technologies for the creation of hybrid cycles [112].

Gas turbine (GT)

Gas turbines are the oldest technology used for electricity generation. The size of gas turbines ranges from 500 kW to 250 MW, thereby making it appropriate for large-scale cogeneration or trigeneration systems. Gas turbines also create high-quality exhaust heat that can be utilised by thermally activated processes in CCHP systems to produce cooling, heating, or drying and increase the overall system efficiency to roughly 70-80% [111], [117]. El-Sattar et al., [118] shows the possible methods waste heat can be utilised within a biomass trigeneration system. Though gas turbines can reach high outputs, the net system efficiency is low compared to other prime movers and it does not compete economically with ICE [119]. Jana and De [120] succeeded in using both the technologies in a 1.1 MWe biomass polygeneration simulation.

Stirling engine (SE)

Stirling engines (SEs) can run more silently than the ICEs mentioned before, function better at partial loads, and require less maintenance because they have fewer moving parts [106]. They are popular in cogeneration applications and when employed in trigeneration systems, being

coupled with adsorption technologies is encouraged due to the capacity to function with little thermal output. The work by Maraver et al., [121] which showed the viability of a CCHP based on SE as the prime mover and biomass combustion, supports this. Further studies show SE feasibility to reduce emissions but also achieve high energetic efficiencies [122], [123]. Murugan and Horák [124] stated Stirling engines may not be economically viable, especially when used in residential and construction applications, because of their high initial investment costs and the requirement for high quality heat to power such engines.

2.3.3. Thermally activated cooling technology

Thermally activated cooling, often known as heat, powered cooling, is the most popular technique for producing cold while using a heat source. Sorption cooling dominates this technique. Both absorption and adsorption can occur during the process of sorption. Adsorption is the process of using a solid to adhere or bond ions and molecules of another substance to its surface. Absorption is the process by which a substance or material is separated in one phase then accumulated into another substance in a different phase. Various studies have shown its feasibility are the positive role it can play in energy and environment for a community or industry [125], [126]

Deng et al., [127] presented an in dept review on various thermally activated cooling technologies concluding with performances and prime mover suitability. Some findings include absorption chillers being the most common due to their high coefficient of performance (COP), low investment and low temperature applications and adsorption chillers having a lower COP and higher investment cost [121]. Lamidi et al., [128] study employed 5 tonne Robur ammonia-water absorption chiller (AWAC) in the aim to provide cooling services for farmers in Nigeria. This system was successful in providing the required temperature to store harvested tomatoes, showing the viability of employing such service in an energy system for a developing country.

2.3.4. Energy storage

Energy storage devices may be key technology for novel energy system. As seen in Wu et al., [129] study they can be used increase efficiency by improving the start-up of an engine through preheating of biofuels. For storing electricity lithium batteries are the popular choice and for thermal energy storage (TES), simple water tanks are the most prevalent alternative due to the high specific capacity of water and ease installation. Phase change materials can offer a more

portable means of thermal energy storage (PCM). The energy required for a phase change is used by these substances to either store or absorb heat [130]. A market for stored energy to customers may be a possible avenue for these type of technologies through partnerships with start-ups such as Reeddi in Nigeria who aim to provide affordable electricity to energy poor individuals. Furthermore, may provide revenue and save cost on building electricity distribution structures. Other TES phase change technologies are critically reviewed in Zalba et al., [131] study focusing on material, heat transfer and applications.

2.3.5. Hydrogen production

Hydrogen is an efficient energy carrier that can be produced from anaerobic digestion and gasification. Catalytic reforming is how hydrogen can be obtained from biomass. Technologies that aid this are steam reforming (SR), partial oxidation reforming (POR), auto-thermal reforming (ATR), dry reforming (DR) and dry oxidation reforming (DOR) [132].

Proton Exchange Membrane (PEM) electrolyser

Electrolysers could convert the electricity provided from an energy generation system into chemical energy in the form of hydrogen. When compared to alkaline devices, PEM electrolysers have several advantages: they are less caustic, have the potential to be reversible, and can function at lower cell voltages, higher current densities, higher temperatures, and pressures, leading to better efficiencies (80–90%). The primary drawbacks are the expensive cost of materials, cross permeation phenomena that get worse with pressure, and the existence of water vapour along with the hydrogen generated, leading to dehumidification maintenances [133].

Taheri et al. [134] successfully employed a PEM electrolyser to produce hydrogen in a biomass multigeneration system by utilising the low-pressure steam leaving a Rankine turbine and the flow of water used for condensation. [135] studied the performance of 3 different biomass energy generation systems with one including a PEM for hydrogen generation. The report found that a system setup with gasifier, SOFC, SE and PEM has a lower levelised emission than just a gasifier and SOFC set up but is worse when compared to a gasifier, SOFC and SE set up. Also discovered was an increase in air blower pressure ratio leads to higher hydrogen production but also higher total product cost. Further studies are available in literature

which show the feasibility of using this technology within a different biomass technology within an energy system [50], [136].

2.3.6. Other technologies

Electric motors can be another area where sustainability can be achieved. Understanding the material logistics, the mining of magnets has high costs, and great environment impacts during its processing. Adopting novel technologies such as synchronous reluctance motors (SynRMs) may have a positive contribution to addressing the sustainability issues caused by using rare earth metals within the manufacturing process of motors.

2.4. Modelling and design of a sustainable biofuel energy system

The connection between the production and use of the energy services required for human activities within a civilisation is represented by energy systems. Models that incorporate waste-to-energy (WTE) applications can be broadly categorised into three groups: models emphasising municipal solid waste management system (MSWMS) cost and environmental impact optimisation; models assessing WTE applications in comparison to other waste treatment options; and models incorporating WTE options as a part of existing energy systems [113]. Based on mathematical formulations, these models depict the interactions of the various energy system components.

When designing a model, the three crucial stages of the system design process are technology and process selection, configuration design and sizing, and capacity sizing [137]. Zhou et al. [138] undertook a survey of the literature on decision analysis in environmental and energy modelling. Wang et al. [139] reviewed the use of multi-criteria decision analysis in making decisions on sustainable energy. Baños et al. [140] offered a discussion of the most recent optimisation techniques for design, planning, and control issues in the realm of renewable and sustainable energy and an overview of single and multi-objective optimisation (MOO).

Achieving a low carbon society (LCS) or a net zero society (NZS) influences an energy system design to be aligned with the 3Es (Environment, Energy and Economy) [113]. A visualisation of this interaction can be seen in Figure 2-3. Furthermore, a crucial element of model implementation is to show coherent technical analysis. Such assessments involve the use of computer tools, a detailed study of computer tools used in various renewable energy system

models can be found in this [141], which can simulate defined energy systems to produce solutions to achieve a low carbon society. The models focused on...

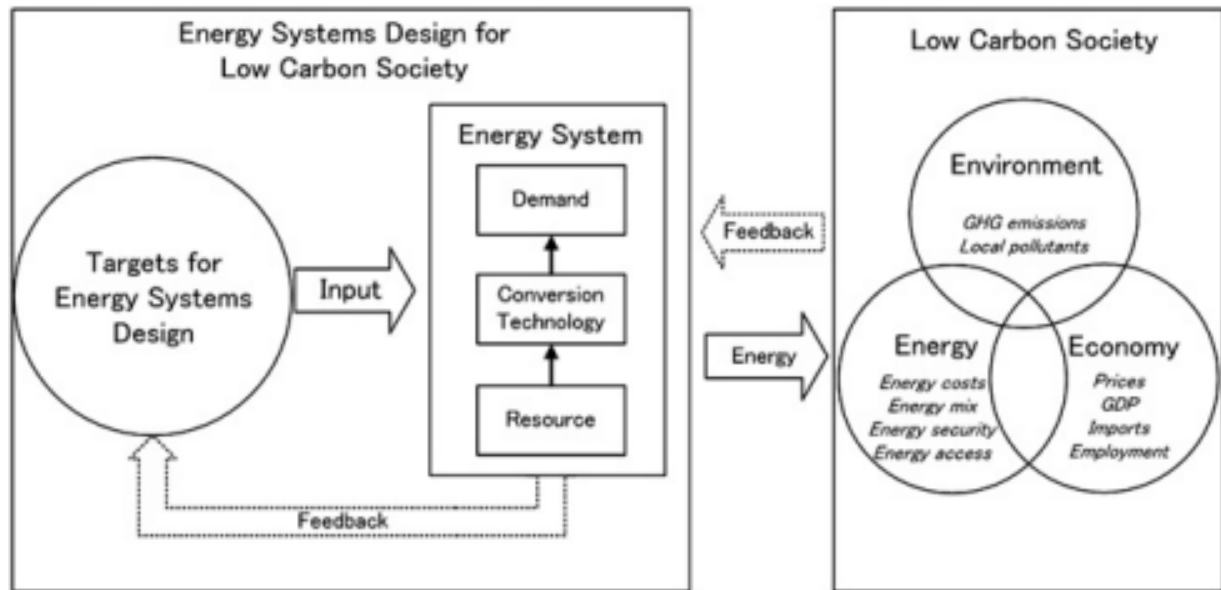


Figure 2-3: Conceptual representation of a low-carbon society (LCS) energy system design [113]

2.4.1. Economic and environmental models

The models that focus on Municipal Solid Waste Management System's (MSWMS) cost and environmental impacts are well known. Karellas et al. [142] provided an overview of anaerobic digestion/reactor technologies based on several feedstocks and created an investment decision tool to assess the economics of biogas generation. The tool created provides performance assumptions and estimates considering market prices of end products, gate fees, total investment costs, total operational costs, financing considerations and costs associated with acquisition. d'Amore and Bezzo's [143] work solves environmental and economic multi-objectives of the provision of energy from biomass for Italy's EV sector. This model calculates the location and capacity of solid waste treatment facilities as well as their level of utilisation throughout various time periods based on cost and emission optimisation. Ayodele et al., [144] looked into how the Ibadan, Nigeria, landfill gas project's impact on the environment and economy was affected by the efficiency of its energy generation. They found it feasible to do and the electricity generation potential from landfill gas technology is directly proportional to collection efficiency. A collection rate change from 50% to 70% projects an increased electricity generation of 33%. It can be assumed that for other biomass conversion technologies the same behaviours are experienced thus to be considered within this study.

2.4.2. Energy recovery performance models

Some key factors considered for energy recovery performance models are generation and demand, installed capacity of generation sources, installed capacity of storage and transmission units, curtailment and excess energy, and hourly generation and storage profiles. Though costly, efficiency is a key component of energy modelling especially for developing countries where a higher efficiency system will accelerate development. An effect of this performance can be the plant's size, as larger plants are typically more productive than smaller ones. This is because of a number of factors, including economic scale effects (larger plants are economically justified in adopting more advanced configurations of the steam cycle), the efficiency of large steam turbines compared to small ones, and a lower relative energy requirement for the plant's auxiliary equipment [145], [146].

Another factor that affects the energy recovery model include plan operation. The major concerns and studies relating to the development of a high-performance anaerobic digester for the production of biogas from municipal solid waste have been discussed in the literature [147], [148]. In comparing various hybrid biomass, standalone biomass, and gas conversion systems, [149] work aims at finding the optimum sizing and operation of a polygeneration plant through multi-objective models.

2.4.3. Energy system integration models

A number of studies have employed modelling strategies, primarily utilising mathematical programming, to examine the integration of bioenergy in urban energy systems. These models consider decisions such as the best sites and kinds of biomass processing and conversion technologies, their operation schedules, and links between urban cells for the transportation of biofuels. Further, cases of energy system integration have been practiced for distributed heat. Heat recovered from waste has a significant potential in northern nations with unique climatic circumstances, such as Sweden, Finland, and Denmark, where DH systems are particularly widespread [150], [151], [152].

2.5. Frameworks to assess system sustainability

Energy system analysis can be used to solve the complicated problem of examining the potential for the switch to low-carbon energy systems and. For sustainable design, developers are to consider the potential environmental and social implications in addition to the technical and financial factors. Techno economic analysis (TEA) assesses a technology's technical performance and economic viability. From the extraction and procurement of raw materials to usage and disposal, life cycle sustainability assessment (LCA) assesses any potential environmental and social effects connected with a product system. Performing TEA and LCSEA together establishes the trade-offs between technical, economic, social and environmental performance. Furthermore, these tools have been used to assess technology readiness levels (TRL).

2.5.1. Techno-economic assessment (TEA)

TEA is a systematic approach for understanding cost standard and potential economic feasibility of technologies, product, or a system of products. A thorough TEA establishes the mass and energy balance on a unit-operation basis along with projected capital and operational costs [153]. Exergy can also be used in TEA to determine how much energy is being used at its full potential. Exergy losses and destructions can be discovered within the system. It may also be used to create sustainable energy systems and suggests ways the system may be improved [154]. TEA is normally limited to cradle-to-gate system boundaries using process design parameters but can be modified to extend system limits to incorporate additional life cycle phases.

Decentralised energy generation using biomass should have a feasible payback period or a return on investment that shows the plant could be commercialised. It is possible to assess the necessary investment and potential payback using techno-economic analysis. A combination of processes has been studied to assess their TEA viability. Li et al. [155] explored a combined anaerobic digestion and biomass gasification system where an upgraded biogas is produced from anaerobic digestion by using hydrogen from the product syngas during gasification. Aziz et al. [156] analysed the potential of an advanced power generation system using gasification for empty fruit bunch, anaerobic digestion for palm oil mill effluent (palm oil waste) and an organic Rankine cycle for utilising unused heat. Power generation and efficiency of 8.3 MW and 30.4% respectively were obtained showing the viability of a similar system however, there

have been studies that have reached a higher overall efficiency. Through modelling in Aspen Plus®, Jana et al. [120] investigated the thermodynamic and economic viability of a polygeneration plant powered by agricultural waste. The technical viability of co-producing biofuels and other chemicals from bio-refineries can be assessed by TEA. Vlysidis et al. [157] investigated alternate plans for the co-production of biofuels (biodiesel) and chemicals (succinic acid) using TEA to investigate the idea of integrated bio-refineries. Gebrezgabher et al. [158] carried out an economic analysis of a Netherlands based biogas plant on a farm with anaerobic digestion; they concluded using internal rates of return (IRR) and net present value (NPV) tools that the conversion process is economically viable.

For the case study of Nigeria, there has been a focus in the area of waste biomass utilisation for energy over the past decade on. Using Aspen plus, Salisu et al. [159] analysed the co-gasification of rice husk and plastic waste to provide off grid power. The system achieved 70% total efficiency and promising economic performance Lamidi et al. [128] also used Aspen plus to analyse a polygeneration plant in Nigeria using cattle waste as an energy source. The study employed an anaerobic digestion unit coupled to a 72kW ICE, cabinet dryer, and absorption chiller to achieve a total efficiency of 74.5% and a payback period of 2.5 to 4.7years. Ogorure et al. [23] proposed plant comprising of solid oxide fuel cell stack, gas turbine, steam turbine, organic Rankine and absorption chiller achieved a net power of 5.226 MW. This plan however had a higher payback period of 7.5 years and a lower total system efficiency of 63.62%. A study by Ogunjuyigbe et al. [37] found a hybrid of Incineration & anaerobic digestion as the greatest potential of electricity generation from MSW in Rivers State and Abuja in Nigeria. Though pyrolysis and gasification were excluded in this study.

2.5.2. Life Cycle Sustainability Assessment

LCSA is a relatively new approach. It is defined as the evaluation of all the negative impacts and benefits associated with environmental, social and economic in decision-making processes towards more sustainable products throughout their life cycle [160], [161]. With the combination of three life cycle perspective assessment types adopted from the life cycle perspective; Environment Life Cycle assessment (E-LCA), Life Cycle Costing (LCC), and Social Life Cycle assessment (S-LCA) combine to form a single assessment that addresses each sustainability dimension ($LCSA = E-LCA + LCC + S-LCA$).

There are two approaches proposed by [162] when suggesting the LCSA framework. The first technique views the three assessments without any formal weighing between them. The second technique implies using LCC and S-LCA as additional impact categories in life cycle impact assessment (LCIA). The first technique is more mature and known to be rigorous but tedious, due to the different methodology choices for each pillar (e.g., allocation procedure, data quality or system boundaries) there is a possibility of the whole assessment can lack harmony [163]. The United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) provide guidelines stating the ISO 14040:2006 and 14044:2006 E-LCA framework should be applied when conducting an LCSA to ensure uniformity.

Studies in the literature have applied this method to biomass energy models. Menikpura et al. [164] suggested a technique known as the broaden and deepen LCA. It was employed by the writers to conduct an LCSA of Thailand's MSW management. Ekener et al. [165] conducted an LCSA for the production and use of transportation fuels by comparing biomass-based fuels to fossil fuels. There are limited studies available in literature that employ this method towards biomass to energy schemes in Nigeria. However, a study by Ayodele et al. [65] used a life cycle assessment (LCA) to study the global warming potential (GWP), acidification potential (AP) and dioxin/furan emission potential of waste treatment plants for some cities in Nigeria. Though insightful, the work was limited by the array of technologies assessed. However, in terms of GWP and ecological potential as determined by AP, the study concluded INC/AD is potentially viable when compared to other techniques and when it comes to the ability to reduce the risk of cancer as indicated by emissions of dioxin and furan, LFGTE technology is the best. Nubi et al. [166] recently conducted an LCSA to determine and contrast the environmental, economic, and social effects of producing energy from municipal solid waste (MSW) in Nigeria's two largest cities, Lagos, and Abuja.

2.6. Summary

The literature review identified that there is great significance of using modern methods for biomass based distributed generation for both developing and developed countries. More specifically polygeneration systems show more promising signs for developing countries as they are more likely to be profitable and socially impactful. The sustainability of these energy generation methods has been proven to yield positive outcomes. Anaerobic digestion has been the most used and best suit method for generating biofuels for Nigeria. The use of other

thermochemical conversion processes such as gasification is rare within the literature. This method produces more valuable products though at a high capital cost. Furthermore, on technologies, the commercial success of the internal combustion engine (ICE) and, more recently, the micro gas turbine (MGT) is largely attributable to the significant energy efficiency improvement obtained from cogenerating heat and electricity to meet the demand of the corresponding energy vectors. ICE have proven to have competitive payback periods when engaged with cassava waste which Nigeria is a large producer of. Within the literature there are limited studies that assess modern technology use for energy production in a sustainable spectrum. The available studies also lack the consideration of socio-economic impact of waste to energy production. Hence the need for this research. For assessing the technical and economic viability of these technologies in an energy generation system for Nigeria, TEA is an effective method. A low payback period is seen to be the most important economic indicator for the model. LCSA is also a fit method to achieve the sustainable viability of the model. It identifies the environmental and social impacts of an energy system. However, the method is complex and there is very limited literature available for the case study area. The development of bioenergy as a renewable energy source in Nigeria is being hampered by several factors. The literature review has provided the reason and to carry out this research and also the materials to achieve the aims and objectives of this research. This next chapter will show the chosen methodology used to do so.

Chapter 3

3. Overall Methodology

This chapter outlines the comprehensive methodology used to assess the feasibility, performance, and impact of biomass-to-energy systems in Nigeria. The primary objective is to establish a robust framework that guides the evaluation in subsequent chapters, focusing on performance metrics, environmental impacts, economic costs, and social implications. This methodology ensures a holistic analysis, integrating multiple dimensions of sustainability.

The research design for this study follows a mixed-method approach, combining quantitative and qualitative data to provide a comprehensive assessment of biomass-to-energy systems. The theoretical framework is grounded in sustainability science, utilising systems thinking to address the complex interactions between technological, environmental, economic, and social factors. The assessment framework integrates several models:

- Techno-economic Assessment (TEA)
- Life Cycle Assessment (LCA) for environmental impact evaluation.
- Life Cycle Costing (LCC) for economic analysis.
- Social Life Cycle Assessment (S-LCA) for social impact assessment.

These models are selected due to their comprehensive nature and ability to capture the full spectrum of impacts associated with biomass-to-energy systems. The system boundaries is defined based on the goal and scope specification to cover the whole life cycle of the system. This includes the collection and transportation of municipal solid waste (MSW), the treatment processes of the waste and the product generation. The methodology is implemented as a case study to one city in Nigeria, Port Harcourt. The rationale for this choice is presented in the following chapters accompanied with the choice of firmly established and commercially available WtE technologies. Followed are the various stages and activities involved in the research work.

3.1. Technical Assessment

The technical assessment seeks to determine the viability and effectiveness of incorporating biomass-to-energy conversion methods, notably anaerobic digestion and gasification, into municipal solid waste (MSW) management strategies. The main goal is to analyse three different systems that use MSW as a feedstock for energy production and agricultural improvement, all while promoting overall environmental sustainability.

3.1.1. Scope of the Technical Assessment

This technical assessment involves the following key stages:

System Development: Three system configurations, System A, System B, and System C, have been developed to explore different utilisation pathways for energy recovery and by-products from MSW. Each system includes different configurations of energy recovery, product utilisation, and community benefits:

- *System A:* This system maximises electricity generation by integrating an Organic Rankine Cycle (ORC) alongside by-products such as digestate and biochar as seen in Figure 3-1. The ORC is implemented as a bottoming cycle to utilise the waste heat from prime movers, enhancing the overall energy efficiency of the system [167]. This system is chosen for its potential to achieve the highest energy output, particularly in scenarios with significant electricity demand.

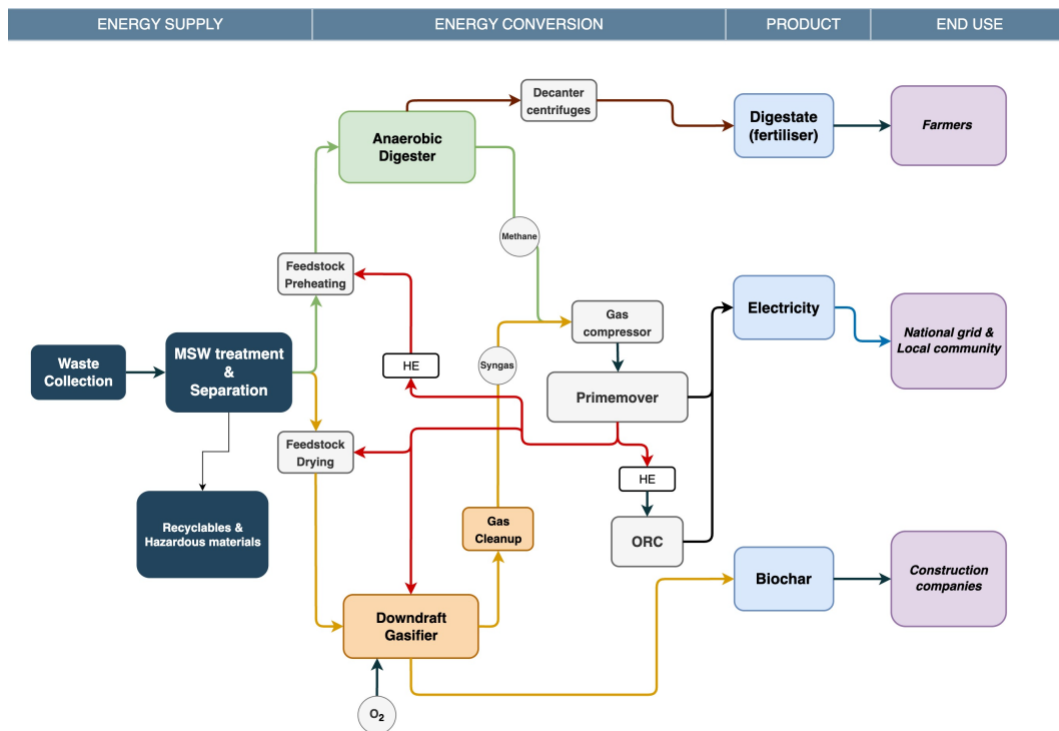


Figure 3-1: System A Flow Chart

- *System B*: Aims for electricity generation without an ORC but includes provisions for crop drying and cooling stations. The inclusion of clean air-drying chambers and an absorption chiller as seen in Figure 3-2 is intended to support local agricultural businesses, providing a means to dry crops and store fruits and vegetables [128]. This will examine the impacts of a combined energy generation with agricultural enhancements.

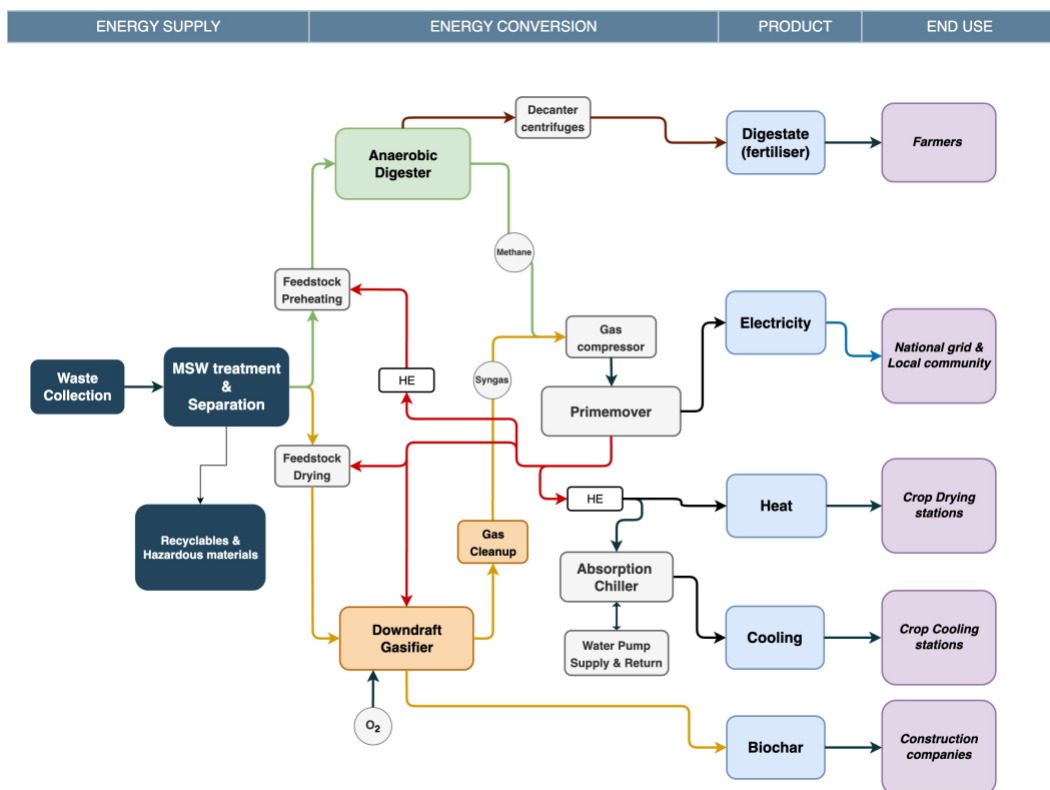


Figure 3-2: System B Flow Chart

- *System C*: Emphasises electricity generation, excluding ORC, but incorporates greenhouse-based urban farming as seen in Figure 3-3. This setup is especially ideal for urban or peri-urban areas, where land is scarce but opportunities for local food production are abundant. Greenhouse farming makes use of surplus heat and electricity, fostering sustainability in urban environments. [168].

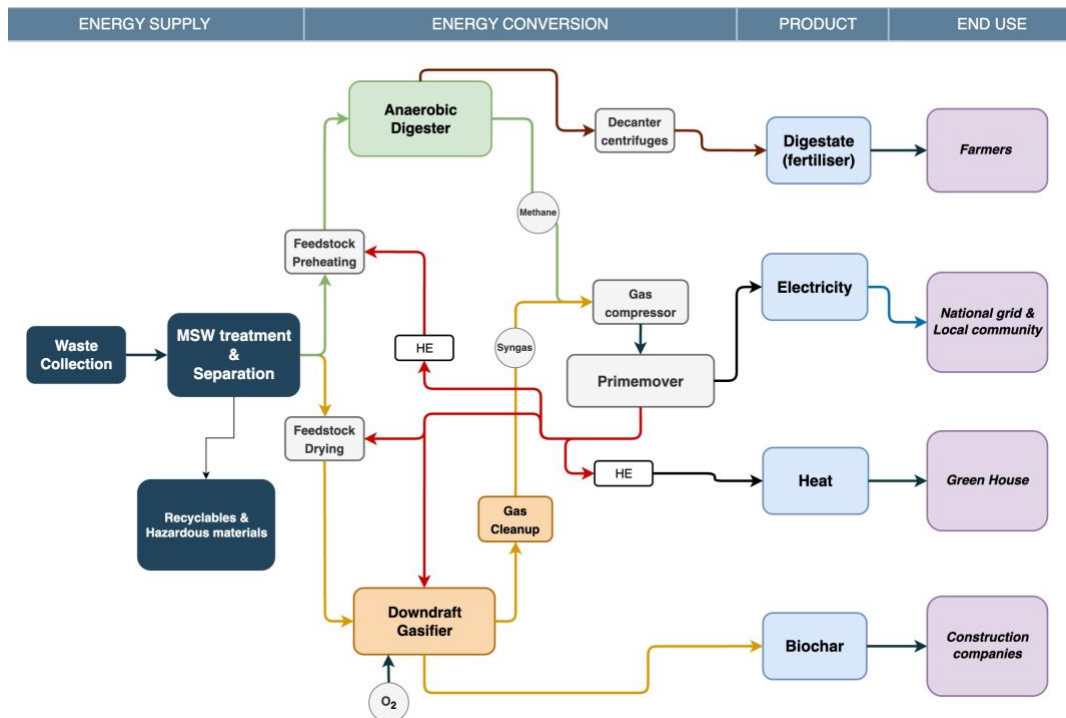


Figure 3-3: System C Flow Chart

3.1.2. Rationale

The fundamental methodological contribution of this research rests on the use of a combined Anaerobic Digestion (AD) and Gasification system as the core waste-to-energy platform. This unique combination was strategically chosen to overcome the limitations of single-technology systems when faced with the high variability and moisture content typical of the heterogeneous composition of Nigerian MSW. Specifically, AD efficiently processes the high-moisture organic fraction, while Gasification handles the drier, high-calorific residual. This integrated approach ensures the most robust and resource-efficient utilisation of the entire waste stream.

This co-processing capability significantly enhances the overall sustainable utilisation of the waste resource compared to single-unit processes. Conversely, technologies such as mass-burn Incineration were excluded due to their high capital cost, stricter flue gas treatment requirements, and often reduced efficiency when processing high-moisture MSW without extensive pre-treatment. Similarly, Pyrolysis was not selected because its liquid product (bio-oil) requires further costly upgrading for energy recovery, which detracts from the aim of developing simple, modular, and reliable distributed energy systems appropriate for the local context.

Building on this robust core platform, three distinct system configurations (A, B, and C) were designed to evaluate the optimal poly-generation end-use strategy. Each configuration

represents a unique pathway to energy recovery and final product mix: System A targets maximum electrical efficiency via ORC integration; System B prioritises non-power outputs (cooling and drying) for local commercial use thereby testing the viability of a non-power-export revenue stream.; and System C is designed for the highest integrated sustainability value, linking energy with high social value products (bio-fertiliser and urban farming), allowing for the assessment of systems designed for optimal social and environmental co-benefits alongside energy generation.

3.1.3. Technology Selection and Justification

Conversion systems

The selection of anaerobic digestion (AD) and gasification was based on their complementary roles in maximising energy recovery from MSW while minimising environmental impacts.

- *Anaerobic Digestion (AD)*: AD is well-suited for the biodegradable fraction of MSW, as it converts organic matter into biogas, which can subsequently be used for electricity or heat generation. AD has several benefits, including reduced greenhouse gas emissions compared to landfilling, and the production of digestate, which can be used as a soil amendment [167], [168]. Studies have consistently demonstrated the potential of AD for efficient waste treatment, energy production, and nutrient recovery, making it a key technology in sustainable waste management [128].
- *Gasification*: Gasification is selected due to its capacity to manage the dry, non-biodegradable portion of the waste stream, offering versatility in the kinds of feedstock it can process [168]. In a low-oxygen environment at elevated temperatures, gasification transforms waste into syngas, a flexible fuel suitable for diverse energy uses, such as heat and electricity production. The versatility of syngas makes gasification an appropriate technology to complement AD in achieving comprehensive MSW treatment and enhanced energy recovery [128].

The system optimises the MSW stream by combining both technologies, enhancing resource efficiency, minimising landfill needs, and producing various energy forms and by-products.

Prime Movers and Energy Utilisation

The selection of Internal Combustion (IC) Engines and Micro Gas Turbines (MGT) as the primary prime movers is based on their adaptability, efficiency, and suitability for the fuel types generated by AD and gasification.

- *IC Engines*: IC engines are highly effective for small to medium power generation using biogas because of their excellent electrical efficiency and relatively low initial costs. Their ability to manage varying loads makes them suitable for decentralised energy systems, where energy demand can vary considerably [128].
- *Micro Gas Turbines (MGT)*: MGTs present multiple advantages. These benefits include reduced emissions, decreased maintenance requirements, and the capability to utilise various types of gaseous fuels, such as syngas derived from gasification processes [169]. When paired with a heat recovery system, MGTs can achieve higher overall energy efficiency, making them suitable for settings that require a combination of heat and power [65].
- *Organic Rankine Cycle (ORC)*: The ORC in System A is intended to enhance overall system efficiency by utilising waste heat from IC engines or MGTs to generate additional electricity. ORC systems are particularly beneficial in applications with significant quantities of low-grade waste heat, contributing to the overall energy output [168].

The choice of prime movers and the inclusion of ORC are validated based on their proven effectiveness in similar MSW-to-energy projects and their ability to maximise energy recovery and reduce emissions [121], [167]. While Stirling Engines (SE) offer fuel flexibility and low noise, they were excluded due to their high capital cost per kW, lower electrical efficiency (typically 15-25%) compared to ICs/MGTs, and limited commercial availability in the >100 kW range required for community-scale distributed energy. Similarly, Fuel Cells (FC), such as Solid Oxide Fuel Cells (SOFC), were not selected despite their high theoretical efficiencies. The stringent fuel purity requirements for FCs would necessitate complex and expensive gas cleaning systems (to remove trace sulphur and tars from biogas/syngas) that are currently economically unviable for rugged, decentralised applications in the Nigerian context. ICs and MGTs were therefore prioritised as the optimal compromise between efficiency, robustness, and capital cost.

3.1.4. Methodology and Validation

The assessment methodology follows a systematic approach, incorporating:

- *System Design and Simulation*: Each scenario's design is based on integrating anaerobic digestion, gasification, and energy conversion technologies. Biogas production from AD is theoretically estimated using a modification of Buswell's equation, which

provides a stoichiometric maximum yield based on elemental composition [170], [171], [172]. To ensure the robustness of these theoretical values, the results were validated against a secondary empirical baseline derived from literature-reported Bio-Methane Potential (BMP) ranges for similar Nigerian municipal waste streams. A biodegradability factor of 0.8 was applied to the Buswell result to account for the refractory organic fraction typically modelled in complex simulations like the Anaerobic Digestion Model No. 1 (ADM1), bridging the gap between theoretical stoichiometry and realistic operational yields. In the context of gasification, operational parameters namely temperature, syngas yield, and efficiency are derived from existing literature. This approach ensures that the model accurately represents realistic performance metrics analogous to comparable systems.

- *Validation of Technology Selection:* The selection of anaerobic digestion and gasification is substantiated by their prevalent utilisation and effectiveness in the management of various waste streams, the mitigation of greenhouse gas emissions, and the provision of multiple forms of energy output [173], [174]. AD has been proven to be one of the most effective methods for processing organic waste, reducing methane emissions from landfills, and providing renewable energy [175]. Gasification, in turn, offers the ability to achieve high energy conversion efficiency and process different feedstock types, making it a crucial component of an integrated MSW management strategy [174], [176].
- *Energy Utilisation Pathways:* The energy utilisation pathways in each scenario are tailored to maximise resource efficiency and provide community benefits. Crop drying and cooling in System B not only enhances agricultural productivity but also reduces post-harvest losses, a critical issue in many developing regions [128]. Greenhouse urban farming in System C leverages excess energy to promote sustainable urban agriculture, thereby contributing to food security and environmental sustainability.
- *Study Area and Assumptions:* The study area for this technical assessment focuses on a locality with projected population growth and waste generation rates that can support the proposed systems. The methodology includes:
- *Population and Waste Prediction:* Future population growth and MSW generation are estimated using predictive models, ensuring scalability of the system to meet increasing demands over time [128].

- *Waste Separation and Treatment:* Assumptions are made about the level of waste separation at the source or facility level, with organic and non-organic fractions being segregated to enhance the efficiency of anaerobic digestion and gasification.
- *Waste Characterisation and Element Analysis:* Waste is characterised in detail to determine its chemical composition, calorific value, and other relevant parameters, which are crucial for optimising the performance of anaerobic digestion and gasification systems.

In-depth performance results and technical details, including population predictions, waste generation modelling, and specific operational parameters for anaerobic digestion and gasification, will be elaborated in Chapter 4: System Design and Performance.

3.2. Life Cycle Sustainability Assessment Methodology

The Life Cycle Sustainability Assessment (LCSA) methodology is a comprehensive tool that integrates the environmental, economic, and social dimensions of sustainability into a unified framework. LCSA aims to evaluate the complete lifecycle impacts of a product or system, from the extraction of raw materials to end-of-life disposal. Given the rising focus on sustainable development, LCSA is essential for decision-making in sectors with complex trade-offs among sustainability criteria [160], [162]. This approach has become vital in assessing waste-to-energy technologies, as they address energy demands and waste management challenges, aligning with the emerging trend of incorporating circular economy principles, emphasising resource recovery and waste minimisation, making LCSA an essential tool for modern environmental assessments [177].

LCSA has been applied across various fields, notably in waste management and energy production. For instance, LCSA studies in municipal solid waste (MSW) systems have shown their potential to guide policy by revealing the environmental impacts, economic costs, and social implications of different waste-to-energy technologies [164]. In studies evaluating energy generation from MSW, frameworks incorporating Multi-Criteria Decision Analysis (MCDA) were shown to support decision-makers by ranking technologies based on sustainability criteria, enabling a balanced assessment of trade-offs across sustainability pillars [178]. Examples from developing countries like Bangladesh, Brazil, India, Indonesia, Nigeria and Thailand illustrate how LCSA frameworks help in evaluating the performance of waste-to-energy systems at both national and local levels, considering not only their carbon emissions

and cost-effectiveness but also their socio-economic impacts on local communities [65], [164], [179], [180], [181].

LCSA is based on the principles of Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA), each of which contributes to the holistic evaluation of the systems under study. This methodology aligns with international standards such as ISO 14040 and ISO 14044 for environmental LCA and guidelines from the UNEP/SETAC Life Cycle Initiative for S-LCA [160]. Adopting these established standards, the LCSA ensures that the assessment is comprehensive and consistent with best practices in sustainability analysis.

To ensure robustness and comparability across the three sustainability pillars (LCA, LCC, and S-LCA), a strict Harmonisation Strategy was employed throughout the inventory and impact assessment phases. Consistency was enforced by aligning the Goal and Scope parameters across all domains. Specifically, an identical Functional Unit (management of 1 tonne of MSW) and System Boundaries (cradle-to-grave) were applied to the environmental, economic, and social assessments, ensuring that all impacts are measured against the same reference flow. Furthermore, a unified Temporal Scope (20-year project lifespan) and Geographical Scope (Port Harcourt context) were maintained for all inventory data. This alignment is a critical prerequisite for the Multi-Criteria Decision Analysis (MCDA), ensuring that the integrated trade-offs such as cost versus emissions are derived from a coherent and mathematically compatible dataset.

The LCSA tool integrates three distinct yet interconnected methodologies:

- *Life Cycle Assessment (LCA)*: Defined by ISO 14044 standards, LCA quantifies a product's or service's environmental impacts over its entire life cycle, from resource extraction to end-of-life disposal [182]. This includes emissions, resource consumption, and energy use, providing a cradle-to-grave analysis highlighting each biomass-to-energy configuration's environmental footprint (ISO 14044, 2006). The LCA component of this study utilises inventory data collected from primary and secondary sources, including emission factors and energy consumption figures, to calculate key environmental indicators such as global warming potential (GWP) and resource depletion.

- *Life Cycle Costing (LCC)*: This assesses the total cost of ownership for each system, including capital expenditures, operating expenses, maintenance costs, and end-of-life disposal costs. The LCC component provides an economic evaluation of each configuration, allowing for the identification of the most cost-effective solution [167], [183]. Economic feasibility is a critical aspect of sustainability, particularly in developing regions where resource constraints necessitate cost-effective waste management solutions [73].
- *Social Life Cycle Assessment (S-LCA)*: This evaluates the social impacts of the systems, including community health, job creation, and overall well-being. Its application has expanded in waste management studies, although methodological challenges remain in quantifying social impacts consistently [184]. The S-LCA methodology follows the guidelines provided by the UNEP/SETAC Life Cycle Initiative and has been adapted with methods from various studies to suit the local context of this study. Social indicators are identified based on factors such as employment opportunities, health and safety, and social acceptability of the technology. This component of the LCSA is crucial for assessing the broader social implications of biomass-to-energy systems, particularly in communities where MSW management plays a significant role in local livelihoods.

These methodologies are collectively analysed in LCSA through frameworks like MCDA, which assist in consolidating varied impacts into a single sustainability score [185].

LCSA is chosen in this study for its holistic approach and capacity to evaluate diverse impacts, particularly in engineering systems like waste-to-energy, where environmental, economic, and social considerations must be balanced. Unlike traditional LCA, which focuses solely on environmental impacts, LCSA's integrated framework aligns with the principles of the Circular Economy, promoting resource efficiency and minimising negative externalities [186]. However, while there are established guidelines for environmental LCA, guidelines for LCC and S-LCA remain less developed due to their relative novelty [165]. Alternative methods, such as cost-benefit analysis (CBA) or material flow analysis (MFA), are comprehensive and simple; however, individually, they fail to have the combined view of LCSA that explores the pillars of sustainability simultaneously [187].

As seen in Figure 3-4, a robust LCSA study involves several stages that interact with each other:

- *Goal and Scope Definition:* This first stage defines the objectives and boundaries of the assessment, ensuring that all sustainability dimensions are adequately addressed.
- *Inventory Analysis:* Data collection for LCA, LCC, and S-LCA is crucial, with each technique requiring distinct datasets that may include emissions data, financial records, and stakeholder impact reports.
- *Impact Assessment:* This step analyses collected data to determine sustainability impacts. For instance, MCDA frameworks often integrate diverse indicators, helping to balance trade-offs.
- *Result Interpretation:* Finally, results are synthesised to guide stakeholders in choosing sustainable options. This involves interpreting each pillar's contribution to the overall sustainability profile, aiding decision-makers in prioritising options based on specific criteria.

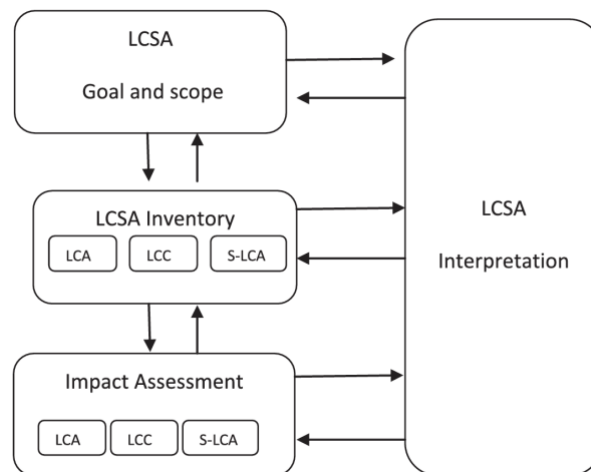


Figure 3-4: LCSA Framework (UNEP SETAC 2009 guidelines)

3.2.1. LCSA Goal and Scope Definition

The primary goal of this study is to evaluate the environmental, social, and economic impacts associated with utilising municipal solid waste (MSW) in Nigeria. The study aims to assess different system configurations to guide decision-makers, including local government authorities, energy planners, and waste management stakeholders, by providing comprehensive insights into the sustainability performance of different waste-to-energy pathways. This assessment seeks to identify the best utilisation method for MSW to maximise sustainability benefits and support Nigeria's goals for renewable energy development and effective waste management.

The functional unit of the assessment is defined as the management and utilisation of 1 ton of municipal solid waste (MSW) for energy generation. This choice allows for direct comparisons across waste utilisation methods while focusing on the efficiency and sustainability of converting waste into usable energy and by-products. Using this functional unit aligns with the study's objective to evaluate the sustainability of waste-to-energy solutions.

System Boundaries

The system boundaries encompass the entire life cycle of the waste-to-energy process, including the following stages:

- *Waste Collection and Transportation:* MSW is collected from urban and rural centres and is transported to processing facilities.
- *Waste Processing and Conversion:* The transformation of MSW into energy products through processes such as gasification or anaerobic digestion.
- *Energy Generation through CHP Systems:* Electricity production and thermal energy recovery, with considerations for system efficiencies and emissions.
- *Operation and Maintenance:* Routine maintenance and operational requirements for the waste-to-energy facilities.
- *End-of-Life Management:* Disposal, recycling, or repurposing of equipment and waste residues from the energy generation process.
- *Avoided Impacts:* The displacement of conventional energy sources and waste management practices, such as landfilling, by the implementation of waste-to-energy systems.

Assumptions and Limitations

- The composition and calorific value of MSW will be considered based on typical Nigerian waste characteristics.
- Energy system efficiencies are derived from literature and reported case studies, as software-based performance modelling will not be conducted.
- Social and economic impacts are evaluated qualitatively and quantitatively, drawing on existing frameworks and reported data for similar contexts.

3.2.2. LCSA Inventory Analysis

Data for analysis can be categorised into three types: quantitative, semi-quantitative, and qualitative. Typically, Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) rely mainly on quantitative data. In contrast, Social Life Cycle Assessment (sLCA) often includes both semi-quantitative and qualitative information, adding complexity to the aggregation of various data types over the product life cycle. The data for this inventory analysis is sourced from both primary and secondary datasets.

Primary Data:

- Observations of informal recycling and scavenging activities at dumpsites.

Secondary Data:

- Published literature and technical reports on waste management and WtE technologies in Nigeria.
- Data from databases such as Ecoinvent for environmental life cycle assessment (LCA).
- Economic data from government and industry reports to evaluate costs and revenues.

The system boundaries encompass the entire life cycle of the WtE systems, including the following stages:

1. *Waste Collection and Transportation:* Quantities of waste collected, distances transported, and fuel consumption of collection vehicles.
2. *Waste Processing and Conversion:* Inputs and outputs for anaerobic digestion and gasification processes, including energy recovery efficiencies.
3. *Energy Generation and Distribution:* Quantities of electricity and thermal energy generated and delivered to end-users.
4. *Operation and Maintenance:* Resources and labour required for system operation and routine maintenance.
5. *End-of-Life Management:* Disposal or recycling of system residues, including ash and digestate.
6. *Avoided Impacts:* Reductions in greenhouse gas (GHG) emissions and other environmental benefits due to displacement of conventional energy sources.

The inventory data is categorised into three sustainability dimensions: environmental, economic, and social.

- *Environmental Data:*
 - Composition of MSW in Port Harcourt (organic waste, plastics, paper, metals, etc.).
 - Emissions from waste collection, transportation, and WtE processing (e.g., CO₂, CH₄, NO_x).
 - Energy conversion efficiencies of proposed WtE technologies.
- *Economic Data:*
 - Capital and operational costs of WtE facilities.
 - Revenue from energy sales and by-products (e.g., digestate, ash).
 - Costs associated with waste collection, transportation, and residue disposal.
- *Social Data:*
 - Employment generated across WtE scenarios, including jobs for informal waste pickers.
 - Health and safety impacts of waste management and energy generation processes.
 - Accessibility of energy generated to local communities.

Data Quantification

- Functional Unit: 1 ton of MSW.
- Reference Flow: Quantified outputs from WtE systems, including energy generated (kWh of electricity and thermal energy) and by-products recovered.
- Indicators for Assessment:
 - Environmental: GHG emissions (kg CO₂-eq), resource use, and waste diversion rates.
 - Economic: Levelised cost of energy (LCOE), capital costs, and payback period.
 - Social: Employment generated (person-years), health impacts, and community benefits.

Gaps

- Limited availability of local emissions data for WtE processes in Nigeria.
- Inconsistent reporting on waste composition across neighbourhoods in Port Harcourt.

Assumptions

- The average composition of MSW is consistent with data from similar urban centres in Nigeria.
- Emissions factors for transportation and WtE technologies are sourced from the Ecoinvent database and adjusted for local conditions.

Data Collection Plan

To address gaps and ensure the reliability of the analysis:

- Additional surveys will be conducted to refine data on waste composition and collection routes.
- Secondary data will be validated against local case studies and reports.
- Stakeholder engagement will continue to update economic and social parameters.

3.2.3. LCSA Impact Assessment

The impact assessment phase of the Life Cycle Sustainability Assessment (LCSA) evaluates the environmental, economic, and social implications of waste-to-energy (WtE) systems in Port Harcourt, Nigeria. By linking the inventory data to relevant impact categories, this phase provides insights into the potential trade-offs and synergies among the three sustainability dimensions. The results of the impact assessment will guide decision-makers in identifying the most sustainable utilisation method for municipal solid waste (MSW).

Approach to Impact Assessment

The LCSA impact assessment integrates results from three complementary frameworks that share the same system boundaries:

- **Environmental Life Cycle Assessment (LCA):** Evaluates the environmental impacts across the life cycle of the WtE scenarios, focusing on emissions, resource use, and waste management efficiency.
- **Life Cycle Costing (LCC):** Assesses the economic performance of the WtE systems, including costs and revenues associated with waste collection, processing, and energy generation.
- **Social Life Cycle Assessment (S-LCA):** Explores the social impacts of WtE scenarios, such as job creation, community health, and energy accessibility.

Impact Categories and Indicators

To ensure a comprehensive assessment, relevant impact categories are selected for each dimension of sustainability. These are aligned with international standards (e.g., ISO 14040 for LCA, UNEP guidelines for S-LCA) and tailored to the local context of Port Harcourt.

- *Environmental Indicators:*

- Climate Change: Greenhouse gas (GHG) emissions (e.g., CO₂-eq, CH₄) from waste collection, processing, and energy generation.
- Resource Use: Depletion of non-renewable resources (e.g., fossil fuels) and water consumption.
- Air and Water Quality: Emissions of pollutants (e.g., NO_x, SO_x, particulate matter) and leachate impacts on water bodies.
- *Economic Indicators:*
 - Capital and Operating Costs: Investments in infrastructure, operational expenses, and maintenance costs.
 - Revenues: Income from energy sales and by-products (e.g., digestate, ash).
 - Levelised Cost of Energy (LCOE): A measure of the cost-effectiveness of energy generation.
- *Social Indicators:*
 - Employment: Jobs created in waste collection, processing, and energy production.
 - Community Health: Reduction in health risks associated with open dumping and unregulated waste burning.
 - Energy Accessibility: Availability and affordability of energy generated through WtE technologies.

The impact assessment relies on inventory data from primary and secondary sources. Environmental impacts will be calculated using emission factors and databases such as Ecoinvent. Economic impacts will be quantified using financial records from existing WtE projects and government reports. Social impacts will be assessed based on literature on health and employment impacts of existing WtE projects.

To integrate the three sustainability dimensions, normalisation and weighting procedures will be applied. During normalisation, impact results will be expressed relative to a reference system (e.g., emissions per ton of MSW or per kWh of energy generated). In weighting, expert opinions and stakeholder inputs will guide the assignment of weights to environmental, economic, and social categories, reflecting local development goals. These steps ensure comparability among impact categories and reflect the priorities of stakeholders in Port Harcourt.

The impact assessment results will be used to compare the sustainability performance of the developed scenarios. These scenarios can include existing business-as-usual (BAU) practices

of establish waste management as a baseline, decentralised WtE systems of small-scale anaerobic digestion or gasification plants and centralised WtE facilities of a large-scale biochemical and thermal treatment technologies.

3.2.4. LCSA Interpretation

The interpretation phase of the Life Cycle Sustainability Assessment (LCSA) synthesises the results from the impact assessment to draw meaningful conclusions and provide actionable recommendations. For this study, the interpretation phase evaluates the sustainability performance of the waste-to-energy (WtE) scenarios in Port Harcourt, Nigeria, based on their environmental, economic, and social impacts. This phase identifies key trade-offs, highlights areas for improvement, and assesses the robustness of the findings through sensitivity analysis.

The primary objective of this phase is to provide decision-makers with clear and transparent insights into the relative strengths and weaknesses of the WtE scenarios. By aligning the interpretation with the study's goal of identifying the most sustainable MSW utilisation method, this phase ensures that the results are practical and actionable. The first step to achieve this is a result evaluation. Here, the results of the environmental, economic, and social assessments are evaluated to determine the overall sustainability performance of each scenario. Emissions reductions, resource conservation, and pollution mitigation are assessed to identify the scenario with the least environmental burden. Costs, revenues, and financial metrics such as the Levelised cost of energy (LCOE) are analysed to determine the economic viability of each scenario.

Impacts on employment, community health, and energy accessibility are compared to identify scenarios with the highest social value. Trade-Off assessment is the next step of the process where trade-offs between sustainability dimensions are systematically analysed. For example, A scenario with high environmental performance (e.g., decentralised WtE systems) may involve higher capital costs compared to the business-as-usual (BAU) scenario. Social benefits, such as job creation in centralised WtE systems, may come at the expense of higher emissions during facility construction and operation.

Thereafter sensitivity analysis is conducted to test the robustness of the results by varying key assumptions and data inputs. Here cases such as the impact of changes in waste composition (e.g., higher or lower organic content) on biogas production, variations in energy prices and their effect on economic viability and different weighting factors for environmental, economic, and social dimensions to reflect diverse stakeholder priorities. Finally, the interpretation considers uncertainties in inventory data and impact calculations, highlighting areas where data quality could be improved. Then based on the results and trade-offs, the scenarios are ranked in terms of their overall sustainability performance. The ranking is presented in a clear format, such as a comparative scorecard or multi-criteria decision analysis (MCDA) results.

3.3. Environmental Life Cycle Assessment (E-LCA) Methodology

Life Cycle Assessment (LCA) is a comprehensive tool used to evaluate the environmental impacts associated with a product, process, or system across its entire life cycle. This methodology, governed by ISO 14040 and 14044 standards, assesses impacts from raw material acquisition to final disposal, ensuring a holistic understanding of environmental trade-offs (ISO 14040:2006). In this study, LCA is employed to analyse waste-to-energy (WtE) systems in Port Harcourt, Nigeria, focusing on the environmental impacts of utilising 1 ton of municipal solid waste (MSW). Similar to the LCSA approach, the LCA comprises of goal and scope definition, inventory analysis, impact assessment, and interpretation. The functional unit will be introduced to ensure comparability across scenarios reflecting the studies focus on waste utilisation efficiency. Considerations for the system boundaries and impact categories will be implemented based on their relevance to Port Harcourt's sustainability challenges.

3.3.1. Goal and Scope Definition

The primary goal of this Life Cycle Assessment (LCA) is to evaluate the environmental impacts associated with different waste-to-energy (WtE) scenarios for municipal solid waste (MSW) management in Port Harcourt, Nigeria. The study aims to identify the most environmentally sustainable option among the proposed scenarios, highlighting trade-offs and providing actionable insights for policymakers, urban planners, and waste management stakeholders. This assessment aligns with broader goals of reducing environmental burdens, improving waste management practices, and enhancing energy generation efficiency in the region. The functional units will be introduced at this stage to ensure the study's results are representative of the real-world waste utilisation. Furthermore, system boundaries, impact categories,

geographic and temporal scope will also be introduced to establish the framework for inventory analysis and subsequent impact assessment.

3.3.2. Inventory of resources use and emissions

The inventory phase of Life Cycle Assessment (LCA) involves compiling and quantifying inputs and outputs throughout the life cycle of the waste-to-energy (WtE) scenarios being assessed. This stage translates the defined scope into measurable data, forming the basis for the subsequent impact assessment. For Port Harcourt, Nigeria, the inventory captures data specific to the collection, processing, and utilisation of municipal solid waste (MSW) for energy generation. Data for this inventory were gathered from primary and secondary sources to ensure reliability and relevance [188]. Primary Data typically include field measurements and observations at waste collection sites and dumps. Secondary Data is primarily what this study is going to be reliant on. These include literature on waste management and WtE practices in Nigeria and comparable regions and databases such as Ecoinvent which has been used for emissions factors and process efficiencies across literature to show accuracy and validity.

Within the inventory phase various system components and inventory data such as waste collection and transportation, waste processing and energy recovery, operations and maintenance, end of life management, and avoided impacts will be monitored to successfully compile the necessary conclusions of the WtE system. The inventory phase ensures comprehensive data coverage for all life cycle stages of the WtE scenarios. By addressing identified data gaps and validating assumptions, this inventory lays the groundwork for an accurate and robust environmental impact assessment.

3.3.3. Impact Assessment

The Life Cycle Impact Assessment (LCIA) phase translates the inventory data into potential environmental impacts, providing a clearer understanding of the implications of waste-to-energy (WtE) systems in Port Harcourt, Nigeria. This phase involves categorising and quantifying impacts across predefined categories, enabling the identification of trade-offs and opportunities for environmental improvement. The LCIA follows the guidelines outlined in ISO 14044, ensuring consistency and robustness in methodology (ISO, 2006). The methodology for LCIA involves three main steps:

- Classification
 - The inventory data is assigned to specific environmental impact categories. For example, emissions of CO₂, CH₄, and N₂O are classified under the global warming potential (GWP) category, while SO_x and NO_x are linked to acidification and eutrophication.
 - Impact categories are selected based on their relevance to the local environmental challenges in Port Harcourt.
- Characterisation
 - The classified inventory data is converted into potential environmental impacts using characterisation factors. For instance, GWP is measured in CO₂-equivalents, reflecting the combined warming effect of various greenhouse gases.
 - Characterisation provides a quantitative measure of the contribution of each input or output to the impact categories.
- Normalisation and Weighting
 - Normalisation expresses impacts relative to a reference system, such as average regional or global emissions, to facilitate comparison across categories.
 - Weighting assigns importance to impact categories based on stakeholder priorities or policy goals, reflecting the sustainability concerns specific to Port Harcourt.

Impact Categories and Indicators

The following impact categories and indicators are prioritised for this study:

- *Global Warming Potential (GWP)*
 - Indicator: Kilograms of CO₂-equivalent per tonne of MSW.
 - Relevance: Nigeria's reliance on fossil fuels for energy generation makes climate change mitigation a priority.
- *Acidification Potential (AP)*
 - Indicator: Kilograms of SO₂-equivalent per tonne of MSW.
 - Relevance: Emissions of SO_x and NO_x from WtE processes can affect air quality and acidify ecosystems.
- *Eutrophication Potential (EP)*
 - Indicator: Kilograms of PO₄-equivalent per tonne of MSW.
 - Relevance: Nutrient releases from leachate and emissions can harm aquatic systems.

- *Resource Depletion Potential (RDP)*
 - Indicator: Megajoules of non-renewable energy consumed per tonne of MSW.
 - Relevance: Resource conservation is critical for sustainable energy transitions in Port Harcourt.
- *Particulate Matter Formation (PMF)*
 - Indicator: Kilograms of particulate matter (PM10) per tonne of MSW.
 - Relevance: Dust and fine particles from combustion processes can impact respiratory health.

While the selected indicators address the primary environmental burdens of waste-to-energy systems, additional categories such as Ozone Depletion Potential (ODP), Land Use, and Water Depletion were considered but excluded from the quantitative assessment for the following context-specific reasons:

- *Ozone Depletion Potential (ODP)*: The biological and thermochemical conversion processes utilised (AD and Gasification) and the resulting biofuels (biogas/syngas) do not emit significant quantities of ozone-depleting substances (e.g., CFCs, HCFCs). Consequently, the ODP impact was deemed negligible compared to the direct combustion emissions (NO_x, CO) captured in the acidification and ozone formation categories.
- *Land Use Impact*: Unlike bioenergy systems reliant on energy crops, this study utilises Municipal Solid Waste (MSW) as feedstock, which carries zero land-use burden for cultivation. Furthermore, the proposed distributed energy systems are designed as modular, containerised units with a minimal physical footprint compared to the extensive land area required for the alternative baseline (sanitary landfills or open dumps).
- *Water Use / Depletion*: Due to the scarcity of reliable, localised Life Cycle Inventory (LCI) data for water consumption rates in the Nigerian waste sector, this category was omitted to avoid introducing significant uncertainty. However, the system designs explicitly incorporate closed-loop cooling (e.g., in the absorption chillers for System B) to minimise operational water demand.

3.3.4. Interpretation

The interpretation phase of Life Cycle Assessment (LCA) synthesises the findings from the inventory and impact assessment phases to derive meaningful conclusions. This phase aims to evaluate the overall environmental performance of waste-to-energy (WtE) scenarios, identify trade-offs, and offer actionable insights for policymakers and stakeholders in Port Harcourt, Nigeria. By aligning the interpretation with the defined goals and scope, this step ensures that the results address the study's objectives and provide robust recommendations.

The interpretation process involves evaluating the results for completeness, consistency, and significance while addressing uncertainties. Results are examined to highlight critical stages and processes contributing to impacts, such as emissions during waste transportation or inefficiencies in energy recovery. Trade-offs are assessed, such as the balance between reduced greenhouse gas (GHG) emissions in one scenario and higher resource use in another, to ensure informed decision-making. Sensitivity analyses are conducted to test the reliability of assumptions, such as variations in waste composition or energy efficiency. This process ensures robustness in recommendations, accounting for local-specific data and regional priorities. For example, aligning with findings from studies like Bernstad and Jansen (2011) on the impacts of organic waste management demonstrates the importance of site-specific data in mitigating uncertainties [189], [190].

The scenarios developed in this study, including business-as-usual practices and proposed WtE systems, are comparatively analysed to rank their environmental performance. Indicators such as global warming potential (GWP), acidification, and eutrophication are normalised to facilitate scenario comparison, reflecting both local and global sustainability priorities. Studies such as Istrate et al. (2020) highlight how such comparative analyses can identify environmentally optimal solutions for specific contexts [190], [191]. The interpretation identifies pathways for improving WtE performance in Port Harcourt. For instance, prioritising technologies like anaerobic digestion for high-organic-content MSW aligns with findings from LCA reviews demonstrating their lower GHG emissions compared to incineration [188], [191]. Furthermore, addressing inefficiencies in waste collection and transportation can reduce overall environmental impacts significantly.

3.4. Life Cycle Costing (LCC) Methodology

Life Cycle Costing (LCC) is an economic assessment tool used to evaluate the total costs associated with a product, process, or system over its entire life cycle. While it originated in the 1930s, LCC has evolved significantly, and its application within sustainability studies now aligns closely with Life Cycle Assessment (LCA) frameworks. This integration enables simultaneous consideration of environmental and economic dimensions, contributing to a holistic sustainability evaluation (ref). Unlike LCA, which has been guided by ISO 14040 and 14044 standards, LCC has only recently gained attention as a standardised methodology. The release of the international standard ISO 15686-5 has provided a foundation for consistent LCC implementation in life cycle sustainability assessments [188], [191]. This standard helps ensure comparability across studies by establishing uniform guidelines for defining system boundaries, cost classification, and data requirements.

LCC shares methodological similarities with LCA, particularly in terms of life cycle stages and system boundaries. Both methodologies involve data collection and analysis for raw material acquisition, processing, use, and end-of-life stages. Additionally, LCC incorporates a functional unit to ensure that cost analyses correspond to the same system evaluated in LCA, such as the treatment of 1 tonne of municipal solid waste (MSW) in this study [192].

3.4.1. Classification of Costs

Life Cycle Costing (LCC) categorises costs associated with a product, process, or system throughout its entire life cycle. For waste-to-energy (WtE) systems, this classification helps identify and quantify financial investments and trade-offs, enabling comprehensive economic assessments.

- *Capital Expenditure (CAPEX)*: CAPEX represents the initial investment required to establish a WtE system. Studies on WtE projects often highlight that CAPEX constitutes a significant proportion of total costs, particularly for advanced thermal treatment systems requiring sophisticated technologies. These costs include:
 - *Equipment and Infrastructure*: Procurement of technologies such as anaerobic digesters, gasifiers, or incinerators, and the construction of facilities.
 - *Installation and Engineering*: Costs associated with equipment setup, engineering services, and system integration.

- *Regulatory Compliance*: Permitting and licensing costs, including environmental impact assessments and other regulatory approvals.
- *Operational and Maintenance Costs (OPEX)*: Critical for assessing the long-term economic viability of WtE systems, the OPEX covers the recurring costs required to sustain system performance. Lower operational costs often favouring decentralised systems over centralised ones [188].
 - *Labour and Utilities*: Wages for operational staff and expenses for electricity, water, and fuel. Energy-intensive processes like incineration may incur higher utility costs.
 - *Consumables and Spare Parts*: Costs for materials such as filters, chemicals, and replacement parts to maintain system efficiency.
 - *Routine Maintenance*: Regular servicing to prevent system failures and extend equipment lifespan.
- *End-of-Life Costs*: Often overlooked during planning stages but are critical for ensuring compliance with environmental regulations and minimising long-term liabilities. These costs include expenses associated with decommissioning WtE facilities and managing residual waste or equipment.
 - *Decommissioning*: Dismantling equipment and facilities at the end of their operational lifespan.
 - *Residue Disposal or Recycling*: Management of by-products such as ash from incineration or digestate from anaerobic digestion.
 - *Land Restoration*: Costs incurred to restore sites to their original condition or repurpose them for other uses.
- *Benefits*: These inflows offset costs and improve the economic feasibility of WtE systems further supporting long-term financial sustainability [177].
 - *Energy Sales*: Revenue from electricity and heat generated by WtE systems.
 - *By-Product Material Recovery*: Income from selling digestate as fertiliser or ash for construction materials.
 - *Government Incentives*: Tax subsidies, feed-in tariffs, and renewable energy grants.
 - *Gate Fees*: Charges for accepting waste at WtE facilities.

3.4.2. Economic Indicators and Impact categories

Essential for evaluating the financial performance and sustainability of waste to energy systems. These indicators provide quantitative measures of costs and benefits allowing for comprehensive economic assessments. Some key economic indicators include:

- *Net Present Value (NPV)*: Represents the difference between the present value of cash inflows and outflows over the system's life cycle. A positive NPV indicates economic feasibility.
- *Internal Rate of Return (IRR)*: Measures the profitability of an investment by calculating the discount rate at which NPV equals zero. A higher IRR suggests a more attractive investment.
- *Levelised Cost of Energy (LCOE)*: Measures the average cost per unit of energy generated, accounting for capital, operational, and maintenance costs over the system's lifespan.
- *Payback Period*: Determines the time required to recover initial investments through operational revenues, a critical metric for investors.
- *Operational and Maintenance Costs (O&M)*: Captures recurring expenditures like energy inputs, labour, and consumables, directly influencing the long-term financial sustainability of the system.

The economic assessments in LCC are structured around midpoint and endpoint categories. The midpoint focuses on specific cost activities, including waste collection, energy production, and maintenance expenditures, providing detailed insights into cost drivers at various life cycle stages. The end points capture the broader financial outcomes, such as total project profitability, cash flow stability, and long-term contributions to municipal budgets, reflecting overall economic sustainability. The usefulness of these indicators and categories highlights trade-offs between WTE scenarios. For instance, decentralised systems may exhibit higher O&M costs but shorter payback periods, while centralised systems with higher CAPEX often benefit from economies of scale and favourable IRR [163], [182], [192].

3.4.3. Limitations and Integration with LCA and SLCA

Life Cycle Costing (LCC) is a valuable tool for assessing the financial viability of waste-to-energy (WtE) systems. However, its standalone application presents certain limitations that necessitate its integration with complementary methodologies like Life Cycle Assessment (LCA) and Social Life Cycle Assessment (SLCA).

Limitations of LCC

- *Data Availability and Quality:* LCC requires detailed financial data across the life cycle, including local cost variations for infrastructure, operations, and maintenance. In developing regions like Port Harcourt, the lack of standardised cost databases can introduce significant uncertainties into the analysis.
- *Exclusion of Non-Economic Impacts:* LCC focuses exclusively on monetary costs and benefits, often overlooking environmental and social dimensions. For instance, it does not account for ecological degradation, community health impacts, or employment benefits, which are critical for sustainable waste management.
- *Uncertain Projections:* LCC relies on assumptions about future costs, such as inflation, energy prices, and technological advancements. These projections can vary significantly, especially in volatile economies.
- *Scope Limitations:* While LCC captures economic performance, it may neglect upstream or downstream processes if system boundaries are not carefully defined. This can result in incomplete assessments.

The integration of LCC with LCA and SLCA creates a comprehensive Life Cycle Sustainability Assessment (LCSA) framework, addressing the limitations of each individual method:

- *LCA Integration:* LCC complements LCA by quantifying the economic impacts of environmental strategies. For example, LCA highlights the environmental benefits of anaerobic digestion for high-organic-content waste, while LCC assesses its financial trade-offs. Together, these methods ensure balanced decision-making by evaluating both cost efficiency and environmental performance.
- *SLCA Integration:* SLCA incorporates social dimensions such as employment, health, and community well-being, filling the gaps left by LCC and LCA. By integrating SLCA, the framework addresses societal concerns such as equitable access to energy and the inclusion of informal waste workers, ensuring that financial and environmental gains do not come at the expense of social equity.
- *Unified Sustainability Framework:* The combined application of LCC, LCA, and SLCA provides a holistic perspective on WtE systems. For instance, a centralised WtE facility may show higher upfront costs in LCC but could offer significant long-term environmental benefits in LCA and social advantages in SLCA, such as job creation and improved waste management.

3.5. Social Life Cycle Assessment (sLCA) Methodology

Social Life Cycle Assessment (SLCA) is a systematic framework designed to evaluate the social and socio-economic impacts associated with the life cycle of products, processes, or systems. It complements Environmental Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) by focusing on the social dimension of sustainability, thereby ensuring a holistic evaluation of the triple bottom line. SLCA identifies potential positive and negative social impacts across the supply chain, from raw material acquisition to disposal, and includes diverse stakeholder groups such as workers, local communities, and value chain actors.

The methodology follows a four-step process inspired by the ISO framework: goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation. Since the release of the UNEP/SETAC SLCA guidelines in 2009 and the updated 2020 version, SLCA has advanced significantly in standardisation, data collection, and impact assessment methodologies. This evolution addresses previous methodological challenges, such as stakeholder inclusion and defining social impact categories [OBJ].

SLCA has gained prominence in the context of global sustainability initiatives, including the United Nations Sustainable Development Goals (SDGs). It supports decision-making by highlighting how processes, such as waste-to-energy (WtE) systems, influence human well-being, social equity, and local community development.

This thesis applies a literature-based SLCA to evaluate the social sustainability of three waste-to-energy systems in Port Harcourt, Nigeria. By relying on secondary data sources and established indicators, the study aims to provide a reliable comparative analysis of the social implications of each scenario. This approach mitigates data collection challenges and offers actionable insights into the social trade-offs and benefits of waste-to-energy systems.

3.5.1. Goal and Scope Definition

The goal and scope are critical steps in Social Life Cycle Assessment (SLCA) as it establishes the framework for assessing social impacts across the life cycle of a product or system. In the context of waste-to-energy (WtE) systems, this involves determining the objectives, functional unit, system boundaries, and stakeholders relevant to the assessment. Literature on SLCA provides diverse methodologies, reflecting variations in sectoral focus, regional contexts, and

stakeholder priorities [184], [193]. The overarching goal in SLCA is to assess the positive and negative social impacts of a product or system while considering the distribution of these impacts among stakeholders. For waste management systems, this often includes evaluating how scenarios influence worker conditions, community well-being, and equity. In literature, SLCA goals have ranged from assessing the labour conditions in bioenergy supply chains to analysing the social acceptability of energy generation technologies.

The scope of an SLCA typically involves the selection of functional units, system boundaries, and stakeholder groups. Studies on waste management often adopt functional units similar to those used in LCA and LCC, such as the treatment of 1 tonne of municipal solid waste (MSW), allowing for comparability between environmental, economic, and social assessments. System boundaries are set to include all relevant life cycle stages, from collection to end-of-life, with stakeholder analysis tailored to the socio-economic context [193], [194].

Although some studies have adopted broader or more context-specific functional units, such as the energy output of waste-to-energy systems, to better align with the study's objectives [195]; the functional unit chosen for this assessment is 1 tonne of municipal solid waste (MSW). This is consistent with the functional units used in Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). Alternative functional units, such as energy output, have been used in other studies, but this research prioritises waste treatment as the basis for evaluation.

Stakeholder inclusion is critical in SLCA. In waste-to-energy systems, key stakeholders typically include workers, local communities, policymakers, and informal waste pickers. Studies have shown that system boundaries must encompass all stages of waste management to comprehensively assess social impacts [194]. This includes:

- Collection and Transportation: Social impacts on waste collection workers and logistics personnel.
- Processing and Energy Generation: Worker health and safety in waste treatment facilities and community impacts from operations.
- End-of-Life Management: Social interactions in residue management and recycling, including informal sector contributions.

3.5.2. Life Cycle Inventory Analysis

The Life Cycle Inventory (LCI) phase of Social Life Cycle Assessment (SLCA) involves identifying and gathering data on social indicators relevant to the assessment. Unlike environmental LCA, where quantitative datasets such as emissions or energy flows dominate, SLCA inventories often rely on qualitative and semi-quantitative data. This presents unique challenges, such as variability in data availability and reliance on secondary sources. For this study, the LCI phase evaluates the social impacts of waste-to-energy (WtE) scenarios in Port Harcourt, Nigeria, using a literature-based approach to ensure consistency and reliability. The LCI leverages existing datasets, case studies, and databases. Some relevant sources include:

- *Academic Literature*: Studies on WtE systems, particularly in developing economies, providing insights into social dynamics and impacts.
- *Social Impact Databases*: Tools like the Product Social Impact Life Cycle Assessment (PSILCA) database, which offer qualitative and quantitative data on worker conditions, health risks, and equity issues
- *Policy and Industry Reports*: Regional and international reports on waste management practices and socio-economic conditions.

A critical step in the LCI is mapping stakeholders affected by the WtE systems. Literature suggests the following groups are most relevant:

- *Workers*: Employees involved in collection, processing, and energy generation.
- *Local Communities*: Residents near WtE facilities who experience changes in quality of life due to reduced waste, pollution, or energy access.
- *Informal Waste Pickers*: Individuals reliant on waste streams for income, often excluded from formal waste management systems.
- *Government & Policymakers*: Stakeholders shape waste management and energy policy

The data collected for the inventory are categorised under key social indicators widely discussed in SLCA literature. These are worker health and safety, community well-being, and stakeholder equity. These all pose sets of challenges such as data availability for informal waste management practices and regional worker conditions but also localised data on community impacts are often absent in secondary dataset. Thus, assumptions and generalisation from regional studies are used to fill gaps, such as the typical health and safety conditions in waste management sectors of similar economies.

3.5.3. Social Impact Assessment and Indicators

The Social Impact Assessment (SIA) aims to evaluate the positive and negative social effects associated with the life cycle of products, systems, or processes. Unlike its environmental counterpart, SIA relies on qualitative and semi-quantitative data, focusing on the well-being of stakeholders and societal systems. In waste-to-energy (WtE) systems, the assessment of social indicators provides insights into how different scenarios affect worker conditions, community welfare, and societal equity. Common social indicators, assessment tools, and methodologies used in SLCA are discussed in this section.

Social indicators capture the societal impacts of a system and provide a basis for comparing scenarios. It is a critical step in SIA as it requires alignment with the studies goals and system boundaries. Literature identifies a wide range of indicators tailored to specific contexts and stakeholder groups. For this study, some of the selected indicators are as follows:

- *Worker Health and Safety*: Evaluates risks faced by workers in waste collection, processing, and energy generation. This includes exposure to hazardous materials, availability of personal protective equipment, and the frequency of workplace accidents. Studies have highlighted the importance of ensuring safe working conditions, particularly in waste collection and energy generation [196], [197].
- *Community Well-Being*: Assesses societal benefits, such as improved access to clean energy, job creation, and reductions in waste-related nuisances like odours and pests. It also considers the impact of WtE facilities on public health and local infrastructure. Indicators in this category align with SDGs focusing on sustainable cities and communities.
- *Inclusion*: Examines the fair distribution of benefits and burdens across stakeholders, particularly the inclusion of informal waste pickers in formalised waste management systems. Studies emphasise that marginalisation of informal workers can exacerbate social inequalities.
- *Social Acceptability*: Reception and acceptance of WtE projects, including potential resistance due to perceived environmental or health risks. Social acceptance is critical for the successful implementation of WtE facilities.
- *Educational and Skills Development*: Knowledge provided by WtE systems for workforce training, education, and skills enhancement. This is particularly relevant in developing regions where such projects can improve human capital.

- *Cultural and Ethical Consideration*: Considers the impact of heritage and ethical concerns, such as the appropriateness of siting facilities near residential or sacred areas.

To evaluate social indicators, SLCA employs quantitative, and semi-quantitative approaches:

- *Scoring and Weighting Systems*: Indicators are often scored on predefined scales (e.g., 1 to 5) to provide a comparative analysis across scenarios. Weighting schemes are used to prioritise indicators based on their relevance to regional or stakeholder-specific contexts.
- *Databases and Frameworks*: Tools like the Product Social Impact Life Cycle Assessment (PSILCA) guidelines provide structured pathways for assessing social impacts across life cycle stages. These frameworks offer standardised indicators and methodologies for data collection and analysis.
- *Pathway-Based Assessment*: Social impact pathways link specific life cycle activities to their corresponding social waste collection activities may be directly linked to worker health and safety, while waste-to-energy operations may affect community well-being through energy provision.
- *Stakeholder Engagement*: Engaging stakeholders through interviews, surveys, or participatory workshops ensures the inclusion of diverse particularly important in identifying context-specific social impacts and refining indicator selection.

3.5.4. Interpretation and Comparative Analysis

The interpretation phase in Social Life Cycle Assessment (SLCA) synthesises findings from inventory and impact assessment to derive actionable insights. For this study, interpretation focuses on comparing the social implications of three waste-to-energy (WtE) scenarios in Port Harcourt, Nigeria, by evaluating trade-offs, identifying critical social impacts, and ensuring alignment with broader sustainability goals. This phase ensures that the results are meaningful and applicable to decision-making processes for policymakers and stakeholders. It has been highlighted within the literature that there is need for a structured and transparent approach to SLCA interpretation. Common strategies include evaluating significant social issues, conducting trade-off analysis, and considering stakeholder priorities:

- *Identification of Significant Social Impacts:* The results from the impact assessment phase are analysed to determine the most critical social impacts across scenarios. For example, worker health and safety might emerge as a major concern in scenarios involving incineration, while community well-being may be more positively influenced in anaerobic digestion-based systems due to lower emissions and job creation.
- *Trade-Off Analysis:* Trade-offs between social indicators are systematically evaluated. For instance, a scenario with higher worker health risks may provide greater community benefits through increased energy access. This analysis is essential to balance stakeholder needs and prioritise social sustainability across the scenarios.
- *Stakeholder Prioritisation:* Recognising that different stakeholders value social impacts differently, this phase incorporates weighting schemes to reflect local priorities. For example, in Port Harcourt, where informal waste pickers play a significant role, equitable inclusion in waste management systems may carry greater importance compared to settings with established formal systems.
- *Scenario Comparison and Ranking:* A comparative analysis ranks the three scenarios based on their overall social performance. Weighting factors derived from stakeholder input, regional socio-economic conditions, and alignment with Sustainable Development Goals (SDGs) are applied to ensure robust results. Tools like multi-criteria decision analysis (MCDA) are often utilised for this purpose.

3.6. Summary

This chapter has established the comprehensive Life Cycle Sustainability Assessment (LCSA) framework required to evaluate the feasibility of biomass-to-energy systems in Nigeria. By integrating Techno-economic Assessment (TEA), Environmental Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA), the methodology ensures a holistic analysis that goes beyond simple energy generation metrics.

The chapter defined the study's specific boundaries, selecting Port Harcourt as the geographical case study and setting the functional unit as the management of 1 tonne of Municipal Solid Waste. Three distinct system configurations were developed to be tested: System A (Electricity focus with ORC), System B (Agricultural focus with cooling/drying), and System C (Urban farming focus). The inventory analysis protocols and impact categories for each sustainability pillar (environmental, economic, and social) have been detailed to address the data constraints typical of developing regions.

With these methodological foundations and system boundaries now firmly established, the research proceeds to the application phase. Chapter 4: System Design and Performance will utilise this framework to model the technical performance and material flows of the proposed systems, providing the quantitative baseline necessary for the subsequent sustainability impact assessments.

Chapter 4

4. System Development and Performance Assessment

As urban populations in developing regions continue to grow, effective and sustainable waste management has become a critical urban management challenge. This chapter delves into the development and assessment of three innovative waste-to-energy (WtE) systems designed to mitigate these challenges by converting municipal solid waste (MSW) into valuable energy resources. Waste-to-energy technology not only offers a promising solution to the escalating problem of waste accumulation but also helps alleviate energy shortages, contributing to urban sustainability. By transforming waste into electrical and thermal energy, WtE systems provide a dual benefit: reducing the environmental burden of waste disposal and enhancing the local energy supply.

The chapter begins by setting the scene with a detailed overview of the current waste management practices in Port Harcourt, informed by recent studies on MSW composition and disposal methodologies. The scenarios developed for this study aim to explore different technological configurations to optimise energy recovery and support local economic activities:

1. System A: Integrates an Organic Rankine Cycle (ORC) to maximise electricity generation from waste heat, producing valuable by-products such as digestate and biochar. This system is evaluated for its high energy output potential, making it ideal for areas with significant electricity demands.
2. System B: Focuses on supporting local agriculture alongside energy generation. It features air-drying chambers and absorption chillers to provide drying and cooling solutions for agricultural produce, enhancing the local value chain and supporting sustainable agricultural practices.
3. System C: Combines electricity generation with urban greenhouse farming, utilising excess heat and electricity to boost local food production. This model is particularly suited to urban settings where space is limited but the demand for local, sustainable food production is growing.

The forthcoming sections will provide a detailed technical assessment of each scenario, including the efficiencies of anaerobic digestion and gasification processes and the applicability of prime movers like gas turbines and internal combustion engines. The evaluation will extend

to the ancillary technologies each system employs, such as ORC, crop drying chambers, and greenhouse operations, to determine their feasibility and performance in the context of Port Harcourt's urban waste management and energy recovery needs.

While Anaerobic Digestion and Gasification are established individual technologies, the novelty of this research lies in their synergistic integration into a 'waste-to-wealth' poly-generation network specifically tailored for the Nigerian socio-economic context. Unlike standard WtE plants that treat homogenous feedstocks, this study proposes a unique hybrid AD-Gasification coupling designed to handle the heterogeneous, unsorted nature of Nigerian Municipal Solid Waste (MSW) directing high-moisture organic fractions to AD and dry combustible fractions to gasification. Furthermore, the novelty extends to the demand-side integration: Systems B and C do not merely generate electricity but are engineered to solve critical local infrastructure gaps, specifically post-harvest loss reduction (via absorption cooling in System B) and Food Security (via CO₂ enrichment in greenhouses in System C). This moves the work beyond simple energy generation into the realm of the water-energy-food Nexus.

The integration of conventional Carbon Capture and Storage (CCS) units was evaluated but excluded from the final design for three critical reasons:

- **Scale Incompatibility:** CCS technologies are currently optimised for large-scale centralised power plants. For the distributed, community-scale systems proposed (kW to low MW range), the capital cost of miniaturised capture units would render the project economically insolvent.
- **Energy Penalty:** Conventional amine-based capture systems typically consume 15–25% of the plant's energy output. Given the primary goal of alleviating Nigeria's acute energy poverty, diverting a quarter of the generated power to CCS was deemed counterproductive.
- **Infrastructural Void:** A CCS unit requires downstream infrastructure (pipelines, geological storage sites) which is non-existent in the target residential/semi-urban locations in Port Harcourt. However, it should be noted that System C incorporates a biological form of Carbon Capture and Utilisation (CCU) by utilising exhaust CO₂ to enhance crop yields in the integrated greenhouse.

4.1. Study Area and Waste Characterisation

Focusing on Nigeria as a case study choice was made due to the rapid economic development, which leads to significant social, environmental and material cultural change. Urbanisation is experienced mostly in Nigeria's major cities through the move to the secondary and tertiary industries. These have been fast growing resulting in change and increase of waste. For development to succeed and be experienced throughout Nigeria, all socioeconomic classes within will need to be included. Resolving areas where there are energy poverty and waste management problems will simultaneously benefit the economy and environment.

Port Harcourt, Nigeria, was selected as the main case study to develop an initial framework to apply to another Nigerian city, as each has different waste characteristics. Port Harcourt lies between latitudes 4°45' N and 4°60' N and longitudes 6°50' E and 7°10' E. It is characterised by a tropical climate with heavy rainfall, which complicates open waste disposal by accelerating leachate production and pollution of nearby water bodies. The city's economy is primarily driven by oil and gas, but informal trading and small-scale manufacturing also contribute significantly to its income generation. Waste management issues in Port Harcourt are further aggravated by its unplanned urban sprawl and limited infrastructure development.

Port Harcourt has a high rate of demographic growth, industrialisation, and urbanisation. Located in the oil-rich Niger Delta region, Port Harcourt spans approximately 369 square kilometres as seen in Figure 4-1 and is home to over 3 million residents. This demographic and economic growth has exacerbated issues of municipal solid waste (MSW) management, making the city an ideal case study for evaluating waste-to-energy (WtE) pathways. Its geographic location does not favour many renewables, and the current energy poverty population is high and economic productivity distress lead to various social vandalism. Environmental concerns are high in the city due to large quantity of particulate matter (soot). The city's Air Quality index reads between 200 -300; the U.S. Environmental Protection Agency (EPA) states a reading of 0 – 50 is good [198]. Port Harcourt generates an estimated 0.7–1.0 kg of waste per capita daily, translating to over 1.5 million tons of MSW annually. Despite this significant waste generation, only about 40% of waste is collected by municipal services or private contractors, while the rest is either openly dumped or burned without energy recovery, contributing to severe environmental and public health risks.

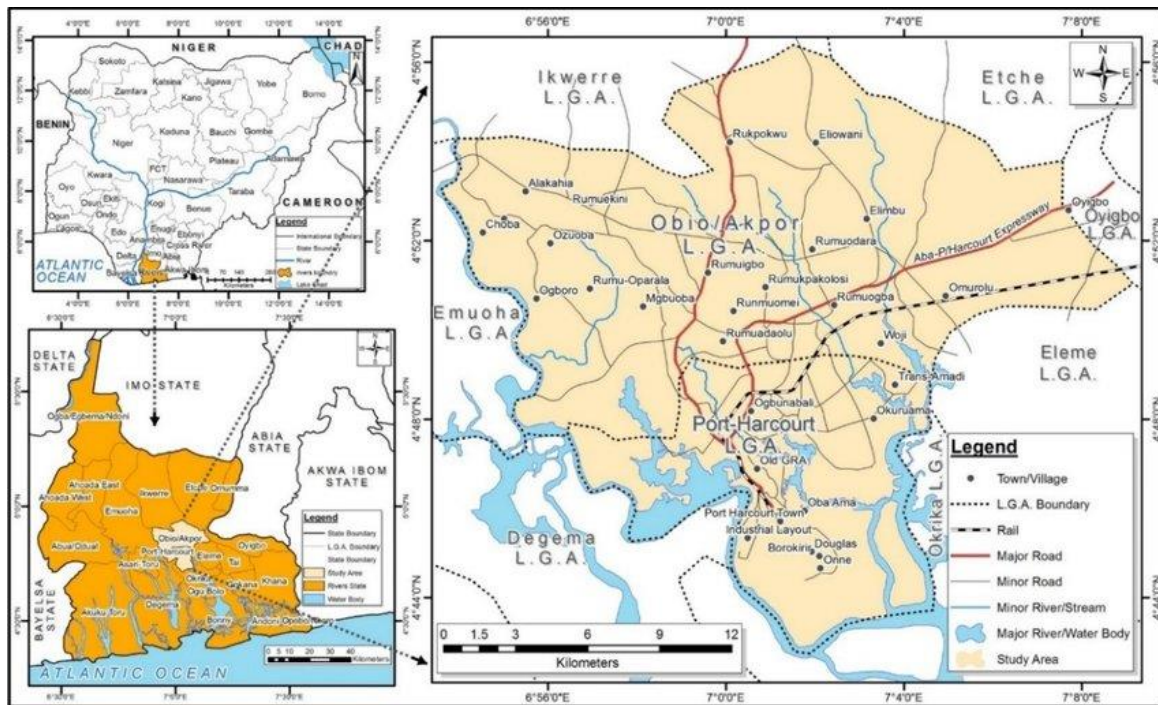


Figure 4-1: Map of Port Harcourt metropolitan area [199].

Critical characteristics of waste management practices in Port Harcourt include:

- *Collection and Disposal:* Waste is collected sporadically, and service coverage is limited to central areas, leaving peripheral neighbourhoods underserved. Most collected waste is disposed of in open dumps such as the Rumuekini dumpsite, which lacks proper lining or leachate management systems [200].
- *Informal Sector Contribution:* Informal waste pickers, often working in hazardous conditions, play a critical role in recycling plastics, metals, and paper, albeit on a small scale. However, their efforts could be more coordinated and better integrated into the formal waste management framework [201], [202].
- *Waste Composition:* The MSW in Port Harcourt is predominantly organic (over 50%), with significant fractions of plastic (15%), paper (10%), and other materials. This high organic content makes the city suitable for adopting anaerobic digestion and composting as waste management options [37], [203], [204].

The Rivers State Waste Management Agency (RIWAMA) is responsible for overseeing waste collection, disposal, and enforcement of environmental sanitation regulations. However, the agency faces challenges such as inadequate funding, outdated equipment, and insufficient human resources. Policies such as the National Environmental Sanitation Policy (2005) provide a framework for waste management, but enforcement remains weak [205], [206]. While Nigeria has outlined guidelines for solid waste management under the Federal Ministry of Environment,

implementation at the state level has been inconsistent [207]. Critical aspects of the policy framework include:

1. Encouraging public-private partnerships (PPPs) to improve waste management.
2. Promoting waste recovery, recycling, and energy generation.
3. Phasing out open dumping and encouraging the development of engineered landfills.

Despite these guidelines, Port Harcourt's waste management systems remain underdeveloped, primarily due to political and financial constraints. Port Harcourt presents significant potential for WtE solutions due to:

- *Energy Demand*: The city faces acute energy shortages, with an average electricity supply of 4–6 hours per day. WtE could contribute to the city's energy mix and enhance energy security.
- *High Organic Waste Content*: The predominance of organic waste offers opportunities for biogas production through anaerobic digestion.
- *Proximity to Industries*: The city's industrial base could utilise by-products such as digestate from anaerobic digestion or ash from thermal processes for agricultural or construction applications.

4.1.1. Population and Waste generation prediction

The population data collected from the World Population Review gives a population census of Port Harcourt for 2024 and projected population for 2035. The population responsible for waste generation in 2050, was predicted using a modified Malthusian model equation [208], in Eq. (2).

$$P_t = P_{(t-1)} \times e^{K_p t} \quad (2)$$

Where t is the time of interest in year, P_t is the estimated population at year t , $P_{(t-1)}$ is the population at the previous year of concern, and K_p is the annual population growth rate which is estimated to gradually decrease over the coming years. The annual population growth is collected from the World Population Review (2022).

According to [37], the waste generated per capital in Port Harcourt is 0.86 kg/capita/day. The rate of waste collection rate was taken as an average from a World Bank study Kaza et al., [13] as 25%. Therefore, the quantity of waste taken to dumpsite is obtained as:

$$M_F = W_C \times M_T \quad (3)$$

M_F is the amount of mass waste at dumpsite (kg/yr), W_C is the waste collection rate and M_T is the total mass of waste generated per year (kg/yr) and it can be calculated as:

$$M_T = P_t \times W_G \times 365 \quad (4)$$

Where P_t is the estimated population at year, W_G is the waste generated per capital per day (kg/capita/day). Due to logistical constraints preventing on-site primary data collection, this study relies on validated secondary data to establish the baseline input parameters. The population and waste generation figures were derived from a critical meta-analysis of recent demographic surveys [209] and region-specific waste audits [210]. These literature values were cross-referenced against state disposal records to ensure they provide a representative and robust baseline for the design simulation.

4.1.2. Waste Separation and Treatment Prediction

After the MSW is generated and collected, it is transported to the facility, where it is dumped into a receiving hopper. The mixed-solid waste is transferred to the primary separation stage, where workers manually separate all potentially recyclable materials which include glasses, plastics, and non-ferrous metals that may be sold. The sanitary landfill receives all the non-recyclable tailings that are separated during the same primary separation process. The residual organic material and paper are delivered to the next step (mechanical treatment) after the primary separation, where the ferromagnetic components (steel and iron) are separated using electromagnetic equipment. Sorting, screening, drying, size reduction (shredding, grinding, and chipping), briquetting, and storing are the steps in the mechanical treatment process that convert SRF into a more manageable and homogeneous product. The recycling state in Nigeria is at its infant stage and the nation lacks official resource recovery facilities or garbage recycling programmes. As a result, data regarding the percentage of recovered materials compared to the overall amount of MSW created annually is genuinely lacking. Hence for this study, the input MSW was divided into separated recyclables and non-recyclable using data from the literature as seen on Table 4-1 and the remaining was used to calculate the available energy.

Table 4-1: Gravimetric composition of recyclables in percent (%)

CITY	METAL	GLASS
IGONI 2007 [211]	17.20	13.50
BABATUNDE 2013 [212]	4.00	2.50
OGUNJUYIGBE 2017 [37]	3.42	1.87

4.1.3. Elemental and Proximate Waste analysis

For the purpose of determining the acceptability of the various municipal waste components for energy recovery, waste classification is essential. The components of a typical MSW are both inorganic (recyclable) and organic (biodegradable and non-biodegradable). Food scraps, yard waste, sewage sludge, paper, cardboard, textiles, leather, and wood all fall under the category of organic waste (biomass). Glass, ceramics, plastics, rubber, and metals are among the inorganic waste's component materials. Combustible garbage includes things like paper, textiles, rubber, plastic, leather, and wood, whereas recyclables include things like metals and glass. Other types of trash, such sand, pottery, etc., are inert. The data used in this study were obtained from. The following relation was used to determine the quantity of waste content that may be used for various technologies:

$$M_{F(i)} = M_F(t) \times f_i \quad (5)$$

Where i is the type of waste-to-energy technology, f_i is the fraction of the waste that goes into the specific technology option and t is the number of years of calculation.

4.2. Waste Conversion system Technical Assessment

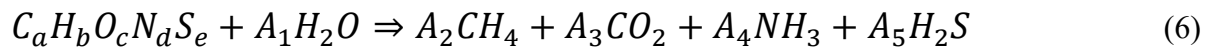
The technical and economic assessment of producing energy from waste are analysed with excel for this part of the study.

4.2.1. Anaerobic Digestion (AD) assessment

The feedstock waste diverted to the AD section of the plant is assumed to be the organic fraction. The annual operating time considered was 8400h (350 days) in a continuous process. A construction period of 30 months, a startup period of 4 months and a projected lifetime of 20 years, i.e., approximately 23 years of evaluation time. The digesters are considered to be

operating under continuously mixed mesophilic conditions (stirring speed and operating temperature of 30 rpm and 35 °C, respectively). Centrifugal compressors are utilised to compress the generated biogas after the recovered digestate has been processed with decanter centrifuges to separate its liquid and solid phases. Biogas flares are incorporated as a safety precaution in the event that electricity generating or biogas upgrading facilities fail. The hydraulic retention time in the digester is 21 days. Assuming the organic fraction has an 80% moisture content.

Methane and carbon dioxide are the major gases within the biogas produced from anaerobic digestion of organic municipal solid waste. The amount of methane generated in the process determines the energy generation potential from the selected municipal solid waste. The following modification of Bushwell's equation will be used to theoretical determine the potential amount of methane generated with the inclusion of nitrogen and sulphur to obtain the fraction of ammonia and hydrogen sulphide in the production process [170], [171], [37], [172]:



Where A_i are the constant for water and respective products of the digestion process, $i = 1, 2, 3, 4, 5$.

$$A_1 = \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2} \right) \quad (7)$$

$$A_2 = \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4} \right) \quad (8)$$

$$A_3 = \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4} \right) \quad (9)$$

$$A_4 = d \quad (10)$$

$$A_5 = e \quad (11)$$

The model assumes that these are the only components of the feedstock. Additionally, the final analysis is chosen by the model's user to ascertain the chemical reaction's constants A_{1-5} by first determining the chemical composition of our feedstock.

The ultimate analysis in yields mass ratios C, H, O, N and S (in grammes), which are then defined as variables. The constant of each element is equal to the ultimate analysis-based mass divided by the element's molar mass. Therefore, the following equation can be used to obtain the constant of each element:

$$a, b, c, d, e = \frac{K_{[C,H,O,N,S]}}{M_{[C,H,O,N,S]}} \quad (12a)$$

Where M is the molar mass of each element (carbon, hydrogen, oxygen, nitrogen, and sulphur) as presented in Table 4-2 and K is the element composition for each carbon, hydrogen, oxygen, and nitrogen obtained from the ultimate analysis of organic municipal solid waste in Tables 4-3.

Table 4-2: Molar mass of the elements [213]

ELEMENTS	CARBON	HYDROGEN	OXYGEN	NITROGEN	SULPHUR
MOLAR MASS (G)	12.017	1.0079	16.010	14.0067	32.065

To ensure the feedstock characterisation accurately reflects the high organic and moisture content specific to the Niger Delta context, the Ultimate Analysis presented in Table 4-3 was derived using a component-specific weighted aggregation model. Unlike generic stoichiometric assumptions, this model synthesises the aggregate elemental composition by calculating the weighted sum of the individual waste fractions identified in the study area. The governing equation for this characterisation is:

$$E_{total}(\%) = \sum_{i=1}^n (E_i \times W_i) \quad (12b)$$

Where E_{total} is the aggregate percentage of the element (Carbon, Hydrogen, Oxygen, Nitrogen, or Sulphur) in the mixed waste stream. E_i is the specific elemental percentage of waste fraction i (e.g., the carbon content of plastics vs. food waste), derived from regional spectroscopic studies for Southern Nigeria [65]. W_i is the gravimetric weight fraction of component i in the

Port Harcourt waste stream. This modelling approach accounts for the heterogeneity of the local waste, capturing the high carbon contribution from the 14% Polythene fraction balanced against the lower carbon intensity of the 63% Organic fraction. The resulting aggregate inputs serve as the precise stoichiometric basis for the Anaerobic Digestion and Gasification simulations.

Table 4-3: Ultimate analysis of MSW generated in southern Nigeria [65]

WASTE COMPONENT	COMPONENT PERCENTAGE % [65]	% CARBON	% HYDROGEN	% OXYGEN	% NITROGEN	% SULPHUR
ORGANICS	63	50.85	5.34	32.27	0.59	0.15
POLYTHENE	14	55.99	4.16	34.26		
PLASTIC	4	50.87	4.80	37.47	0.04	0.02
PAPER	10	54.24	4.54	36.66		0.04
WOOD	5	49.74	5.79	42.72	0.21	0.22
TEXTILES	4	52.84	5.13	38.06	0.05	0.07
ULTIMATE WASTE COMPOSITION	100	51.72	5.07	33.78	0.38	0.11

The biogas yield simulation was executed using a stoichiometric computational model developed within an integrated spreadsheet environment (MS Excel). This custom-built platform functions as the process engine, directly linking the feedstock elemental composition (from Table 4-3) to the reaction kinetics. Figure 0-1 (see Appendix) provides a detailed snapshot of the modelling interface showing the stoichiometric yield calculation module based on the Buswell-Mueller equation.

The amount of methane (kg) given as M_{CH_4} that can be obtained from any potential waste-to-energy project that employs anaerobic digestion technology can be calculated using:

$$M_{CH_4} = \frac{A_2 \times 16.0486}{12.017a + 1.0079b + 15.999c + 14.0067d + 32.065e} \quad (13)$$

Consequently, the mass of other products from the anaerobic process such as carbon dioxide (M_{CO_2}), ammonia (M_{NH_3}), hydrogen sulphide (M_{H_2S}) can be calculated using the following:

$$M_{CO_2} = \frac{A_3 \times 44.037}{12.017a + 1.0079b + 15.999c + 14.0067d + 32.065e} \quad (14)$$

$$M_{NH_3} = \frac{A_4 \times 17.0304}{12.017a + 1.0079b + 15.999c + 14.0067d + 32.065e} \quad (15)$$

$$M_{H_2S} = \frac{A_5 \times 34.0808}{12.017a + 1.0079b + 15.999c + 14.0067d + 32.065e} \quad (16)$$

The methane obtained is converted to Kg so the volume of the methane can be calculated Where ρ_{CH_4} is the density of methane (0.717 kg/m³)

$$V_{CH_4} = \frac{M_{CH_4}}{\rho_{CH_4}}$$

Appels et al., [214] states that, methane generation is lower than what is predicted to occur. This is due to the digester being unable to break down roughly 10% of the organic material. Additionally, 5–10% of the organic material in garbage will be used to create the cell tissue of organisms that influence microbial breakdown [73]. Consequently, the digester's actual methane yield can be calculated as:

$$T_{CH_4} = M_{F(AD)} \times \frac{M_{CH_4}}{1 \times 10^6} \times F_{OM} \quad (17)$$

Where T_{CH_4} is the mass of methane produce in ton/yr, $M_{F(AD)}$ is the annual feedstock suitable for the anaerobic digestion process and F_{OM} is the fraction of organic matter utilised for cell tissue synthesis.

4.2.2. Gasification Assessment

MSW is known to include some material which lead to a sizable amount of ash, fixed bed downdraft gasifiers are taken into consideration in this study due to its ability to manage high ash feed. Furthermore, with an internal combustion engine (ICE), downdraft fixed bed reactors function well as the gas they create is cleaner. The downdraft gasifiers produce a syngas with a low tar content ($<2.0 \text{ g/Nm}^3$ for biomass) and the highest Carbon Conversion Efficiency (CCE) of any biomass. They also produce very little ash. When biomass is sourced from wood, the downdraft gasifiers' Cold Gas Efficiency (CGE) approaches 75% [215].

Following mechanical processing, the material is fed in batches via the load chamber at the top of the gasifier into the gasification and combustion zone, which is located at the bottom of the primary chamber. From there, the gas and solids (char and ash) move down in the downdraft gasifier, with some of the pyrolysis gas possibly burning above the gasification zone. Part of the biomass char is burned to provide the thermal energy needed for drying, pyrolysis, and gasification (autothermal gasification). To prevent the bottom ash from melting, the temperature of the bed, which is maintained between 700 and 950 °C, and the primary air injection rate determine how quickly the ash gasifies [215], [216]. To gasify the waste, the downdraft reactors under consideration in this work will run at atmospheric pressure, with air serving as the gasification agent. *Table 4-4 & 4-5* summarises the average reported values for the operational parameters, syngas composition, and primary downdraft gasifier characteristics that have been published in the literature for the waste gasification process.

After it is recommended to clean up the producer gas before being fed into downstream applications. The procedure is categorised as hot gas cleaning (HGC) and cold gas cleaning (CGC) and the impurities that will be removed include particulate matter, condensable hydrocarbons (tars) sulphur compounds, nitrogen compounds, alkali compounds, halides compounds and trace contaminants. For this study CGC was chosen as the cleaning system. It combines dry and wet cleaning process comprising a cyclone, fabric filter, thermal cracking, and removal of tars in a wet scrubber. Finally, a floating-drum gas storage recipient, absorbs variations in the producer gas flow, when supplied to a prime mover. It is assumed that a percentage of impurities such as char, ash and other residues are present in the input waste mass which is not converted into syngas.

Table 4-4: Characteristics of downdraft gasifier, operational parameters and syngas composition ([168])

GASIFIER CHARACTERISTICS	UNIT	VALUE
GASIFICATION PRESSURE	kPa	101.325
GASIFICATION TEMPERATURE	°C	800
EQUIVALENCE RATIO (ER)	-	0.30
SPECIFIC VOLUMETRIC AIR FLOW CONSUMPTION	Nm ³ /kg _{MSW}	2.30
SPECIFIC AIR MASS FLOW RATE CONSUMPTION	kg/kg _{MSW}	1.69
MAXIMUM SIZE OF SRF	Mm	100
MAXIMUM MOISTURE CONTENT ALLOWED IN SRF	%	30
ASHES METING POINT	°C	1200
SPECIFIC MASS FLOW RATE OF ASHES GENERATED	kg/kg _{MSW}	0.30
SPECIFIC THERMAL POWER	kW/m ²	1200
MAXIMUM RANGE OF THE REACTOR SCALE-UP	MW _{th}	15.0
SPECIFIC ENERGY CONSUMPTION OF THE PROCESS	kW h/kg _{MSW}	3.5
HEAT LOSSES	% input MSW _{LHV}	5.0
CARBON CONVERSION EFFICIENCY (CCE)	%	85
COLD GAS EFFICIENCY (CGE)	%	75

Table 4-5: Characteristics and Composition of Producer Syngas

CHARACTERICS		
SYNGAS EXIT TEMPERATURE	°C	670
SYNGAS EXIT PRESSURE	kPa	101.325
SPECIFIC PRODUCER SYNGAS FLOW RATE YIELD	Nm ³ /kg _{MSW}	3.2
SYNGAS DENSITY	kg/Nm ³	1.45
H ₂	% vol _{d.b.}	7.92
CO	% vol _{d.b.}	11.57
CH ₄	% vol _{d.b.}	3.90
CO ₂	% vol _{d.b.}	14.90
N ₂	% vol _{d.b.}	60.53
C ₂ H ₄	% vol _{d.b.}	0.80
C ₂ H ₆	% vol _{d.b.}	0.05
C ₂ H ₂	% vol _{d.b.}	0.08
C ₆ H ₆	% vol _{d.b.}	0.25
H ₂ S	g/Nm ³	0.45
HCL	g/Nm ³	1.04
NH ₃	g/Nm ³	2.00
SYNGAS TARS	g/Nm ³	2.00
ASHES AND PARTICULATES IN THE SYNGAS	g/kg _{syn}	27.6
SYNGAS LHV	MJ/Nm ³	4.6
SYNGAS LHV	MJ/kg _{syn}	3.17

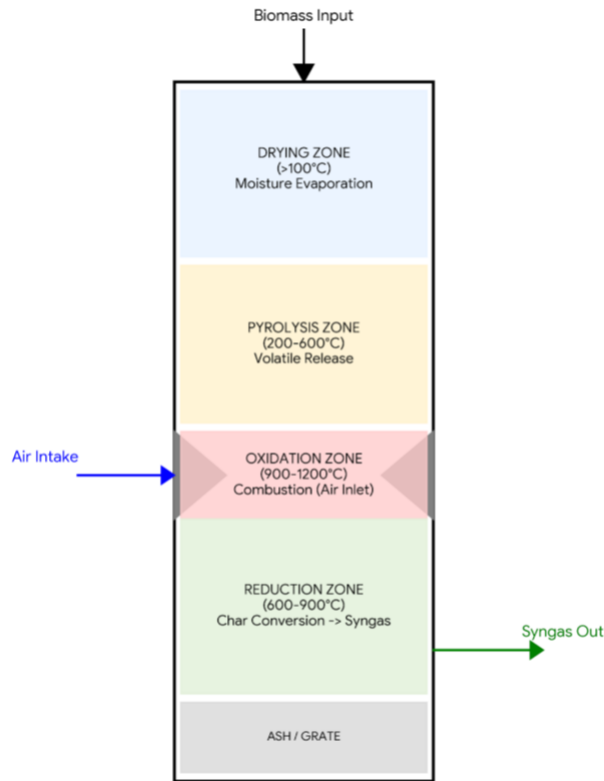


Figure 4-2: Schematic diagram of a downdraft gasifier

To calculate the energy content, also known as Lower Calorific Value (LCV), of the available feed stock will be:

$$LCV \text{ (kcal/Kg)} = 40 (a + b + c + d) + 90e - 46w \quad (18)$$

Where a is paper, b is textiles c is wood & leaves, d is organic e is plastics & rubber w is water (equals to zero as the moisture is removed during preheating of the MSW). 1 MJ/Kg will be equal to 238.8549 kcal/Kg. Adjustment for system losses are also applied. These include char, ash and other residues accounting for roughly 30% of the input waste.

4.2.3. System Integration and Gas Conditioning Assumptions

The successful coupling of Anaerobic Digestion (AD) and Gasification relies on critical assumptions regarding gas quality, blending, and utilisation:

- **Gas Cleaning Strategy:** To protect the prime movers, distinct cleaning protocols are assumed for each stream. Biogas from AD undergoes biological desulphurisation and dehumidification to remove hydrogen sulphide (H_2S) and moisture. Simultaneously, syngas from gasification undergoes a Cold Gas Cleaning (CGC) process, utilising

cyclonic separation and wet scrubbing to reduce tar content to $< 50 \text{ mg/Nm}^3$ and particulates to $< 30 \text{ mg/Nm}^3$, ensuring compliance with manufacturer specifications for Internal Combustion Engines and Micro Gas Turbines.

- Separation and Mixing: Rather than separate fuel trains, the model assumes a homogenised fuel strategy. Post-cleaning, both gas streams are fed into a common buffer storage unit. This effectively dampens the calorific fluctuations inherent in gasification syngas and ensures a stable, blended fuel input for the prime movers.
- Carbon Capture and Utilisation (CCU): For System C, a Carbon Capture and Utilisation scenario is assumed where prime mover exhaust gases are treated via catalytic conversion to remove NO_x and CO , cooled to $< 50 \text{ }^\circ\text{C}$, and directed into the greenhouse modules. This provides CO_2 enrichment (targeted at 800–1000 ppm) to enhance crop photosynthesis, converting a waste emission into a productive agricultural input. Systems A and B assume standard exhaust venting.

4.3. Prime Mover

For energy production assessment, this study will explore various prime movers that accept the product biofuel from the two conversion systems employed earlier. Initially, a comparative performance analysis of various prime mover types will be conducted based on technical specifications, including electrical and thermal efficiency, and integration potential with the system. Afterwards, a selection of prime movers will be further assessed on biofuel required per hour of energy production, exhaust gas temperature and the proportion fed back to the system.

4.3.1. Electricity Generation and Sizing estimation

The estimation of prime mover sizing and daily electricity generation capacity is based on the available mass of municipal solid waste (MSW), the yield of biofuel production per unit of MSW, the lower heating value (LHV) of the biofuel, and the electrical efficiency of the selected energy conversion system. The total daily electrical energy output ($E_{\text{electricity}}$) is determined through a two-stage process. The technical efficiencies and energy outputs for the CHP systems were modelled using a steady-state thermodynamic analysis developed in Microsoft Excel. Unlike complex dynamic simulations, this model relies on fundamental mass and energy balance equations governed by the first law of thermodynamics to determine system states at nominal full-load operation. Key performance parameters for the prime movers specifically

electrical efficiency (η_{el}), exhaust mass flow rate (\dot{m}_{ex}), and exhaust gas temperature (T_{ex}) were not assumed generically but were derived directly from manufacturer technical datasheets. These inputs were validated against peer-reviewed literature values for similar biomass-fed applications. The model assumes standard ISO conditions (15 °C, 1 atm) with a conservative parasitic load factor of 5-10% applied to account for auxiliary plant consumption (pumps, blowers, and control systems)."

First, the chemical energy available from the waste-derived biofuel is calculated the net daily electrical energy output is then obtained using these:

$$E_{biofuel} = M_{MSW} \times Y_{biofuel} \times LHV_{biofuel} \quad (19a)$$

$$E_{electricity} = E_{biofuel} \times \eta_{el} \quad (19b)$$

Where M_{MSW} is the mass of MSW available per day (kg/day), $Y_{biofuel}$ is the biofuel yield per unit mass of MSW ($kg_{net_biofuel}/kg_{msw}$), $LHV_{biofuel}$ is the lower heating value of the produced biofuel (MJ/kg), and η_{el} is the electrical efficiency of the selected prime mover. Finally, the number of prime mover units required (N_{units}) to meet the power generation is determined by:

$$N_{units} = \frac{E_{electricity}}{P_{unit} \times H} \quad (20)$$

Where P_{unit} is the rated electrical power output of a single prime mover unit (kW), and H is the number of operational hours per day (hours/day).

4.3.2. Comparative Assessment of Prime Mover Technologies

To identify the optimal power generation unit for the proposed waste-to-energy network, a comprehensive evaluation of commercially available prime movers was conducted. The assessment categorises available technologies into two distinct classes based on capacity and application scope:

- Class A: Domestic-Scale Micro Turbines (3–100 kWe) This category includes ultra-micro units like the MTT EnerTwin (3 kWe) and Bladon Micro Turbine (12 kWe), which are optimised for single-household or telecom applications. While these units offer high granularity for "prosumer" models, their low individual capacity renders them

unsuitable for handling the high gas volumes generated by a 500 tpd municipal facility, as synchronising hundreds of units would create excessive operational complexity.

- **Class B: Community and Industrial-Scale Units (>100 kWe)** This category comprises larger units capable of absorbing municipal-scale fuel loads, including the Capstone C1000 (1 MW), the Opra OP16 (1.85 MW), and the GE Jenbacher Type 3 (1 MW). These systems offer superior electrical efficiencies (33–39%), lower specific capital costs, and the robustness required for baseload generation.

While Class A units offer excellent granularity for individual "prosumer" models, the high specific capital cost and the operational complexity of synchronising multiple units render them unviable for a municipal-scale project. Consequently, Class B units were selected as the primary reference technologies for this study to match the projected 4–6 MW output potential of the Port Harcourt waste stream. They provide the optimal balance between operational efficiency and maintenance requirements.

4.3.3. Performance Comparison

After a comparative analysis of various prime movers was conducted based on maturity, technical specifications, including electrical efficiency, exhaust gas characteristics, and integration potential with the overall system. Micro gas turbines and internal combustion engines have been chosen to have the highest potential of enhancing the overall systems efficiency. This is due to the electrical efficiencies, exhaust gas utilisation as both technologies provides high temperature exhaust gases suitable for heat recovery in the organic ranking cycle (ORC) system. Micro gas turbines offer significant advantages in modularity and ease of scaling, making them suitable for distributed energy systems. Internal combustion engines have slightly lower exhaust gas temperatures but higher mass flows, providing steady thermal energy for recovery systems. Fuel cells, while efficient, are excluded due to high capital costs and limited commercial maturity.

- **Electrical and Thermal Efficiency:** ICEs achieve a total system efficiency of 75–85%, while MGTs reach 65–75% when combined with the ORC system.
- **Waste Heat Utilisation:** Both prime movers contribute significantly to the ORC input, with ICEs providing higher mass flows and MGTs delivering higher exhaust temperatures.
- **Operational Flexibility:** ICEs are more suitable for applications requiring consistent base-load power, whereas MGTs excel in distributed systems with variable loads.

To ensure the technical robustness of the proposed systems, the inventory data includes an assessment of technical maturity and operational reliability. Table 4-6 summarises the Technology Readiness Level (TRL) and assumed availability for the selected prime movers.

Table 4-6: Technical Maturity (TRL) and Reliability Indicators for Selected Technologies.

TECHNOLOGY	MODEL	TECHNOLOGY READINESS LEVEL (TRL)	TYPICAL AVAILABILITY / RELIABILITY	COMMERCIAL STATUS	REF.
RECIPROCATING ENGINE (ICE)	Spark Ignition (e.g., Caterpillar G3516)	9	92% – 96%	Mature / Fully Commercial	[217], [218]
MICRO GAS TURBINE (MGT)	Recuperated Cycle (e.g., Capstone C65/C1000S)	9	90% – 95%	Mature / Commercial	[217], [219]
INDUSTRIAL GAS TURBINE (GT)	Simple Cycle (e.g., Siemens SGT-400)	9	95% – 98%	Mature / Fully Commercial	[217], [218]
BIOMASS GASIFIER	Fixed Bed Downdraft	8-9	80% – 85%	Early Commercial	[220], [221]
ORGANIC RANKINE CYCLE (ORC)	Low-temp Waste Heat Recovery	9	90% – 95%	Mature / Commercial	[222]

4.4. System-Specific Features Assessment

This section evaluates the unique attributes of each system designed within the waste-to-energy framework, focusing on their distinct integrations and outcomes. The assessment involves creating methodologies for comparative results based on the energy, thermal, and ancillary benefits provided by each system.

4.4.1. System A: Maximising Electricity Generation (ORC Integration)

To maximise electricity output by integrating an Organic Rankine Cycle (ORC) system that utilises waste heat from gas turbines and internal combustion engines. The Organic Rankine Cycle (ORC) in this waste-to-energy system recovers waste heat from the prime movers to generate electricity efficiently. This approach maximises energy recovery and enhances the overall system efficiency. The below methodology includes waste heat from both sources.

The assumptions for the operation of the ORC are:

- Heat Sources:
 - Prime Movers: Nominal full power performance at ISO conditions 15 °C.
- Thermal Efficiency of ORC:
 - The ORC system's exergy efficiency considers the useful work potential relative to ambient conditions. Exergy destruction identifies where system losses occur, helping refine efficiency. As seen in Behzadi's WtE ORC study [223], the exergoeconomic analysis optimises cost vs. efficiency for efficiency.
- Working Fluid:
 - Dependent on the exhaust temperature of the prime mover which ranges from 185°C to 600°C, the working fluid changes. For high temperature (450-600°C) the ORC will work with toluene, MDM, or MM (siloxanes), for medium (280-450°C) it will be R123 or n-pentane and low temperatures (185-280°C) it will be R245fa or Isobutane due to its low boiling point and suitability for low-temperature applications [224].
- Simplified Flow Rates:
 - Combined waste heat is calculated based on the mass flow rates and specific heat capacities of the flue gases.

Energy balance

Heat recovered from the gas turbine exhaust:

$$Q_{recoverable} = \dot{m}_{PM\ ex} \times \eta_{heat\ recovery} \times C_p \times \Delta T_{PM} \quad (21)$$

Where $\dot{m}_{PM\ ex}$ is the mass flow rate of prime mover exhaust (kg/s), $\eta_{heat\ recovery}$ is the efficiency of recovering heat C_p is the specific heat capacity of flue gas (1.1 kJ/kg·K), and $\Delta T_{PM} = (T_{exhaust} - T_{outlet})_{PM}$ which is the difference between the inlet and exhaust flow temperature of the prime mover. The estimation for the ORC output power will be as follows:

$$P_{net} = Q_{recoverable} \times \eta_{ORC\ assumed} \quad (22)$$

Where $Q_{recoverable}$ is the heat recovered and $\eta_{ORC\ assumed}$ is the assumed efficiency dependent on the temperature grade of the selected prime mover.

4.4.2. System B: Electricity Generation with Crop Drying and Cooling Stations

To evaluate the dual-purpose use of waste heat for electricity generation and agricultural enhancements, waste heat is allocated for waste treatment, anaerobic digestion and gasification use. The assumptions of the operation of the dryer and cooling station are:

- Heat recovery:
 - Heat recovery efficiency
 - Usable exhaust temperature after heat exchanger downstream is 200°C
- Drying Unit
 - Dryer type is a crossflow convective cabinet
 - Drying temperature is 65°C W
 - drying efficiency 60%
 - Dryer operation is 24hours per batch
 - Average crop moisture content is initially 40% and final is 10%
 - Total drying duty
- Cooling Unit
 - Single stage absorption chiller COP is 0.7
 - Chiller water temperature range is 12.5°C to 7.5°C
 - Cold Storage temperature is 12°C
 - Cooling efficiency is 65%

To begin assessing the potential of this system, the biogas energy per day will be determined using the following equation

$$E_{biogas} = Total\ volume_{biogas} \times LHV_{biogas} \quad (23)$$

Where E_{biogas} is the potential biogas energy per day in MJ/day, $Total\ volume_{biogas}$ is the total volume per day in m³/day and LHV_{biogas} is the lower heating value of both syngas and biomethane. The electrical power output will then be calculated using

$$E_{electric} = E_{biogas} \times \eta_{electric} \quad (24)$$

Where $E_{electric}$ is the electrical power output in kWh/day, E_{biogas} is the potential biogas energy per day in MJ/day and $\eta_{electric}$ is the electrical efficiency of a selected prime mover. Next the recoverable thermal energy per day will be assessed using the thermal recovery efficiency for each prime mover, specific heat capacity of air mass flow rate of exhaust gas and temperature change. Finally, the recoverable thermal energy is allocated to the heating and cooling unit, assessed using:

$$E_{drying} = E_{heat} \times \eta_{dryer} \quad (25)$$

$$E_{cooling} = \frac{E_{heat \text{ remaining after drying}} \times \eta_{chiller}}{COP} \quad (26)$$

Where E_{heat} is the heat is the recoverable thermal energy in MJ/day. η_{dryer} and $\eta_{chiller}$ is the dryer and chiller efficiency, $E_{heat \text{ remaining after drying}}$ is the remaining thermal energy after the drying unit and COP is the coefficient of performance for the chiller.

4.4.3. System C: Electricity Generation with Greenhouse-Based Urban Farming

The aim of this system is to utilise waste heat for greenhouse heating alongside electricity generation. The input of this system follows the same as the others where there is a daily waste feedstock being fed into the anaerobic and gasification conversion units. The product gas is then utilised in a selected prime mover then the exhaust heat is utilised in a greenhouse. The assumptions for the operation of the greenhouse are:

- Greenhouse area is 1,000 m²
- Heat demand per unit area is 25,000 kWh/m²/year
- Electricity demand per unit area for lighting, irrigation and ventilation is 20,000 kWh/m²/year
- Revenue or value from agricultural produce (\$ per m²/year)

To integrate the greenhouse, it will be based on the cultivation of high-demand crop in Nigeria such as tomatoes, peppers, cucumbers and leafy greens. The size would be aimed at a small to medium scale urban farming system to be manageable but large enough to produce meaningful quantities of crops for local markets in Nigeria.

$$GH \text{ Heat}_{demand} = GH_{area} \times \text{Heat requirement} \quad (27)$$

$$GH \text{ Electricity}_{demand} = GH_{area} \times \text{Electricity requirement} \quad (28)$$

Where $GH \text{ Heat}_{demand}$ is the greenhouse heat demand per year in kWh/year GH_{area} Greenhouse area in m² and the yearly heat and electricity requirement is in kWh/m²/year and kWh/year respectively. Finally, from the generated heat and electricity the greenhouse demands will be subtracted to determine if there is surplus or a deficit of heat and electricity.

4.5. Comparative Performance Results

Understanding the performance of each component of the system is critical to know the most sustainable utilisation. The biofuel yield per kilogram of waste from the conversion system can be seen in Table 4-7.

Table 4-7: Total system biofuel yield per kg of waste

DESCRIPTION	UNIT	VALUE
ANAEROBIC DIGESTION METHANE YEILD	kg _{Fuel} /kg _{MSW}	0.13
GASIFICATION BIOGAS SYNGAS	kg _{Fuel} /kg _{MSW}	1.44
TOTAL SYSTEM BIOFUEL YEILD	kg _{Fuel} /kg _{MSW}	1.57

Prime mover performance

The decision to utilise micro gas turbines and internal combustion engines was guided by their compatibility with the waste-to-energy system's design and operational objectives.

Internal Combustion Engines (ICEs):

- **Maturity:** ICEs are well-established in waste-to-energy applications due to their robust design and widespread availability.
- **Scalability:** Engines like the Caterpillar G3516J are readily available and suitable for scaling based on system capacity requirements.
- **Thermal Characteristics:** Exhaust gases at approximately 450°C ensure effective integration with the ORC system.

Micro Gas Turbines (MGTs):

- **Modularity:** MGTs, such as the Capstone C1000S, provide flexible scaling options and are ideal for small-to-medium-scale systems.
- **Fuel Versatility:** MGTs are capable of handling syngas produced from gasification systems with minimal modifications.
- **Exhaust Utilisation:** High-temperature exhaust (up to 600°C) enhances waste heat recovery efficiency.

Table 4-8: Selected prime mover performance

PARAMETER	UNIT	MGT	GT	GT	ICE	ICE	ICE	ICE
PRIME MOVER		C1000S Capstone	SGT- 50	SGT- 400	G3516	G3616	Wärtsilä 9L34DF	Wärtsilä 12V34DF
UNIT POWER RATING	kW _e	1,000	2,000	10,500	1,660	3,105	3,888	5,760
ELECTRICAL EFFICIENCY	%	33	26	34.8	37.7	41.4	44.7	44.7
EXHAUST GAS TEMPERATURE	°C	280	600	510	510	388	359	353
MSW REQUIRED	T _{MSW} /day	23.62	59.95	235.16	34.32	58.45	67.79	100.43
UNUTILISED WASTE HEAT	%	82.65	68.93	66.15	70.72	54.40	43.44	44.45
UNITS REQUIRED FOR TOTAL WASTE	#	21	8	2	14	8	7	4
ELECTRICITY POTENTIAL	MWh/day	505.59	389.34	533.17	577.60	634.29	684.85	684.85

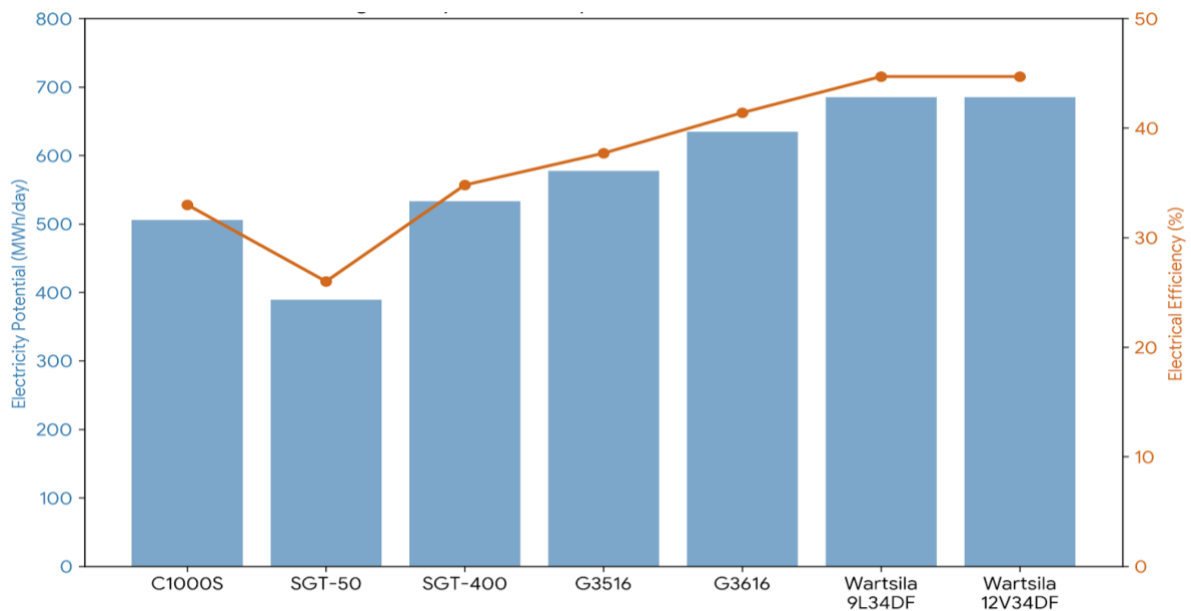


Figure 4-3: Comparative Electrical Performance

The ORC integration increases the electrical power output. Below shows the power rating the ORC must be for the selected prime mover.

Table 4-9: Ideal ORC selection

PARAMETER	UNIT	MGT	GT	GT	ICE	ICE	ICE	ICE
PRIME MOVERS		C1000S Capstone	SGT-50	SGT-400	G3516	G3616	Wärtsilä 9L34DF	Wärtsilä 12V34DF
RECOVERABLE ENERGY	kW	1106	4912	14296	2412	1791	1486	2183
POWER OUT PER UNIT	kW _e	166	1228	3574	603	269	223	328

For System B the electrical production potential will be the same as System A without the ORC. Instead, the thermal heat will be used for drying and cold storing crops as explained in the methodology. The results of this integration can be seen in table 4-10 where the proportion of thermal energy left after being fed upstream in the system has been utilised for System B. The Gas Turbines (SGT-50 and SGT-400), despite their lower electrical efficiency, reject significantly higher quantities of high-grade exhaust heat. This results in the highest Recoverable Thermal Energy (>48,000 MJ/day), making them the superior choice for high-demand drying operations. The reciprocating engines, while efficient electricity generators, offer roughly 50% less thermal energy for processing tasks.

Table 4-10: System B Drying and Cooling Potential

PARAMETER	UNIT	MGT	GT	GT	ICE	ICE	ICE	ICE
		C1000S Capstone	SGT-50	SGT-400	G3516	G3616	Wärtsilä 9L34DF	Wärtsilä 12V34DF
HEAT RECOVERY	%	57	50	50	34	28	40	40
RECOVERABLE THERMAL ENERGY	MJ/day	39,466	48,070	36,491	43,096	20,157	15,174	12,845
POTENTIAL DRYING ENERGY	MJ/day	19,571	19,886	14,484	18,287	6,579	3,955	3,426
POTENTIAL COOLING ENERGY	MJ/day	8,475	26,175	20,436	23,037	12,608	10,418	8,746

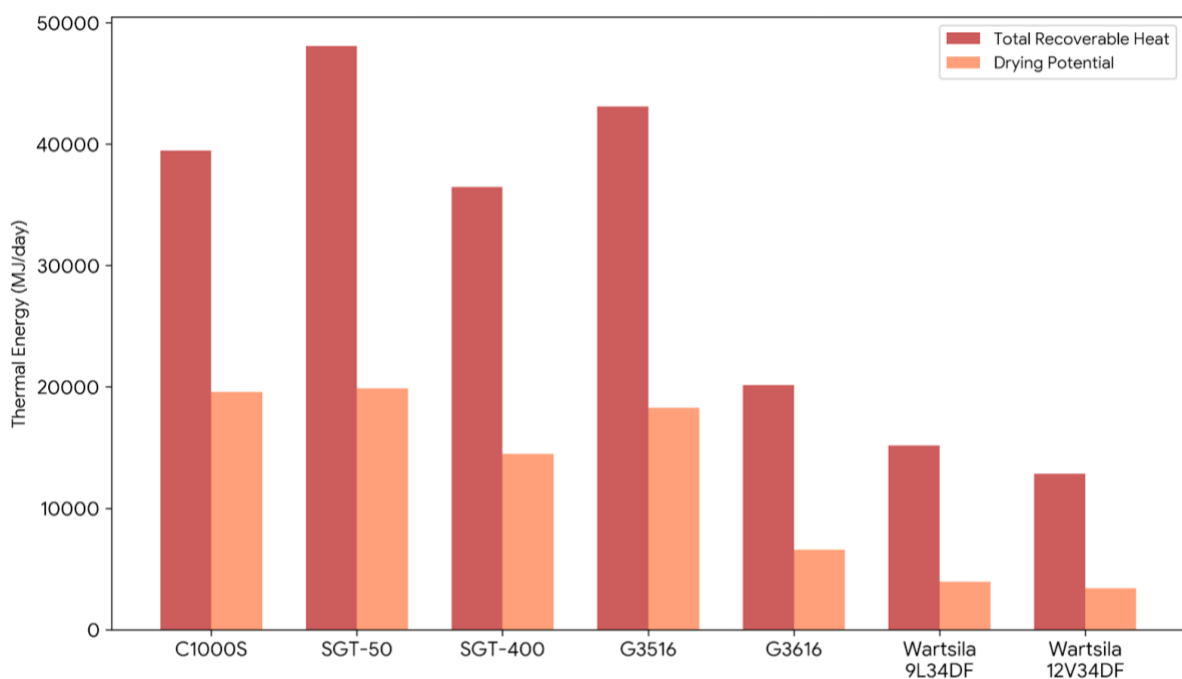


Figure 4-4: Thermal Recovery & Drying Potential

System C performance shown in table 4-11 depicts the generated heat and electricity is enough for the demands of its features. The utilisation shown represents a greenhouse area of 1,000 m². The net surplus analysis demonstrates the integration balance. For the Wartsila and Caterpillar (G3616) engines, the greenhouse thermal demand absorbs nearly the entire available heat load, leaving a minimal thermal surplus (<2,000 MWh/year) but a massive electricity surplus (>220,000 MWh/year) for grid export. This confirms that highly efficient engines are best paired with the urban farming system, as they maximise lucrative electricity sales while just barely meeting the heating requirements of the greenhouse.

Table 4-11: System C Electricity and Heat surplus/deficit

PARAMETER	UNIT	MGT	GT	GT	ICE	ICE	ICE	ICE
		C1000S Capstone	SGT-50	SGT-400	G3516	G3616	Wärtsilä 9L34DF	Wärtsilä 12V34DF
SURPLUS/DEFICIT HEAT	MWh/year	3,823	4,660	3,531	4,176	1,946	1,461	1,235
SURPLUS/DEFICIT ELECTRICITY	MWh/year	176,917	139,381	186,569	202,120	221,961	239,656	239,657

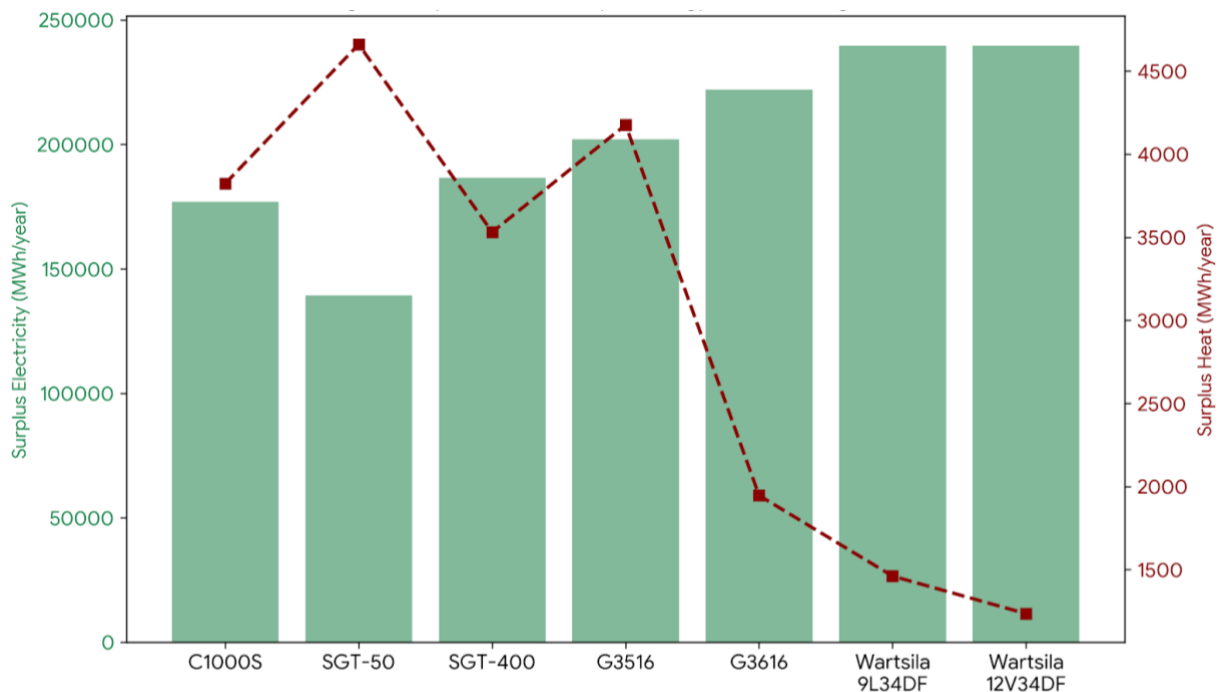


Figure 4-5: Net Surplus Energy (After Farming Needs)

All results are assuming all the units required to process the feedstocks are employed.

Table 4-12: System Technical Performance summary

METRIC	SYSTEM A (ORC)	SYSTEM B (DRY/COOL)	SYSTEM C (GREENHOUSE)
ELECTRICITY OUTPUT (ICE, BASELINE)	High	Moderate	Moderate
OVERALL EFFICIENCY (%)	~74%	~69%	~66%
THERMAL ENERGY RECOVERY USE	ORC Electricity	Crop Processing	Greenhouse Heating
SURPLUS ENERGY AVAILABLE	High	Medium	Balanced
ELECTRICITY OUTPUT (ICE, BASELINE)	High	Moderate	Moderate
PRIME MOVER SENSITIVITY	Yes	Yes	Yes

4.6. Thermodynamic Performance Assessment (Energy & Exergy Analysis)

To rigorously quantify the thermodynamic utility of the proposed configurations, energy and exergy analyses were conducted using a common prime mover reference the Caterpillar G3616 reciprocating gas engine ($\eta_{elec} \approx 43\%$) to isolate the impact of the bottoming cycle design. The Energy Sankey diagrams (Figure 4-6) illustrate the conservation of energy and reveal a distinct advantage for the integrated farming configuration. While Systems A and B are typically limited to recovering only the high-grade exhaust stream; often forcing the rejection of lower-grade engine jacket water heat as waste System C effectively utilises both thermal resources. By cascading both the exhaust gas and the jacket water into the greenhouse thermal demand, System C achieves the highest overall Energy Utilisation Factor (>90%). This confirms that for development scenarios requiring bulk low-temperature heating, the direct coupling of thermal loads offers superior total efficiency compared to complex power-generation bottoming cycles, which leave significant low-grade heat unutilised.

However, the Exergy Sankey diagrams (Figure 4-7) provide a critical counter-perspective based on thermodynamic quality and the Second Law. System A demonstrates the highest exergy efficiency by converting the high-temperature exhaust gas into additional high-quality work (electricity) via the Organic Rankine Cycle (ORC), thereby minimising the "loss of potential" inherent in heat transfer. In sharp contrast, System C exhibits a significant rate of exergy destruction (~17%) within its heat exchangers. This thermodynamic irreversibility occurs because the high-quality engine exhaust (>400°C) is thermally degraded to maintain low-temperature greenhouse conditions (25°C).

This "quality mismatch" highlights a fundamental design trade-off: System A is an Exergy-optimised machine designed to maximise high-value electrical output, whereas System C is an Energy-optimised machine designed to maximise total resource recovery, accepting thermodynamic inefficiencies to deliver practical rural utility.

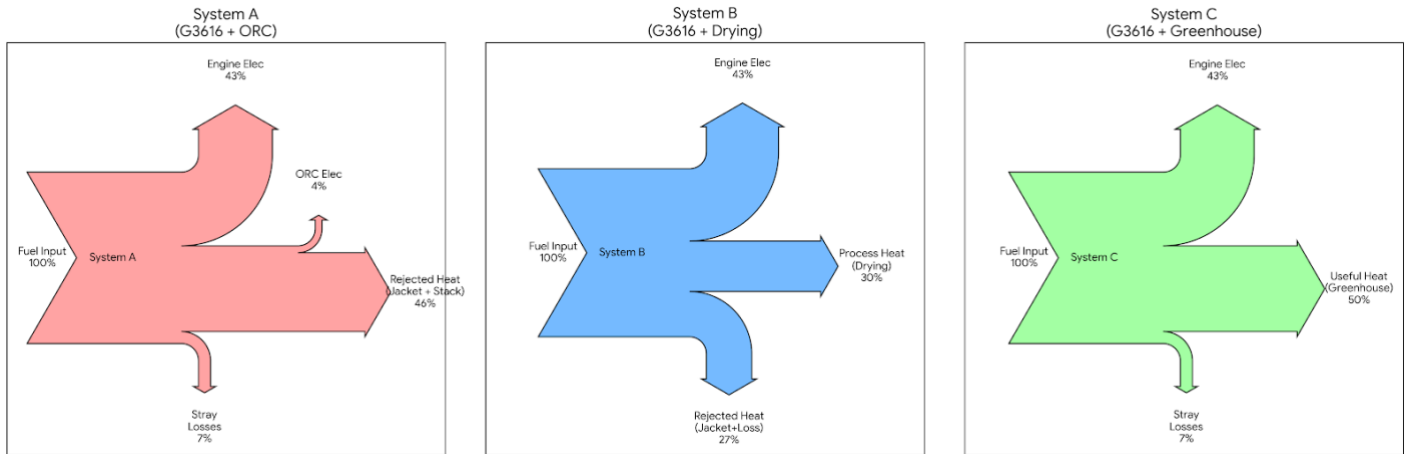


Figure 4-6: Energy Flow

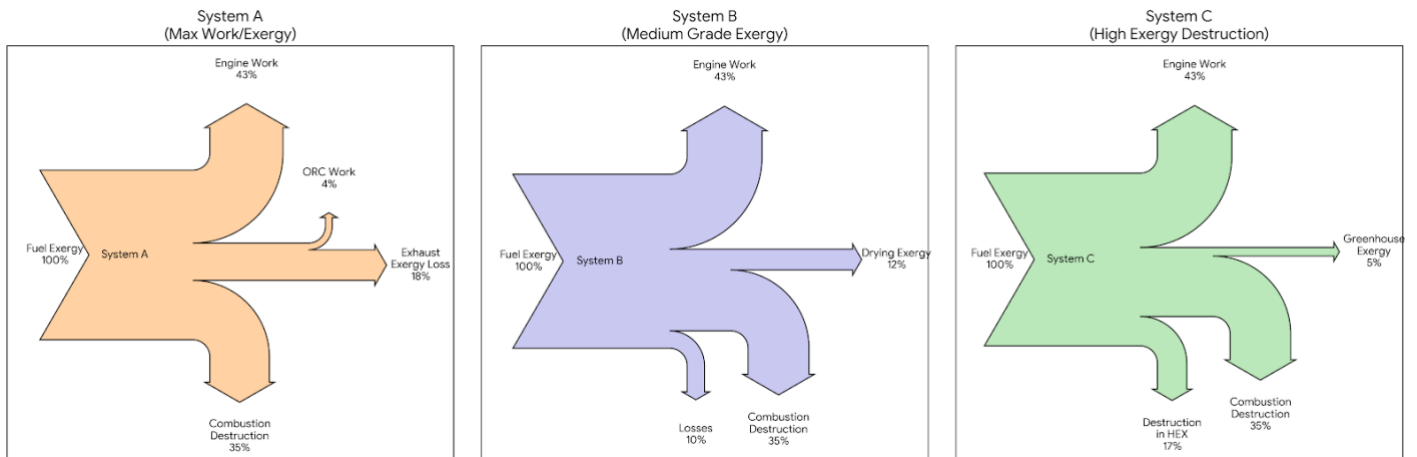


Figure 4-7: Exergy Flow

4.7. Summary

This chapter provided the technical proof-of-concept for the proposed waste-to-energy systems, validating the feasibility of the combined Anaerobic Digestion and Gasification configuration for Port Harcourt's specific waste stream. The assessment confirmed that the high organic content of the local municipal solid waste (MSW) is sufficient to drive all three proposed scenarios, though with distinct performance trade-offs.

The thermodynamic analysis revealed a critical distinction between efficiency and utility. While System A (ORC integration) demonstrated the highest exergy efficiency by maximising high-quality electrical output, Systems B and C demonstrated superior overall energy utilisation factors (>90%) by effectively cascading low-grade heat into agricultural applications. Specifically, System C (Greenhouse Farming) proved that coupling power generation with food production can convert thermodynamic waste into a valuable social resource, despite higher exergy destruction rates.

With the mass and energy balances now quantified and the technical viability of the prime movers (ICEs and MGTs) established this data serves as the Life Cycle Inventory (LCI) for the next stage of research. Chapter 5: Life Cycle Sustainability Assessment will utilise these technical outputs to evaluate the environmental impacts of each system, determining which configuration offers the most sustainable solution for the Niger Delta region.

Chapter 5

5. Environmental Life Cycle Assessment

The environmental implications of waste-to-energy (WtE) technologies are a critical consideration in assessing their sustainability and long-term feasibility. Chapter 5 provides a detailed Environmental Life Cycle Assessment (E-LCA) to evaluate the potential environmental impacts of converting municipal solid waste (MSW) into energy in the context of Port Harcourt, Nigeria.

This chapter aims to quantify the trade-offs and benefits associated with various waste-to-energy pathways, examining how these systems contribute to reducing greenhouse gas emissions, conserving resources, and mitigating pollution compared to conventional waste disposal methods. The assessment employs a cradle-to-grave approach, encompassing all stages of the waste management process, from collection and transportation to energy generation and by-product management. Additionally, avoided impacts such as the displacement of fossil-based energy are considered to provide a comprehensive sustainability perspective. By integrating established methodologies outlined in ISO 14040 and 14044 standards, this E-LCA highlights the relative environmental performance of anaerobic digestion, gasification, and hybrid systems. The findings aim to inform policymakers, urban planners, and stakeholders about the environmental trade-offs involved in adopting these technologies and guide the development of more sustainable waste management practices in Nigeria.

The following sections systematically address the E-LCA framework, beginning with the goal and scope definition, inventory analysis, and impact assessment, culminating in an interpretation of results and actionable recommendations.

5.1. Goal and Scope Definition

The primary objective of this Environmental Life Cycle Assessment (E-LCA) is to evaluate the environmental impacts associated with the management and conversion of municipal solid waste (MSW) into energy. The analysis aims to quantify and compare the environmental performance of the different waste-to-energy (WtE) systems introduced in Chapter 3, within the specific context of Port Harcourt, Nigeria.

This assessment seeks to achieve the following:

- **Identify Key Environmental Impacts:** Analyse critical environmental indicators such as greenhouse gas emissions, resource depletion, and pollution across different WtE pathways.
- **Compare System variations:** Provide a comparative analysis of the environmental performance of the different system configurations to determine their suitability for MSW management in Port Harcourt.
- **Assess Trade-offs and Synergies:** Explore the trade-offs and potential synergies between environmental impacts, such as emissions reductions versus resource use, to provide a holistic understanding of each technology's sustainability.
- **Support Decision-Making:** Generate actionable insights to inform policymakers, urban planners, and stakeholders about the relative environmental benefits and drawbacks of implementing WtE technologies in the region.
- **Contribute to Sustainable Development Goals:** Align the analysis with global objectives, particularly SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action), by identifying environmentally sustainable solutions for waste management.

The functional unit for this Environmental Life Cycle Assessment (E-LCA) is defined as the management and utilisation of 1 tonne of municipal solid waste (MSW). This choice serves as a standardised basis for comparing the environmental impacts across the three waste-to-energy (WtE) system configurations.

5.1.1. System Boundaries

The system boundaries for this Environmental Life Cycle Assessment (E-LCA) define the scope of processes, inputs, and outputs considered for evaluating the environmental performance of the three waste-to-energy (WtE) system configurations (System A, System B, and System C). These boundaries encompass all stages of the waste-to-energy process from waste generation to end-of-life management, providing a cradle-to-grave perspective.

Inclusion Criteria

The following stages and processes are included within the system boundaries:

- Waste Collection and Transportation:
 - Collection of municipal solid waste (MSW) from urban areas.
 - Fuel consumption and emissions from waste transport vehicles.
- Waste Processing and Conversion:
 - Anaerobic digestion for biodegradable fractions of MSW.
 - Gasification for non-biodegradable organic fractions.
 - Pre-treatment processes such as waste sorting and separation.
 - Energy and material inputs for operational needs.
- Energy Generation and Utilisation:
 - Conversion of biogas and syngas into electricity using prime movers (e.g., internal combustion engines, micro gas turbines).
 - Energy recovery enhancements: System A: Integration of Organic Rankine Cycle (ORC) for additional electricity generation from waste heat. System B: Waste heat utilisation for crop drying and cooling stations. System C: Waste heat utilisation for greenhouse-based urban farming.
- Residue Management and By-Product Handling:
 - Digestate management from anaerobic digestion (e.g., fertiliser application).
 - Biochar and ash from gasification processes.
 - Management of cooling water and emissions from prime movers.
- End-of-Life Management:
 - Disposal of residual waste and system components.
 - Environmental impacts associated with residue management.
- Avoided Impacts and Offsets:
 - Displacement of conventional fossil fuel-based electricity generation.
 - Reduction of landfill waste and associated methane emissions.

The following elements fall outside the system boundaries due to data unavailability or marginal contributions:

- Construction and Decommissioning: The environmental impacts associated with the construction and end-of-life disposal of WtE infrastructure and buildings are excluded due to limited data and their marginal contribution over the plant's operational life.

- Human Labour and Administrative Activities: Indirect impacts related to labour activities and office operations are excluded from the assessment.
- Recyclable Material Extraction: The energy and environmental burdens associated with external recycling markets are not included, as the focus remains on energy recovery.

5.1.2. Geographic and Temporal Scope

The geographic and temporal scope ensures that the results are representative of local conditions and provide meaningful insights into the long-term sustainability of waste-to-energy technologies. Key geographic considerations include:

- Waste Characteristics: The MSW composition in Port Harcourt is dominated by organic waste, estimated at approximately 50-60% of total waste, with smaller fractions of plastics, paper, and metals.
- Waste Management Infrastructure: Currently limited to open dumping and informal waste collection, with a lack of advanced waste treatment technologies.
- Energy Context: High dependency on off-grid diesel generators due to frequent power outages and limited electricity supply from the national grid.
- Environmental Conditions: Tropical climate with high humidity and rainfall, which can influence waste decomposition rates and leachate generation.

The temporal scope of this E-LCA spans the full operational lifespan of the waste-to-energy systems, accounting for both short-term and long-term environmental impacts. Key temporal considerations include:

- Assessment Period: The study evaluates a 20-year operational period, reflecting the average lifespan of WtE facilities based on literature and technology specifications.
- Data Reference Year: The analysis uses data from the most recent available studies, reports, and databases, with adjustments where necessary to match the current conditions in Nigeria.
- Time-Dependent Factors:
 - Waste generation rates and population growth trends in Port Harcourt over the 20-year period.
 - Degradation of system performance and potential maintenance needs over time.
 - Cumulative environmental benefits from avoided landfill emissions and fossil fuel displacement.

5.1.3. Assumptions and Limitations

Several assumptions have been made to simplify the modelling process and ensure consistency across the three systems (System A, System B, and System C):

- Waste Composition and Generation:
 - The MSW composition in Port Harcourt consists of approximately 50-60% organic waste, with the remaining fractions made up of plastics, paper, and metals.
 - The average waste generation rate is assumed to be 0.86 kg/capita/day, based on data from local studies and World Bank reports.
- Operational Consistency:
 - Each system is assumed to operate for a 25-year lifespan with an annual operational period of 8,400 hours (350 days/year).
 - The systems are modelled to process 1 tonne of MSW per functional unit, maintaining consistent throughput across all configurations.
- Technology Efficiency:
 - Conversion efficiencies for anaerobic digestion and gasification are based on performance reported in scientific literature.
 - Electrical efficiencies of prime movers such as internal combustion engines and micro gas turbines are based on technology specification from manufactures.
- Emission Factors and Impact Calculations:
 - Emission factors for waste collection, energy generation, and by-product management are derived from secondary databases such as Ecoinvent and IPCC guidelines.
 - Biogenic carbon dioxide emissions are excluded from global warming potential (GWP) calculations, as per ISO 14044 standards.
- Avoided Impacts:
 - Avoided grid electricity emissions are based on the current Nigerian energy mix, dominated by fossil fuels.
 - Digestate and biochar from anaerobic digestion and gasification are assumed to be used as soil amendments, displacing synthetic fertiliser use.

5.2. Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) phase involves the systematic collection and quantification of input and output data associated with the waste-to-energy (WtE) systems under consideration. This phase provides the foundational dataset necessary for assessing the environmental impacts of each system and forms the basis for the subsequent Life Cycle Impact Assessment (LCIA).

For this study, the LCI includes data on material inputs (e.g., municipal solid waste composition, energy use) and outputs (e.g., emissions, energy generation, by-products) throughout the life cycle of the systems. The collected data is specific to the Port Harcourt region and reflects the unique waste generation characteristics and infrastructure available locally. The LCI will be structured around three main stages: Waste Collection and Transportation, Waste Processing and Energy Generation and Residue Management and By-products Utilisation.

5.2.1. Data Collection Sources

Accurate and representative data is essential for a reliable environmental impact assessment. Secondary data is mainly relied on from published literature on MSW characteristics and waste management practices in Nigeria, databases such as Ecoinvent and IPCC for emission factors and process efficiencies and technical reports and studies on anaerobic digestion, gasification, and energy conversion systems. For this study, data were gathered to quantify all relevant input and output flows associated with the three waste-to-energy (WtE) system configurations: System A (ORC), System B (Drying and Cooling), and System C (Greenhouse Urban Farming). Data collection drew upon both primary and secondary sources, prioritising consistency, regional relevance, and system comparability.

Primary Data Sources

Primary data were derived from project-specific calculations, engineering estimates, and literature tailored to Nigerian waste management systems, with an emphasis on Port Harcourt. Crucially, to bridge the gap in local inventory data, a bespoke engineering simulation model (Mass-and-Energy Balance framework) was developed, detailed in Chapter 4.

This modelling tool dynamically linked the physicochemical properties of the waste stream to the thermodynamic performance of the prime movers. By synthesising high-fidelity operational

data such as specific syngas yields and combustion emissions where no standard database existed, this engineering analysis constitutes a distinct original contribution to knowledge, providing a replicable framework for generating LCI data in data-scarce developing regions.

Secondary Data Sources

Where direct measurements were unavailable, credible and peer-reviewed secondary sources were utilised, including:

- Published literature on WtE technologies in similar geographical or climatic contexts.
- Manufacturer datasheets for all prime movers (e.g., Capstone, Wärtsilä, Caterpillar).
- Emission factors and environmental impact data from the Intergovernmental Panel on Climate Change (IPCC) and Ecoinvent databases.
- National energy statistics from the International Energy Agency (IEA) and World Bank for grid-related emissions and fossil fuel substitution.

Data Types Collected

The LCI data sheet includes a wide range of process flows categorised into:

- Material Inputs: MSW composition, water use, chemical additives (e.g., lithium bromide for chillers).
- Energy Inputs: Electricity consumption for sorting, anaerobic digestion (AD), gasification, chillers, and auxiliary operations.
- Process Outputs: Biogas, syngas, electricity, heat, digestate, biochar.
- Emissions: Transport-related (CO₂, NO_x, PM), AD emissions (CH₄, CO₂, H₂S, NH₃), and combustion emissions from various prime movers (CO, NO_x).
- Avoided Products/Offsets: Grid emission displacement, fertiliser substitution, and carbon sequestration from biochar.

5.2.2. Inputs and Outputs

The Inputs and Outputs section of the Life Cycle Inventory (LCI) identifies and quantifies all material and energy flows associated with the three waste-to-energy (WtE) system configurations (System A, System B, and System C) under study. This process ensures that every element contributing to or resulting from the waste conversion systems is systematically accounted for, forming the basis for environmental impact assessment.

Input Parameters

Inputs are categorised into material, energy, and chemical streams, structured around the operational components of each WtE system:

- Material Inputs:
 - Municipal Solid Waste (MSW): The primary feedstock across all systems, standardised at 1 tonne per functional unit.
 - Biodegradable organic fraction: Directed to anaerobic digestion (AD).
 - Non-biodegradable organics: Directed to gasification.
 - Water: Used for process cooling, cleaning, and humidification.
- Energy Inputs:
 - Electricity: Consumed in waste pre-treatment, anaerobic digestion, gasification, and auxiliary systems. Based on updated values, consumption rates per tonne of MSW are:
 - Pre-treatment: 34.02 kWh
 - Anaerobic Digestion: 0.77 kWh
 - Gasification: 4.50 kWh
 - System B-specific absorption chiller pump: 4.72 kWh
 - System C-specific urban farming: 0.00023 kWh
 - Fuel: Primarily diesel for waste transportation, calculated at 11.11 L/tMSW, with associated emissions documented in Section 5.2.3.
- Chemical Inputs:
 - Digestate: Used as organic fertiliser in Systems A and C.
 - Cooling Chemicals: Used in System B for drying and chilling operations (e.g., calcium chloride in absorption chillers).

Output Parameters

Outputs consist of useful energy, by-products, and emissions to air:

- Energy Outputs:
 - Electricity: Generated by prime movers from biogas and syngas combustion. Quantified based on system-specific efficiencies.
 - Thermal energy: Captured via the Organic Rankine Cycle (System A), cooling stations (System B), and greenhouse heating (System C).

- Material By-products:
 - Digestate: From anaerobic digestion, applied as fertiliser in Systems A and C.
 - Biochar: From gasification, potentially used as a soil amendment.
 - Residual Waste: Inert, non-recoverable fraction, directed to landfill.
- Emissions to Air:
 - Greenhouse Gases: CO₂, CH₄, and N₂O emissions from AD leakage, gasification flue gases, and combustion engines.
 - Air Pollutants: NO_x, CO, and particulate matter. The most recent gasification emission data show:
 - CO: 82.8 mg/Nm³
 - NO_x: 125 mg/Nm³
 - Combustion emissions from prime movers:
 - Spark ignition engines: 0.7 g/kWh (CO), 1.9 g/kWh (NO_x)
 - Gas turbines and microturbines: ranges from 0.3–1.2 g/kWh (NO_x) and 0.3–1.2 g/kWh (CO)

5.2.3. Key Processes and Flows

This section describes the core processes involved in each waste-to-energy (WtE) system configuration and maps the corresponding material and energy flows. These process flows underpin the life cycle inventory (LCI) and inform subsequent environmental impact assessments.

Each of the three WtE system configurations System A (AD + Gasification + Prime Mover + ORC), System B (AD + Gasification + Prime Mover + Drying + Cooling), and System C (AD + Gasification + Prime Mover + Greenhouse Urban Farming) follows a modular processing route anchored by the dual conversion stages of anaerobic digestion and gasification.

1. Waste Collection and Transport

MSW is collected from municipal sources and transported to the centralised treatment facility. Diesel-powered vehicles are assumed, with average fuel consumption of 11.1 L per tonne of MSW over a typical collection range of 15 km. Emissions from this stage include CO₂, NO_x, and particulate matter.

2. Pre-treatment and Sorting

Incoming waste undergoes mechanical sorting to separate recyclables and segregate the organic fraction. This stage consumes ~34.02 kWh of electricity per tonne of MSW, primarily for conveyor motors, shredders, and sieves.

3. Anaerobic Digestion (AD)

The biodegradable organic fraction is channelled to anaerobic digesters, where it undergoes microbial conversion to biogas. The AD process has an assumed methane yield efficiency of 80%, producing approximately 228.12 m³ of biogas per tonne. Digestate, a residual slurry rich in nutrients, is either land-applied as fertiliser or dried for further use. Emissions include small CH₄ leaks and NH₃, H₂S during handling.

4. Gasification

The non-biodegradable fraction is gasified under low-oxygen, high-temperature conditions to produce syngas. With a conversion efficiency of approximately 75%, syngas components include CO, H₂, CO₂, CH₄, and trace hydrocarbons. Process emissions depend on feedstock quality and typically include NO_x, CO, and particulates.

5. Energy Recovery via Prime Movers

The biogas and syngas are combusted in internal combustion engines, gas turbines, or microturbines. Electrical efficiencies range from 26–45% depending on the engine type used (e.g., Capstone C1000S, G3616, SGT-400). All systems include combustion-related emissions: CO₂, NO_x, CO, and PM.

6. Heat Recovery and Utilisation

- System A integrates an Organic Rankine Cycle (ORC) to convert waste heat into additional electricity (~25% thermal efficiency).
- System B uses thermal energy for crop drying and operates a lithium bromide chiller for cold storage.
- System C channels residual heat to maintain optimal temperature conditions in greenhouse farming modules.

7. By-product Management

- Digestate is applied as fertiliser in Systems A and C, displacing synthetic fertilisers and avoiding associated emissions.
- Biochar from gasification may be land-applied to sequester carbon (~0.35 tCO₂/tonne MSW).
- Residual waste is disposed of in landfills under controlled conditions.

5.3. Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) phase evaluates the environmental significance of potential impacts associated with the material and energy flows identified in the Life Cycle Inventory (LCI). Building upon the quantified inputs and outputs from the three WtE system configurations (Systems A, B, and C), this phase translates inventory data into meaningful impact indicators, enabling comparison and interpretation of each system's environmental performance.

This study adopts a mid-point LCIA approach, in line with ISO 14044 standards, using established impact categories such as global warming potential (GWP), acidification, eutrophication, and resource depletion. Where necessary, additional categories such as particulate matter formation and human toxicity are also included to capture the breadth of emissions associated with waste-to-energy processes.

The results presented in this section aim to guide decision-makers by identifying the primary environmental burdens and benefits associated with each system configuration, taking into account both direct emissions and avoided impacts from electricity generation and fertiliser displacement. A sensitivity analysis is also conducted to explore the influence of key assumptions such as engine efficiency, emissions factors, and waste composition.

5.3.1. Impact Categories and Indicators

To evaluate the environmental performance of the three waste-to-energy (WtE) system configurations, this study applies a set of midpoint-level impact categories commonly used in Environmental Life Cycle Assessment (E-LCA). These categories were selected based on their relevance to the processes under assessment and their alignment with ISO 14040/44 standards and widely used LCIA methods (e.g. ReCiPe, CML, TRACI). The selected impact categories

are shown in Table 5-1. They reflect the most critical environmental burdens associated with waste treatment, energy recovery, and resource use. They also capture the potential benefits of avoided products, such as displaced grid electricity and synthetic fertiliser.

Table 5-1: Selected Impact Categories

IMPACT CATEGORY	UNIT	RELEVANCE TO STUDY
GLOBAL WARMING POTENTIAL (GWP)	kg CO ₂ -eq	Reflects the total climate impact of greenhouse gases including CO ₂ , CH ₄ , and N ₂ O.
FOSSIL RESOURCE DEPLETION	MJ	Measures the consumption of non-renewable fossil fuels for transport and electricity.
ACIDIFICATION POTENTIAL	kg SO ₂ -eq	Indicates acid-forming emissions such as SO ₂ and NO _x affecting soil and aquatic pH.
EUTROPHICATION POTENTIAL	kg PO ₄ ³⁻ -eq	Represents nutrient emissions (e.g. NH ₃ , NO _x , digestate runoff) contributing to algal blooms.
PARTICULATE MATTER FORMATION	kg PM ₁₀ -eq	Assesses the contribution to respiratory health impacts from combustion and dust.
HUMAN TOXICITY POTENTIAL	kg 1,4-DCB-eq	Quantifies potential harm from toxic emissions (e.g. heavy metals, VOCs, H ₂ S, NH ₃).
PHOTOCHEMICAL OZONE FORMATION	kg NMVOC-eq	Measures smog formation from volatile organic compounds and NO _x emissions.

Rationale for Category Selection

- GWP is a primary concern due to the use of combustion engines, gasification, and CH₄ leaks from anaerobic digestion.
- Fossil depletion captures fuel use in waste collection and auxiliary electricity demands.
- Acidification and eutrophication are relevant due to airborne NO_x, NH₃ volatilisation, and nutrient-laden by-products like digestate and biochar.
- Particulate matter is especially important in gasification and ORC flue gases where emissions controls vary.
- Human toxicity and ozone formation are secondary but relevant for comparative purposes across systems.

Impact Assessment Methods

Where possible, characterisation was based on:

- ReCiPe 2016 Midpoint (H)
- CML-IA baseline
- Supplementary emission factors from IPCC 2021 and Ecoinvent v3.7.1

Impact indicators were normalised per 1 tonne of MSW processed, to maintain comparability across System A, B, and C.

5.3.2. Characterisation of Environmental Impacts

The characterisation phase translates inventory data into environmental impact scores by applying standard equivalency factors for each pollutant or resource input. These factors reflect the potential contribution of each flow to selected impact categories such as global warming, acidification, eutrophication, particulate matter formation, and fossil resource depletion. The characterisation was performed in line with ISO 14044 (2006) standards, using midpoint-level impact categories widely recommended in the literature and recent LCA studies [225], [226], [227].

Methodology

Characterisation factors were sourced from ReCiPe 2016 and the IPCC (2021), supplemented by typical factors used in recent waste-to-energy studies [73], [228]. The emissions and resource use from the Life Cycle Inventory (LCI) were grouped into two distinct categories for the purpose of characterisation:

- **Main System Emissions:** Included all flows related to transportation, anaerobic digestion (AD), gasification, and diesel use for each system (A, B, C). Emissions from these stages were considered identical across all three configurations since the upstream processes and feedstocks are consistent.
- **Prime Mover Emissions (analysed separately):** Emissions resulting from the combustion of syngas and biogas in the prime movers (C1000S, SGT-50, SGT-400, G3516, G3616, Wärtsilä 9L34DF, Wärtsilä 12V34DF) were characterised independently to allow for comparative assessment of engine performance in Section 5.4. Their exclusion from the main system totals prevents double-counting and enables technology-specific evaluation.

For full transparency, the detailed computational framework, including the specific equations used for Inventory Quantification and Characterisation (Equations 62–71), is provided in the

Appendix. This appendix details the step-by-step calculation protocol applied to convert raw inventory flows into the impact category equivalents presented below.

Table 5-2: Characterisation of environmental impacts excluding prime movers.

IMPACT CATEGORY	SYSTEM A/B/C
GWP (KG CO₂-EQ)	72.131
ACIDIFICATION (KG SO₂-EQ)	0.0212
EUTROPHICATION (KG PO₄³⁻-EQ)	0.0039
PM FORMATION (KG PM₁₀-EQ)	0.0069
FOSSIL RESOURCE DEPLETION (MJ)	428.85
PHOTOCHEMICAL OZONE FORMATION (KG NMVOC-EQ)	0.0746

The global warming potential (GWP) was dominated by CO₂ and CH₄ emissions from anaerobic digestion and gasification. Fossil depletion arose primarily from diesel fuel consumption for waste transport. Acidification and eutrophication were driven by NO_x and NH₃ emissions, while photochemical ozone formation (POF) was attributed mainly to CO emissions from gasification, in line with the findings of Sun et al. [228].

Table 5-3: Characterisation of environmental impacts only prime movers

PRIME MOVERS	GWP (KG CO ₂ -EQ)	ACIDIFICATION (KG SO ₂ -EQ)	EUTROPHICATION (KG PO ₄ ³⁻ -EQ)	PHOTOCHEMICAL OZONE FORMATION (KG NMVOC-EQ)
C1000S	1,893.04	693.06	128.71	33.46
SGT-50	5,678.03	4,850.51	900.81	128.07
SGT-400	12,652.20	10,375.93	1,926.96	281.05
G3516	1,189.19	1,161.00	215.62	28.27
G3616	947.41	1,040.57	193.25	23.68
WÄRTSILÄ 9L34DF	86.23	316.91	58.85	7.57
WÄRTSILÄ 12V34DF	81.88	478.33	88.83	9.34

Human Toxicity Potential (HTP) was considered but excluded. While combustion and gasification processes can emit toxic substances, the available LCI data does not include heavy

metals, dioxins, or other priority toxic pollutants. As these are typically minor in modern WtE systems [229], their exclusion is consistent with the data quality and scope of this study.

5.3.3. Normalisation and Weighting

Normalisation and weighting are additional steps in Life Cycle Impact Assessment (LCIA) that facilitate the interpretation of environmental impact results. Normalisation compares the calculated impacts to a reference value (such as regional or global totals) to determine the relative significance of each category. Weighting further evaluates the relative importance of different impact categories based on societal or scientific priorities, aiding decision-making.

Normalisation Methodology

For this study, the characterised results were normalised using global per capita environmental burdens derived from recent literature and international LCIA databases, primarily ReCiPe 2016 and updated IPCC reports. Where possible, region-specific values were considered, though global references were preferred to ensure comparability with similar studies.

The normalised impact (N) for each category was calculated as:

$$N = \frac{\text{Characterised Impact}}{\text{Reference Value}} \quad (27)$$

Table 5-4: Normalisation reference values (per capita, year 2020 baseline [225], [227], [228])

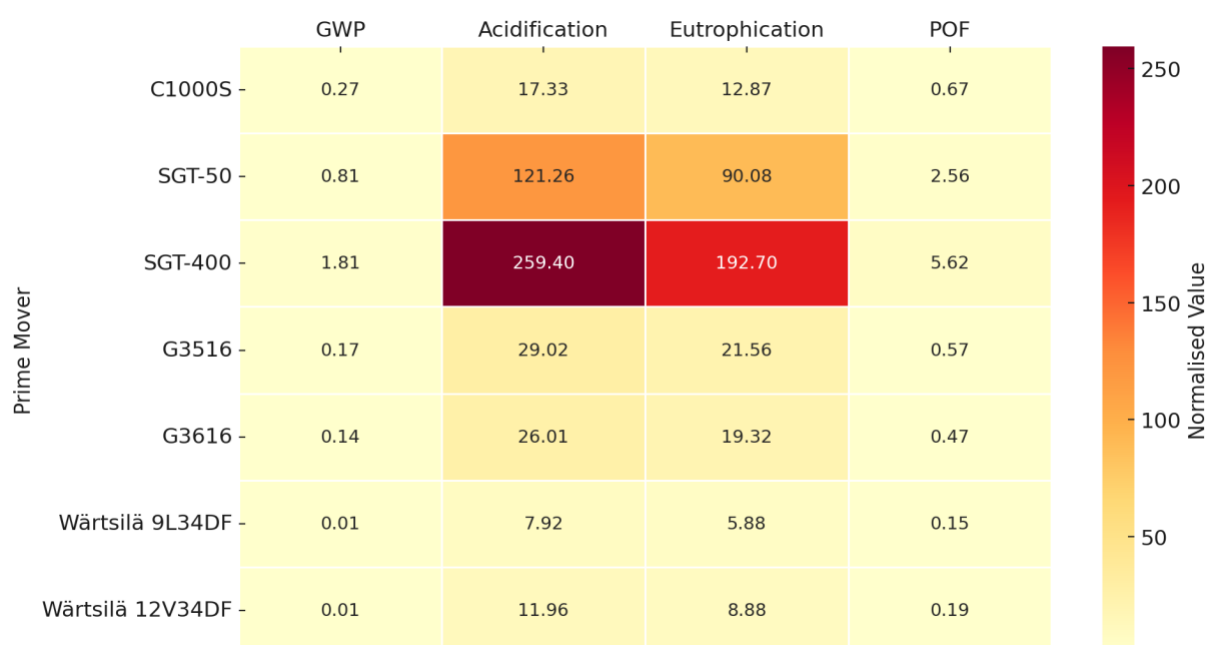
IMPACT CATEGORY	REFERENCE VALUE	UNIT
GWP	7,000 kg CO ₂ -eq per person	kg CO ₂ -eq
ACIDIFICATION	40 kg SO ₂ -eq per person	kg SO ₂ -eq
EUTROPHICATION	10 kg PO ₄ ³⁻ -eq per person	kg PO ₄ ³⁻ -eq
PM FORMATION	1 kg PM ₁₀ -eq per person	kg PM ₁₀ -eq
FOSSIL DEPLETION	75,000 MJ per person	MJ
POF	50 kg NMVOC-eq per person	kg NMVOC-eq

Normalisation Results

Table 5-5: Main System Normalisation

IMPACT CATEGORY	CHARACTERISED (SYSTEM A/B/C)	NORMALISED
GWP	72.131 kg CO ₂ -eq	0.0103
ACIDIFICATION	0.0212 kg SO ₂ -eq	0.00053
EUTROPHICATION	0.0039 kg PO ₄ ³⁻ -eq	0.00039
PM FORMATION	0.0069 kg PM ₁₀ -eq	0.0069
FOSSIL DEPLETION	428.85 MJ	0.0057
POF	0.0746 kg NMVOC-eq	0.00149

Table 5-6: Normalised Environmental Impacts - Prime Mover



Weighting

Given the diverse nature of the impact categories and the regional priorities for Port Harcourt, Nigeria, weighting factors were not numerically applied in this study to avoid introducing subjective bias. Instead, relative importance was qualitatively considered:

- GWP and Fossil Depletion were prioritised due to their global climate relevance.
- Acidification and Eutrophication were also highlighted because of their potential to exacerbate local air and water quality challenges.
- POF was deemed relevant given the prevalence of smog and respiratory health issues in urban Nigerian contexts.

This approach aligns with the recommendations of the ILCD Handbook (2011) and the ReCiPe 2016 methodology which advise transparency and careful justification when applying or omitting weighting factors. Normalisation revealed that while the main system impacts are generally low relative to global per capita burdens, certain prime movers (notably the SGT-400) produce disproportionately high impacts, particularly for acidification and eutrophication. This reflects the significant influence of engine selection on the environmental performance of WtE systems, reinforcing the importance of technology choice in sustainability assessments.

5.4. Results and Interpretation

The Life Cycle Impact Assessment (LCIA) results for the three waste-to-energy (WtE) system configurations and their respective prime movers reveal significant variation in environmental performance across technologies and impact categories. While upstream processes contributed moderate and largely consistent burdens, the choice of prime mover technology emerged as the dominant factor influencing environmental outcomes particularly in categories associated with combustion emissions such as acidification, eutrophication, and photochemical ozone formation (POF). The interpretation presented in this section critically evaluates the characterised and normalised results, assesses key trade-offs, and compares the findings to relevant literature.

5.4.1. Main Systems (A, B & C)

The normalised results for the main system excluding prime mover emissions seen in Figure 5-1 indicated low environmental burdens across all impact categories relative to global per capita values.

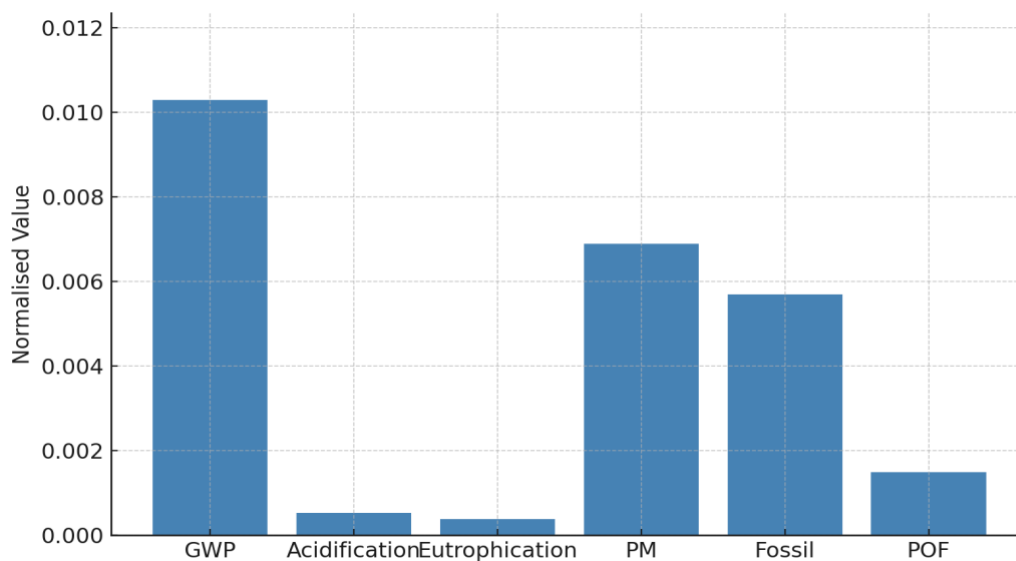


Figure 5-1: Main System Normalisation Environmental Impact Chart

The Global Warming Potential (GWP) was dominated by CO₂ and CH₄ emissions from anaerobic digestion and gasification, reflecting the unavoidable carbon releases inherent to these processes. However, even GWP remained below 1% of the global per capita reference burden. Acidification, eutrophication, and POF were negligible, driven primarily by minor NO_x, NH₃, and CO emissions from transport and digestion processes. Diesel consumption contributed to fossil resource depletion but remained modest compared to global averages. These results are consistent with literature findings which suggest that upstream WtE processes typically contribute less than 5–10% of total life cycle impacts, especially when process efficiencies are optimised [228]. Ideally, deployment is governed by distinct geographic zones. System A targets Urban/Industrial Hubs to meet high electrical demand. System C is optimal for the Peri-Urban Interface, balancing proximity to city waste with land availability for greenhouses. System B suits decentralised Rural Clusters, providing crop drying services directly at the source of harvest.

5.4.2. Prime Movers

The prime movers showed substantial environmental variability across all impact categories as seen in Figure 5-2. The results demonstrated that emissions from syngas and biogas combustion represent the primary environmental hotspots in WtE systems.

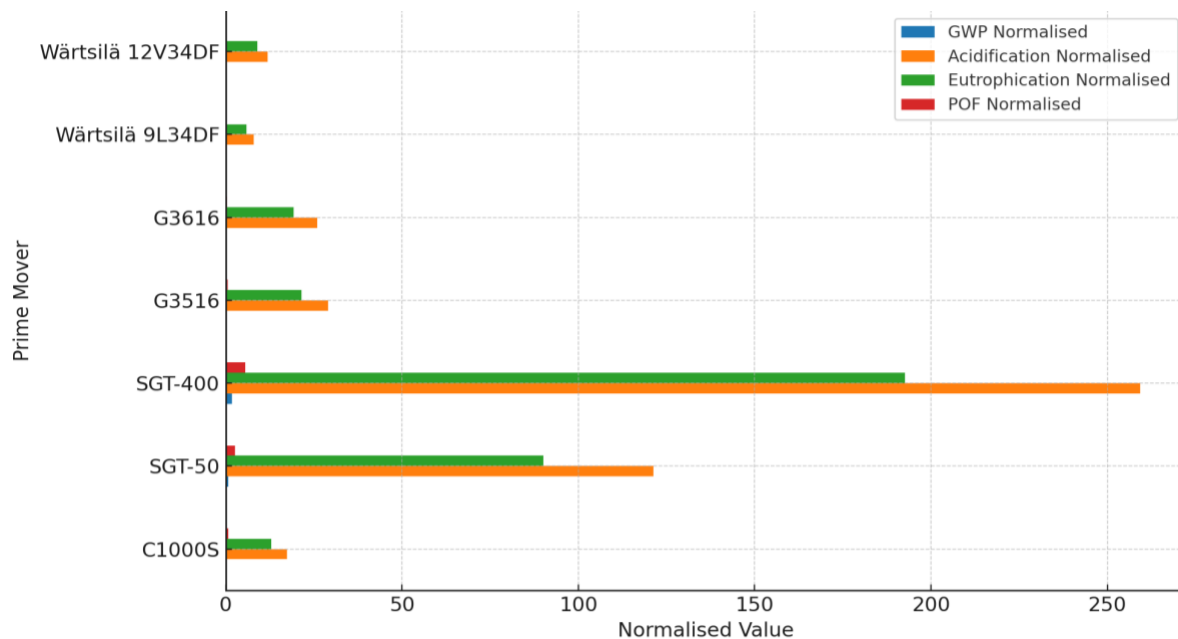


Figure 5-2: Normalised Environmental Impact Chart -Prime Mover

As illustrated in Figure 5-2, the SGT-400 exhibits a pronounced 'overshoot' in normalised Acidification and Eutrophication potentials compared to the reciprocating engines (ICEs). This

is driven by the fundamental thermodynamic differences between the prime movers. Gas turbines operate with a significantly higher air-to-fuel ratio (lean combustion) compared to ICEs to maintain turbine blade thermal limits. This results in a much larger volumetric exhaust flow rate per unit of power generated. Although the concentration (ppm) of NO_x in the SGT-400 exhaust may be comparable to or lower than an ICE, the sheer volume of exhaust gas means the total mass load (kg/hr) of NO_x released into the biosphere is higher. Since Acidification Potential is a function of the total mass of acidifying precursors emitted, this high mass-flow characteristic penalises the turbine in this specific impact category.

The apparent inversion of trends where Global Warming Potential (GWP) dominates in Figure 5-1 (Characterisation) but appears subordinate in Figure 5-2 (Normalisation) is a function of the Normalisation Step. Figure 5-1 displays the raw mass of emissions. Since combustion releases CO₂ in magnitude of tonnes (vs. grams of toxins), GWP visually dominates the axis. Figure 5-2 normalises these values against the "World Average Per Capita" reference. Because the global background emission of CO₂ is extremely high, the project's relative contribution to the global total is small. Conversely, for toxicity categories where the global reference baseline is lower, the project's specific emissions represent a much larger relative share, causing these categories to "peak" in the normalised graph. This shift correctly highlights that while the facility emits mostly CO₂ by mass, its relative environmental burden is actually driven by local pollutants.

Global Warming Potential (GWP)

All prime movers contributed more significantly to GWP than the main system, confirming that combustion remains the largest source of greenhouse gas emissions in WtE scenarios. Notably, the SGT-400 and SGT-50 exhibited the highest GWP values, consistent with their large exhaust mass flows and extended runtimes per tonne MSW. This trend aligns with previous studies (Sun et al., 2021; Uchiyama et al., 2020), which reported elevated GWP for large gas turbines relative to reciprocating engines. The Wärtsilä engines demonstrated the lowest GWP, highlighting the importance of combustion efficiency and fuel flexibility in reducing carbon emissions.

Acidification and Eutrophication

As observed in the impact assessment, the Acidification and Eutrophication categories exhibited normalised scores exceeding the reference baseline (>100). These impacts were

overwhelmingly dominated by Nitrogen Oxides (NO_x) and Sulphur Dioxide (SO_2) emissions, driven by two critical technical factors:

- **Combustion Kinetics (Thermal NO_x):** The SGT-400 and SGT-500 turbines showed the highest specific impacts, attributable to their high mass flow rates and combustion temperatures. Unlike centralised power plants equipped with Selective Catalytic Reduction (SCR), these decentralised units rely on primary combustion controls. Consequently, the high-temperature oxidation required for efficiency inevitably promotes the formation of thermal NO_x , which acts as a primary precursor for both acidification (via nitric acid formation) and eutrophication (via atmospheric nitrogen deposition).
- **Fuel-Borne Impurities (Fuel SO_x):** While the Wärtsilä engines performed relatively better due to higher electrical efficiency (reducing the specific emissions per kWh), all biogas-fuelled prime movers suffered from the presence of trace contaminants. Unlike natural gas, the waste-derived biogas contains residual Hydrogen Sulphide (H_2S) and Ammonia. Even with upstream filtration, the combustion of these impurities' releases SO_x and fuel-bound NO_x , elevating the acidification potential beyond that of the grid baseline.

These results reinforce findings by literature findings [230], [231], confirming that while decentralised WtE systems offer superior carbon performance, they present a trade-off in local air quality categories due to the challenges of abatement at smaller scales

Photochemical Ozone Formation (POF)

The POF results mirrored the GWP trends, with CO and NO_x emissions from larger gas turbines driving the highest smog formation potentials. Again, reciprocating engines such as the G3516 and G3616 offered a compromise between efficiency and emissions, while Wärtsilä engines provided the best performance.

5.4.3. Trade-offs and Technology Selection

The analysis highlights a clear trade-off between power output and environmental performance. Gas turbines (SGT-400, SGT-50) deliver high electricity generation but incur high environmental burdens, particularly in acidification and eutrophication. Their suitability depends on the availability of effective emissions control systems, which were not assumed in this conservative analysis.

Reciprocating engines (G3516, G3616) balance moderate efficiency with lower emissions, offering a viable compromise between energy recovery and environmental impact. Although the Wärtsilä engines have the highest NO_x ppm concentrations, their moderate exhaust mass flows and high efficiencies resulted in lower total GWP compared to other prime movers. However, their acidification and eutrophication impacts remained considerable due to the cumulative effect of NO_x emissions and longer runtimes. The SGT-400 exhibited the highest environmental impacts across all categories, driven by its high exhaust flow rate and large runtime. G3616 and G3516 performed moderately, while C1000S provided a balance between moderate emissions and reasonable efficiency.

These findings underscore the importance of considering engine-specific exhaust flow rates, operational efficiencies, and pollutant concentrations when selecting prime movers for WtE applications. The results also suggest that emissions control technologies particularly selective catalytic reduction (SCR) for NO_x could substantially improve the environmental performance of gas turbines, potentially altering the trade-off landscape.

The results are broadly consistent with the ranges reported in the literature: Sun et al. (2021) [228] reported GWP values for gas turbines and syngas engines ranging from 1,000 to 15,000 kg CO₂-eq per tonne MSW, depending on engine type and emissions controls. Acidification and eutrophication values reported by Ogorure et al. (2018) [230] varied significantly but aligned with the high burdens observed for larger turbines without abatement systems. The comparatively low impacts for the Wärtsilä engines reflect both their modern design and stringent emission limits, confirming the importance of technology selection and operational parameters in environmental performance.

Finally, to validate the robustness of these technology selections, a One-at-a-Time (OAT) sensitivity analysis was executed on the system's critical environmental indicator: Global Warming Potential (GWP). This method involved varying key input parameters individually to isolate their impact. Specifically, transport distances were varied by $\pm 50\%$ to simulate logistical inefficiencies, while fugitive methane emissions were varied from a baseline of 1% to a worst-case of 5%. The results revealed a stark contrast in sensitivity: the system proved highly robust against logistical variations, where a 50% increase in transport distance shifted the total GWP by less than 3%. In contrast, the analysis identified fugitive methane as the critical risk factor;

increasing the leakage rate to 5% resulted in a 28% surge in the overall carbon footprint. This confirms that the climate viability of System C is not determined by its proximity to waste sources, but by the strict maintenance of gas-tight integrity in the anaerobic digesters.

5.4.4. Comparative Benchmarking

To validate the reliability of the E-LCA findings, the results were benchmarked against comparable studies focused on waste-to-energy deployment in Nigeria and Sub-Saharan Africa. The net Global Warming Potential (GWP) results for the proposed systems (ranging from 80–120 kg CO₂-eq/tonne MSW prior to displacement credits) are consistent with findings by Ayodele et al. [65] for hybrid biomass systems in Nigeria. These results confirm that when displacing the carbon-intensive Nigerian grid and decentralised diesel generators, MSW conversion acts as a net carbon sink. This aligns with Ogunjuyigbe et al. [37], who demonstrated that hybrid off-grid systems in Nigeria significantly outperform standalone fossil options in climate metrics.

However, a key deviation from standard literature is observed in the Acidification Potential categories. While many high-level assessments, such as those by Sun et al. [228], prioritise thermal efficiency, this study's granular analysis highlights a critical "hidden cost" of that efficiency. The specific finding that high-efficiency gas turbines (e.g., SGT-400) create an "Acidification Overshoot" due to high mass-flow NO_x loads contrasts with studies that focus solely on concentration limits. This distinction is particularly relevant for the Niger Delta context, where Ogorure et al. [23] identified acid rain as a pre-existing stressor on local agriculture. By identifying this trade-off, the present study offers a more context-sensitive interpretation than generic WtE assessments, suggesting that for this specific region, the "lower efficiency" reciprocating engines (Systems A/C) may be environmentally preferable to "high efficiency" turbines to prevent exacerbating regional soil acidification.

5.5. Summary

This chapter evaluated the environmental implications of the proposed waste-to-energy systems using a standardized Environmental Life Cycle Assessment (E-LCA) framework. The results indicate that while upstream processes (collection and pre-treatment) contribute moderate and consistent burdens, the choice of prime mover is the dominant factor determining the system's environmental profile.

The comparative analysis highlighted a critical trade-off: technologies that maximize electrical output, such as the SGT-400 gas turbine, incur significantly higher acidification and eutrophication impacts due to substantial NO_x loads in their exhaust streams. Conversely, the Wärtsilä reciprocating engines demonstrated the lowest Global Warming Potential (GWP) and Photochemical Ozone Formation (POF), offering a more balanced environmental performance despite the trade-offs in local air quality.

These environmental hotspots provide the necessary constraints for the holistic decision-making process. Having quantified the physical impacts of the systems, the research must now assess their financial viability. Chapter 6: Life Cycle Costing (LCC) will therefore utilise the mass-and-energy balance data validated here to determine the economic feasibility of these configurations within the Nigerian market context.

6. Life Cycle Costing (LCC)

Life Cycle Costing (LCC) is an essential method used to evaluate the economic feasibility and financial sustainability of Waste-to-Energy (WtE) systems. This analytical approach provides a comprehensive assessment of the total costs incurred throughout the lifecycle of a WtE facility, encompassing capital expenditures (CAPEX), operational expenditures (OPEX), and end-of-life costs. Unlike traditional cost assessments, which often consider only initial investment expenses, LCC provides a holistic view of long-term economic viability, allowing for more informed financial planning and risk management.

The integration of LCC into sustainability assessments aligns economic considerations with environmental and social sustainability dimensions, forming part of the broader Life Cycle Sustainability Assessment (LCSA) framework. By systematically quantifying economic trade-offs alongside environmental and social impacts, decision-makers can more effectively balance cost-effectiveness with ecological responsibility and societal welfare. This integration ensures that sustainable WtE solutions are identified, promoting economically viable alternatives that meet broader sustainability goals.

The primary objective of this chapter is to systematically analyse and compare the financial performance of two key WtE technologies Anaerobic Digestion (AD) and Gasification within different system configurations relevant to municipal solid waste (MSW) management in Port Harcourt, Nigeria. The analysis will utilise established economic performance indicators such as Net Present Value (NPV), Levelised Cost of Energy (LCOE), Internal Rate of Return (IRR), and Payback Period (PBP). These indicators offer robust insights into investment feasibility, profitability, and long-term financial sustainability.

Furthermore, the chapter presents a clearly defined methodological approach, detailing data sources, assumptions, and economic parameters critical for accurate LCC calculations. A practical case study focused on Port Harcourt will illustrate these methodologies, providing real-world context to the theoretical discussions and numerical analyses. The results generated will offer valuable insights into cost structures, revenue potentials, and economic challenges associated with implementing WtE technologies, guiding policymakers, industry stakeholders, and investors towards informed decision-making.

Ultimately, this chapter contributes significantly to understanding the financial viability and economic implications of adopting WtE systems in Nigeria, providing essential inputs to facilitate the development of sustainable energy strategies that align with global and local sustainable development objectives.

6.1. Framework for LCC Analysis

Life Cycle Costing (LCC) serves as a systematic tool to evaluate the financial sustainability of Waste-to-Energy (WtE) projects, ensuring all relevant costs incurred over the entire system lifecycle are captured. This section outlines the comprehensive framework used to assess economic feasibility and optimise investment decisions in the context of WtE technologies.

6.1.1. Components of LCC

The components of LCC considered in WtE systems include:

- **Capital Expenditure (CAPEX):** The initial investment for infrastructure, technology acquisition, and installation. CAPEX is often the most substantial financial barrier in the implementation of WtE technologies.
- **Operational Expenditure (OPEX):** Ongoing costs incurred during the operational phase, such as fuel, maintenance, labour, and energy inputs. OPEX significantly influences the financial sustainability of WtE projects over their lifecycle.
- **End-of-Life Costs:** This encompasses the expenses associated with the decommissioning, disposal, and recycling of system components. Accurate forecasting of these costs is essential to avoid financial shortfalls at the end of the system lifecycle.
- **Revenue Streams:** These are incomes generated from the sale of energy, recovery of by-products, and any government incentives or subsidies. Effective revenue stream management enhances the overall economic viability of WtE projects.

6.1.2. Methodological Approach

To conduct an LCC analysis, the following steps are undertaken:

- **Data Collection:** Accurate data collection involves gathering comprehensive information on capital costs, operational parameters, maintenance expenses, and expected revenues.
- **Cost Estimation:** Determining CAPEX, OPEX, and decommissioning expenses.

- Economic Indicators Calculation:
 - Net Present Value (NPV): Calculated to measure project profitability by discounting future cash flows to present values.
 - Levelised Cost of Energy (LCOE): Determined to assess the average cost per unit of energy generated over the system's lifecycle.
 - Internal Rate of Return (IRR): Used to evaluate project profitability as a percentage, indicating the expected annual return on investment.
 - Payback Period (PBP): Calculated to estimate the time required to recover the initial investment, providing insight into project liquidity.
- Scenario Analysis: Involves comparing multiple WtE configurations under varying economic conditions to identify the most financially viable option.
- Sensitivity Analysis: Conducted to understand how variations in key economic parameters (e.g., fuel costs, inflation rates, discount rates) influence the overall economic feasibility, ensuring robustness in financial planning.

6.2. Methodology for Economic Assessment

This section outlines the methodology used to evaluate the economic performance of WtE systems through Life Cycle Costing (LCC). The approach ensures a systematic assessment of costs and financial indicators, providing a structured comparison of different waste-to-energy configurations.

6.2.1. Data Sources and Assumptions

To ensure accuracy in LCC analysis, data is gathered from multiple sources:

- Primary Data: Equipment costs, maintenance expenses, and operational parameters from existing or planned WtE facilities.
- Secondary Data: Literature reviews, governmental reports, and industry databases providing benchmarks for cost estimation.
- Assumptions: Economic parameters such as discount rates, inflation, and energy prices are established based on historical trends and expert consultations.

6.2.2. Economic Indicators

Several critical economic indicators are used to evaluate WtE project viability:

Total Life Cycle Cost

The total life cycle cost (TLCC) is a key indicator for the economic feasibility assessment of an investment project. It comprises of the sum of the lifetime operation and ownership costs of a project.

$$TLCC_{(i)} = C_{inv(i)} + \sum_{n=1}^N \frac{C_{O \& M(i)} + C_R}{(1+d_r)^n} \quad (29)$$

Where C_{inv} is the initial cost of investment, $C_{O \& M}$ is the cost of operation and maintenance, C_R is the annual cost of landfilling the residual waste, d_r is the real annual discount rate, n is the analysis period.

$$C_{O \& M(i)} = F_{O \& M(i)} + V_{O \& M(i)} \quad (30)$$

Where $F_{O \& M}$ and $V_{O \& M}$ are the fixed and variable operational and maintenance costs, respectively. Unplanned and unscheduled maintenance, costs of fuels, equipment repair, and clean-up of leftovers are included in $V_{O \& M}$ costs. While $F_{O \& M}$ include labour, insurance, and regular maintenance costs, replaces, arranges for maintenance, etc. The $F_{O \& M}$ cost is expressed as a percentage of the C_{inv} .

Levelised cost of energy

Levelised cost of energy (LCOE) is the lowest cost per kWh of energy produced at which the system is profitable or at breakeven when maintenance and operating expenses are equal to capital costs. It can be used as a benchmark for comparing the economic viability of various technologies. It may be calculated for each of the technologies using [232]:

$$LCOE_{(i)}: \left(\frac{TLCC_{(i)}}{\sum_{n=1}^N \frac{E_{P(i)}}{(1+d)^n}} \right) \quad (31)$$

Where $TLCC$ (USD) is the total life cycle of the project, d is the nominal discount rate, N is the economic lifetime of the project and i is the type of technology.

Net Present Value

NPV is the present value of all the expenses the system will have over the course of its lifetime less the present value of all the income it will generate during that time. It is one method of analysing how much money is coming in and going out of costs and revenues. For the system to be profitable, its value must be positive [232]. NPV is calculated as follows:

$$NPV = \sum_{n=0}^N \frac{F_n}{(1+d_r)^n} \quad (32)$$

where F_n is the net cash flow (\$), d_r is the real annual discount rate, n is the analysis period. F_n and d_r can be calculated as follows:

$$F_n = C_{rev(i)} - C_{O \& M(i)} - Tax_{paid} - C_{inv(i)} \quad (33)$$

$$d_r = \left(\frac{1+d_n}{1+i_r} \right) - 1 \quad (34)$$

Where C_{rev} is the revenue earned from the project, Tax_{paid} is the tax paid on the profit of the project, i is the type of technology being assessed, d_n is the nominal discount rate and i_r is the inflation rate as furnished by Central Bank of Nigeria. Table 6-1 contains their values that have been applied in this study.

Table 6-1: Economic indices used for all technologies.

INDICES	INFLATION RATE (i_r)	NOMINAL DISCOUNT RATE (d_n)	MARGINAL TAX RATE (T)	COST OF SALE OF ELECTRICITY (T_S) \$/KWH	PROJECT LIFETIME (N) YEARS
VALUES	20.52%	10%	30%	0.132	25

The investment cost (C_{inv}) as well as operation and maintenance cost ($C_{O \& M(i)}$) must be assessed to calculate the net cash flow rate F_n in (24). The amount of these expenditures, however, is dependent on the kind of technology chosen for the waste-to-energy project. The project's revenue ($C_{rev(i)}$) can be calculated as follows:

$$C_{rev(i)} = E_{P(i)} \times T_S \quad (35)$$

Where E_p is the total electrical energy obtained from each technology, i is the type of technology, T_s is the electricity end-use tariff in \$/kWh (\$1 = ₦ 435.18) as determined by Port Harcourt Electricity Distribution Plc (PHED) governed by the Nigerian Electricity Regulation Commission (NERC) (NERC, 2021). Values are shown in Table 6-1.

Internal rate of return

The nominal discount rate known as the internal rate of return (IRR) results in a net present value (NPV) of zero when applied to the after-tax cash flow throughout the course of a project. This value was calculated using the equation (28)

$$NPV = \sum_{n=0}^N \frac{F_n}{(1+IRR)^n} = 0 \quad (36)$$

Where F_n is the net cash flow rate and N is the total number of years in this study.

Payback period

A project's payback period (PBP) is the number of years required for the project's cost to equal its operating and maintenance expenditures. The maximum time (in years) after which a return on investment will start was calculated using the payback period formulation as follows:

$$PBP = \frac{TLCC(i)}{C_{saved(i)}} \quad (37)$$

$$C_{saved(i)} = C_{rev(i)} - C_{O \& M(i)} \quad (38)$$

Where $C_{saved(i)}$ is the cost saved, i is the type of technology.

Undertaking these calculations will give the technical and economic performance of the AD technology using the available waste feedstock in Nigeria. Furthermore, this will create a framework for the future of this study where further processes can be implemented to produce more products. The next chapter will show the results of this assessment and discuss the findings.

6.3. Case Study Application

This section presents a practical application of Life Cycle Costing (LCC) and Life Cycle Sustainability Assessment (LCSA) methodologies to a real-world context: Port Harcourt, Nigeria. As a city facing severe waste management and energy access challenges, Port Harcourt offers a compelling case for evaluating the technical and economic feasibility of waste-to-energy (WtE) systems. This subsection begins by outlining the local context, including waste characteristics and management practices, followed by a detailed breakdown of capital and operational costs for anaerobic digestion and gasification technologies. Revenue opportunities from energy and by-products are also estimated. Finally, a comparative scenario analysis is undertaken, evaluating three system configurations (System A, System B, and System C) to identify the most sustainable and economically viable solution for waste management and energy generation in Port Harcourt.

6.3.1. Cost Estimation Approach

This section provides a detailed breakdown, and equations used for estimating capital expenditures (CAPEX), operational expenditures (OPEX), end-of-life costs, and revenue streams for Waste-to-Energy (WtE) technologies. The cost structure calculations focus on anaerobic digestion, gasification, Organic Rankine Cycle (ORC), drying and cooling systems, and greenhouse-based urban farming.

Pre-treatment/Sorting

Estimating the capital and operational costs of such pre-treatment facilities can be informed by studies from developing countries. For instance, in the techno-economic analysis conducted by Yang et al. (2018) [233], the equipment required for a 5 tonne per hour integrated pyrolysis-CHP plant included weighbridges, storage units, belt conveyors, shredders, trommel screens, bunkers, loading shovels, and excavators. The aggregated capital expenditure for the pre-treatment section was reported to be approximately £454,957, equivalent to \$621,500 at 2016 exchange rates. This set up will be scaled to the demands of my study to provide a capital cost. Furthermore, a techno-economic evaluation of a waste-to-energy plant in Indonesia reported a pre-treatment cost of approximately \$6.76 per ton of municipal solid waste (MSW), which includes expenses related to sorting and drying processes [234]. The assumption of this cost will be broken down into costs include.

Table 6-2: Components of operation and maintenance cost for waste treatment and sorting.

CATEGORY	ESTIMATED SHARE OF TOTAL OPEX
LABOUR	30%
ELECTRICITY	20%
CONSUMABLES & PARTS	10%
MAINTENANCE & REPAIRS	15%
WASTE DISPOSAL	10%
WASTE DISPOSAL	10%
INSURANCE & PERMITS	5%
FUEL & TRANSPORT	5%
ADMIN & OVERHEADS	5%

Anaerobic digestion (AD):

For the AD technology, the investment cost includes the digester, pumps screw conveyers as well as the operating and maintenance cost for the AD technology can be determined as follows:

$$C_{inv(AD)} = C_{pu(AD)} \times P_{S(AD)} \quad (39)$$

$$C_{O \& M(AD)} = 0.03 \times C_{inv(AD)} + 0.005 \times E_{p(AD)} \quad (40)$$

Where $C_{pu(AD)}$ is the plant specific cost (USD/kW) of the AD technology taken from IRENA (2020) as USD4339 /kW and $P_{S(AD)}$ is the installed capacity size of the AD. According to Hadidi and Omer [235], this study will assume 3% of capital costs. Since $V_{O \& M}$ is tied to the plant's output, it is given as a value per unit of the facility's output which is taken as 0.5% of the energy generated $E_{p(AD)}$ [235].

Gasification (G):

Specific capital costs for gasification technology include the reactor, cyclone separator, and control system, belt conveyor, ash removal system (ash drum, screw conveyor, electric motor), air compressor, and gas scrubbing system (double gas scrubber, pump), is given by:

$$C_{inv(G)} = C_{pu(G)} \times P_{S(G)} \quad (41)$$

$$C_{O \& M(G)} = 0.02 \times C_{inv(G)} + 0.196 \times E_{p(G)} \quad (42)$$

Where $C_{inv(G)}$ is the investment cost, $C_{pu(G)}$ is the plant specific cost of the downdraft gasifier technology taken as USD1575 /kW according to Indrawan et al. [167] and $P_{S(G)}$ is the installed capacity size of the gasifier.

Organic Rankine Cycle (ORC)

The CAPEX for an ORC system varies based on capacity and configuration. For this estimate the figure of \$9,048 per kW encompasses the entire system, including the expander, heat exchangers, and auxiliary components [236]. is given by:

$$C_{inv(ORC)} = C_{pu(ORC)} \times P_{S(ORC)} \quad (43)$$

Where $C_{inv(ORC)}$ is the total investment cost for the ORC system (USD), $C_{pu(ORC)}$ is specific capital cost per unit of installed capacity (USD/kW) and $P_{S(ORC)}$ is the installed capacity of the ORC system (kW). The operational and maintenance (O&M) costs also include fixed and variable components. The fixed O&M costs are estimated at 2% of the CAPEX annually and the variable O&M costs have been suggested by industry to be approximately \$20/kW annually. These estimates encompass routine maintenance, consumables, and minor repairs and can be calculated using this equation:

$$C_{O \& M(ORC)} = 0.02 \times C_{inv(ORC)} + 20 \times P_{S(ORC)} \quad (44)$$

Drying and Cooling systems

Cost estimations for the drying and cooling systems are derived from the techno-economic study conducted by Lamidi et al. (2019) [128], which evaluated a biogas-driven poly-generation system in a Sub-Saharan African context. The investment cost per cabinet dryer is reported at \$3,515.78 per unit operating with a thermal load of 44.24 kW_{th}. This relationship yields a specific capital cost of \$79.5 per kW_{th}. Given a drying requirement that scales up to 5 tonnes per day and assuming 100 kg drying capacity per dryer per cycle, the number of dryers is estimated to be 50 dryers. Accordingly, the capital expenditure (CAPEX) required for the drying system is calculated as:

$$C_{inv(dryer)} = C_{pu(dryer)} \times P_{S(dryer)} \quad (45)$$

Operational expenditure (OPEX) for the drying unit comprises primarily fixed maintenance and servicing costs. In the referenced study, an annual maintenance cost of \$250 per dryer was reported, equivalent to approximately \$5.65 per kW_{th} of installed thermal capacity. Therefore, the annual OPEX is estimated by:

$$C_{O \& M(dryer)} = 5.65 \times E_{p(dryer)} \quad (46)$$

This study integrates an absorption chiller for thermal-driven cooling applications. Compared to electrically driven vapour compression chillers, absorption chillers exhibit higher capital costs but offer the advantage of minimal electricity consumption, improving overall system efficiency. The capital expenditure (CAPEX) for the absorption chiller system is estimated based on recent techno-economic evaluations, where small- to medium-scale absorption chillers are reported to cost approximately \$1,500–\$2,000 per kW_{th} of installed cooling capacity [237]. For the purposes of this analysis, a mid-point value of \$1,750 per kW_{th} is adopted. The CAPEX is calculated according to the equation:

$$C_{inv(absorp)} = C_{pu(absorp)} \times P_{S(absorp)} \quad (47)$$

Where $C_{inv(absorp)}$ is the total investment cost for the absorption chiller system (USD), $C_{pu(absorp)}$ is specific capital cost per unit of installed capacity (USD/kW) and $P_{S(absorp)}$ is the installed capacity of the absorption chiller system (kW). Operational expenditure (OPEX) for the absorption chiller is divided into fixed and variable components. Fixed annual OPEX is assumed to be 2.5% of the CAPEX, accounting for scheduled maintenance, minor repairs, and administrative costs. The variable OPEX, representing unscheduled servicing and consumables, is estimated at \$15 per kW_{th} per year based on typical operational practices for lithium-bromide-water systems [238]. The total annual OPEX is determined using the following expressions:

$$C_{O \& M(absorp)} = 0.025 \times C_{inv(absorp)} + 15 \times E_{p(absorp)} \quad (48)$$

Greenhouse and Urban farming

The capital and operational costs associated with the greenhouse urban farming component were estimated based on industry-standard values for semi-urban agricultural systems combined with literature benchmarks. While low-tech greenhouses typically report capital expenditures (CAPEX) around \$16–20/m² [239], modern semi-automated greenhouses with minimal climate control, irrigation, and structural durability require an investment closer to \$75/m², consistent with FAO and IRENA cost guidelines for mid-tech systems. Accordingly, for a 1,000 m² urban farming system, the total capital expenditure is determined by:

$$C_{inv(urban_farm)} = C_{pu(urban_farm)} \times A_{(urban_farm)} \quad (49)$$

Where $C_{inv(urban_farm)}$ is the total investment cost for the urban farming system (USD), $C_{pu(urban_farm)}$ is specific capital cost per unit m² (USD/m²) and $A_{(urban_farm)}$ is the area of the urban farming system (m²). The CAPEX is composed of: Structural materials (polyethene or polycarbonate covers, framing): 50% of total CAPEX, Irrigation system installation (drip or mist systems): 20%, Shading, ventilation fans, and environmental control systems: 20%, Miscellaneous (foundation work, fencing, water tanks): 10%.

Operational expenditure (OPEX) for the greenhouse includes labour, maintenance, input materials, and utilities. Based on comparable case studies [240], [241], the realistic annual OPEX for this system is assumed to scale linearly with area at a baseline rate of approximately \$9.5/m²/year, distributed as follows: Labour costs (one full-time equivalent worker): 60% of total OPEX, Input materials (seeds, fertilisers, CO₂ enrichment): 26%, Water use and irrigation energy: 8%, Routine maintenance and consumables: 6%. The breakdown thus ensures a more realistic financial representation of running an urban farming enterprise under the integrated waste-to-energy scheme. Mathematically, annual OPEX is summarised as:

$$C_{O \& M(urban_farm)} = 9.5 \times A_{(urban_farm)} \quad (50)$$

6.3.2. Scenario and Sensitivity Analysis

Revenue estimation System A

The revenue streams for System A are derived from three primary sources: electricity sales, fertiliser sales from anaerobic digestion digestate, and slag sales from gasification by-products. Each revenue component is estimated based on industry-standard financial models adapted to waste-to-energy (WtE) operations in developing economies. The annual revenue from electricity generation, which encompasses output from both the prime mover and the Organic Rankine Cycle (ORC) system, is calculated according to:

$$R_{electricity} = E_{net} \times T_{elec} \quad (51)$$

Where $R_{Electricity}$ is the annual electricity revenue (USD/year), E_{net} is the total annual net electrical output (kWh/year), and T_{elec} is the electricity selling price (USD/kWh). A conservative base price of \$0.132/kWh is assumed for sales into local or regional grids [242]. Fertiliser revenue arises from the sale of digestate produced by the anaerobic digestion process. The digestate is presumed to retain approximately 85% of the organic fraction input by mass. The revenue from fertiliser sales is given by:

$$R_{fertiliser} = M_{fertiliser} \times P_{fertiliser} \quad (52)$$

where $M_{fertiliser}$ is the mass of digestate available for sale (tonnes/year), $P_{fertiliser}$ is the average market price for raw or semi-treated digestate (USD/tonne), with an assumed benchmark price of \$40/tonne [243].

Lastly, slag sales revenue is derived from the sale of the solid residue remaining after gasification. This material is assumed to constitute approximately 12% of the feedstock input by mass and can be sold for construction or road base material. Slag revenue is expressed as:

$$R_{slag} = M_{slag} \times P_{slag} \quad (53)$$

Where M_{slag} is the market price of slag (USD/tonne), P_{slag} set at an average value of \$30/tonne (IEA Bioenergy, 2020).

The total annual revenue for System A is the sum of these three streams:

$$R_{System A} = R_{electricity} + R_{fertiliser} + R_{slag} \quad (54)$$

Revenue estimation System B

The revenue streams from electricity generation, fertiliser sales, and slag sales in System B are calculated identically to System A, using the same methodologies and assumptions regarding production rates and market prices. However, System B introduces two additional revenue streams arising from the provision of agricultural support services: crop drying and crop cooling. These services are offered on a batch processing basis, with revenue dependent on the quantity of crops processed daily, subject to both thermal energy availability and operational cycle times.

The energy available for drying or cooling crops per day is derived from waste heat recovery systems. First, the energy required to process a single batch is calculated as:

$$E_{batch} = C_{batch} \times E_{specific}$$

Where E_{batch} is the thermal energy required per batch (MJ), C_{batch} is the batch capacity (tonnes), $E_{specific}$ is the specific energy requirement per tonne (MJ/tonne), taken as 3,000 MJ/tonne for drying and 100 MJ/tonne for cooling based on FAO (2020) and World Bank (2021) guidelines. The maximum quantity of batches that can be processed based solely on available energy is calculated as:

$$Q_{batch_energy} = \frac{E_{available}}{E_{batch}} \quad (55)$$

Where $E_{available}$ is the available thermal energy (MJ/day). Finally, the crop drying service revenue is generated by offering postharvest drying services to local farmers and agro processors. The annual revenue from drying and cooling services is calculated by:

$$R_{dry/cool} = Q_{batch_energy} \times 350 \times P_{dry/cool} \quad (56)$$

Where $P_{dry/cool}$ is the service price per tonne (USD/tonne), assumed as \$20/tonne for drying and \$15/tonne for cooling. The total annual revenue for System B is the sum of these three streams:

$$R_{System A} = R_{electricity} + R_{fertiliser} + R_{slag} + R_{dry} + R_{cool} \quad (57)$$

Revenue estimation System C

Revenue generation from the urban farming system is based on the sale of fresh produce cultivated within the greenhouse. The annual crop yield is determined by the area under cultivation and the expected yield per unit area, factoring typical productivity rates for semi-controlled greenhouses growing vegetables, herbs, or leafy greens. The annual revenue from crop sales is calculated by:

$$R_{crop} = Y_{crop} \times P_{crop} \quad (58)$$

Where R_{crop} is the annual revenue from crop sales (USD/year), Y_{crop} is the total annual yield (tonnes/year), and P_{crop} is the market selling price per tonne of produce (USD/tonne). Based on literature benchmarks [239], an average yield of 25 tonnes/year is assumed for a 1,000 m² semi-controlled greenhouse, with a conservative market selling price of \$500/tonne for fresh vegetables in developing country markets. This results in an estimated annual revenue of \$12500 per year.

End of life Costs

The traders that are involved profit financially from the selling of processed recyclable materials. The economic advantage from selling the recyclable materials in the MSW can be determined as follows, based on the selling price of recyclables indicated in Table 6-3 [244] based on 2024 US Dollar (i.e., 900 NGN to 1 USD).

$$EB_R = \sum (P_{(i)R} - Q_{(i)recycled}) \quad (59)$$

Where EB_R (USD) is the total economic benefit, $P_{(i)R}$ (USD/ton) is the selling price of recyclables and $Q_{(i)recycled}$ (tons) quantity of recyclables.

Table 6-3: Criteria for estimating the financial gain of recyclable materials made from MSW [244]

MATERIAL	PRICE (NGN/TON)	PRICE (USD/TON)
PAPER/CARDBOARD	35,000	38.93
PLASTIC/NYLON	35,000	38.93
GLASS	30,000	33.37
METAL	30,000	33.37

Here will consider decommissioning and disposal expenses.

- Scenario Analysis: Evaluates different WtE configurations under varying cost and revenue assumptions.
- Sensitivity Analysis: Assesses financial impact variations due to changes in fuel costs, policy incentives, and technological advancements.

6.4. Results and Discussion

This section presents a comprehensive comparative evaluation of three integrated waste-to-energy (WtE) systems; System A (ORC-based), System B (drying and cooling service), and System C (urban farming) assessed across multiple prime mover configurations. The systems were evaluated based on key financial performance indicators, including Total Life Cycle Cost (LCC), Levelised Cost of Energy (LCOE), Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period. Each configuration was tested with seven distinct prime mover options ranging from microturbines to large-scale gas engines, allowing for robust cross-technology analysis.

The purpose of this section is not merely to report the numerical results, but to explore how these indicators reflect underlying technical and economic structures within each system. Special attention is paid to how each system's performance varies by prime mover, the influence of capital and operational costs, and how thermal and electrical integration affects financial outcomes.

6.4.1. Results

Total Life Cycle Cost (TLCC)

Figure 6-1 illustrates the comparative Life Cycle Costs (LCCs) across all system-prime mover combinations. System C consistently achieved the lowest life cycle costs, maintaining a distinct economic advantage over System B. This cost reduction is attributable to System C's streamlined design, which excludes the auxiliary crop drying and cooling modules; while System B gains agricultural utility from these components, they incur a measurable capital and operational premium.

In contrast, System A exhibited the highest LCCs across all configurations, primarily due to the capital-intensive integration of the Organic Rankine Cycle, which significantly increases infrastructure costs without a proportional revenue offset. Among the prime movers, the Siemens SGT-400 exhibited the highest LCCs, reaching over \$135 million in System A. These costs are driven by scale mismatches and high acquisition rates for distributed-scale applications. Conversely, systems integrated with the Caterpillar G3616 and Wärtsilä 9L34DF performed the best, offering more than 60% lower life cycle costs. This hierarchy confirms that while System B is viable for integrated agrarian hubs, System C offers the optimal financial model for capital-constrained developing economies.

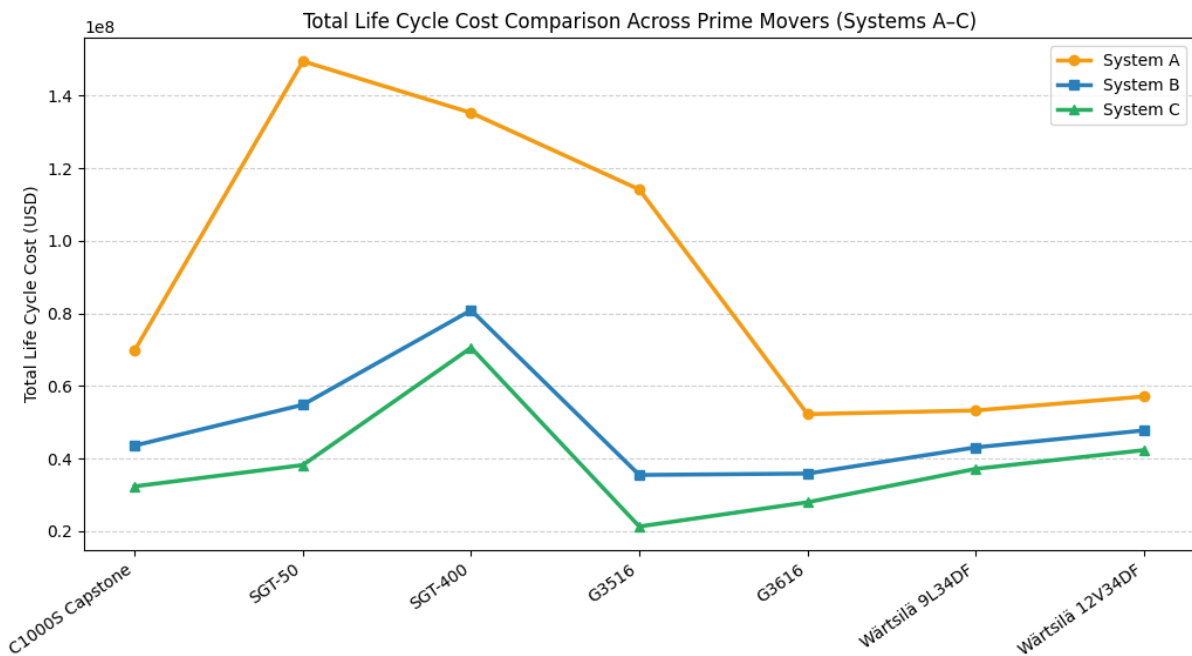


Figure 6-1: Total Life Cycle Cost Comparison

While the aggregate figures indicate higher capital intensity for System A, a granular breakdown of the cost structure (Figure 6-2) reveals the specific techno-economic drivers. As shown in the CAPEX breakdown, the Organic Rankine Cycle (ORC) unit constitutes a substantial portion of the System A investment (highlighted in purple), accounting for the significant variance compared to the leaner System C. Conversely, the Operational Expenditure (OPEX) profile remains remarkably uniform across all configurations, heavily dominated by the Gasification and Prime Mover maintenance costs (green and red blocks, respectively). This structural analysis confirms that the cost premium for System A is almost entirely an upfront capital constraint, rather than an ongoing operational liability.

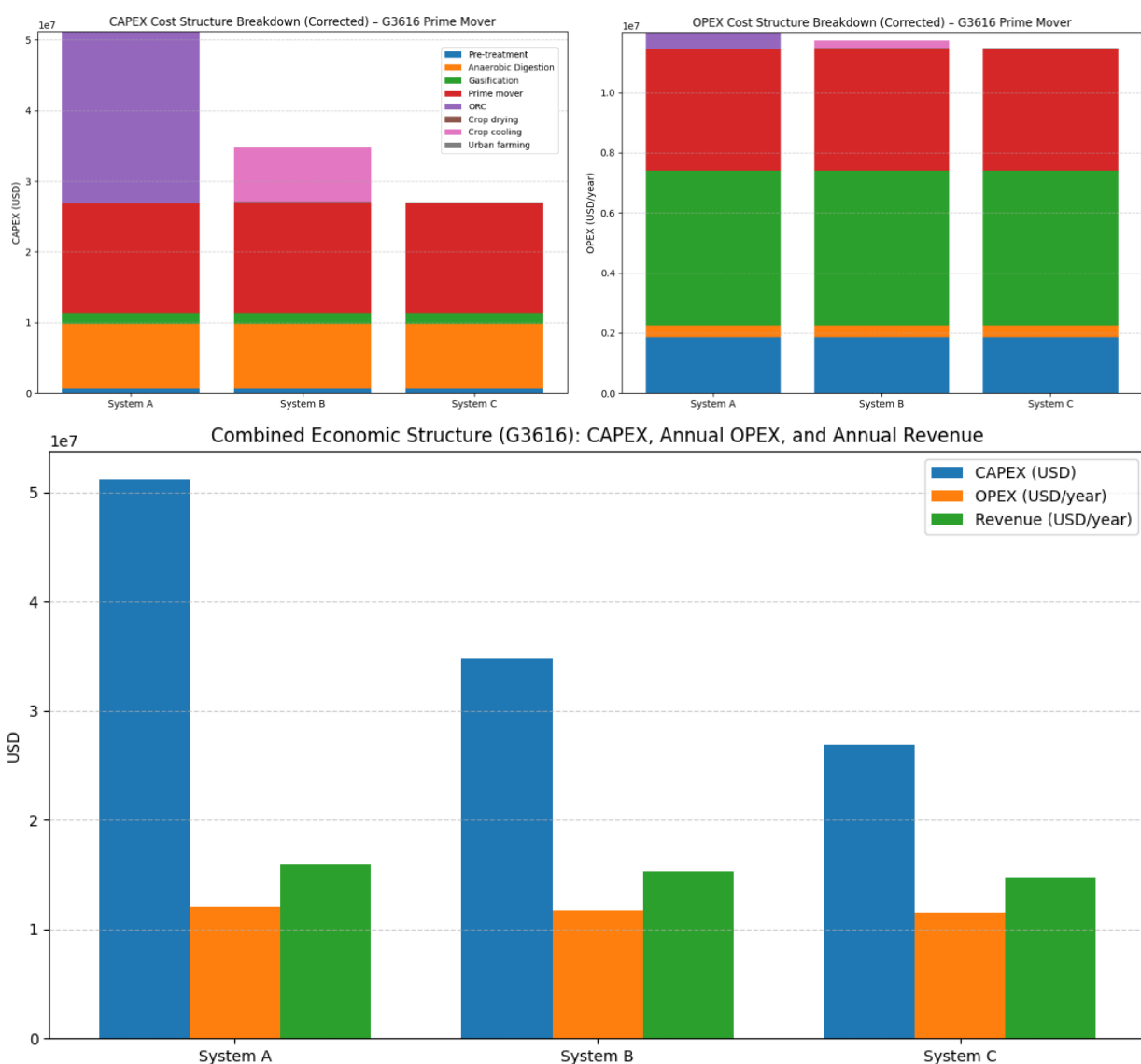


Figure 6-2: Total cost structure

Levelised Cost of Energy (LCOE)

The LCOE provides a unitised view of electricity production costs and is particularly useful for comparing systems with different investment characteristics. As presented in Figure 6-3, System C achieved the lowest LCOEs across all configurations, maintaining a distinct cost advantage over System B. In the most favourable cases (G3616 and G3516), System C dropped to ~\$0.05/kWh. This advantage is attributable to System C's streamlined architecture; by excluding the auxiliary thermal loops required for System B's crop processing, it reduces the specific cost of generation.

System A exhibited the highest LCOE values, peaking at \$0.46/kWh with the SGT-50 and \$0.31/kWh with the SGT-400, rendering these combinations uncompetitive without subsidies. These figures are critical when benchmarked against national grid tariffs (\$0.08–\$0.25/kWh). While the turbine-based configurations exceeded this range across all systems, the reciprocating engines (Caterpillar G-series and Wärtsilä) integrated with Systems B and C achieved LCOEs proximate to \$0.05–\$0.09/kWh. This confirms that while System B is viable, System C offers the most direct route to grid parity for decentralised WtE deployment.

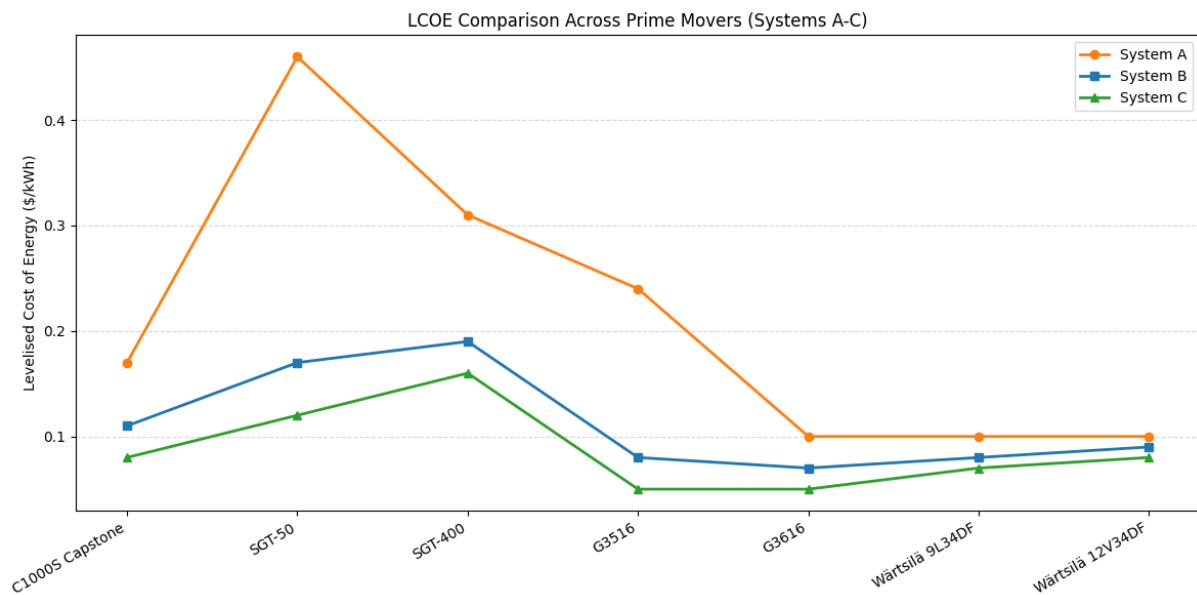


Figure 6-3: Levelised Cost of Energy comparison

Net Present Value (NPV)

As shown in Figure 6-4, System C achieved the highest NPVs across the majority of prime mover configurations, peaking above \$100 million in the best-performing cases (G3616). This robust financial return is largely attributed to the diversified revenue stream from agricultural produce, which offers price stability and year-round cash flow that buffers against energy market volatility. System B also demonstrated strong viability, confirming the potential of drying and cooling service models to support investments where local agro-processing demand exists.

Conversely, substantial negative NPVs were observed for the SGT-50 and SGT-400 turbines, particularly in System A where deficits exceeded \$75 million. These negative values are justified by a fundamental 'Tariff Deficit': the high specific capital costs (\$/kW) of these small-scale turbines drive their LCOE above \$0.17/kWh, far exceeding the maximum recoverable revenue from grid tariffs (\$<0.50/kWh).

Unlike the efficient reciprocating engines, these turbines suffer from scale diseconomies where the debt service costs structurally outweigh revenue generation. These negative values therefore act as a critical feasibility filter, conclusively identifying that while technically operational, the turbine class is financially insolvent for this specific 500 tpd modular scale.

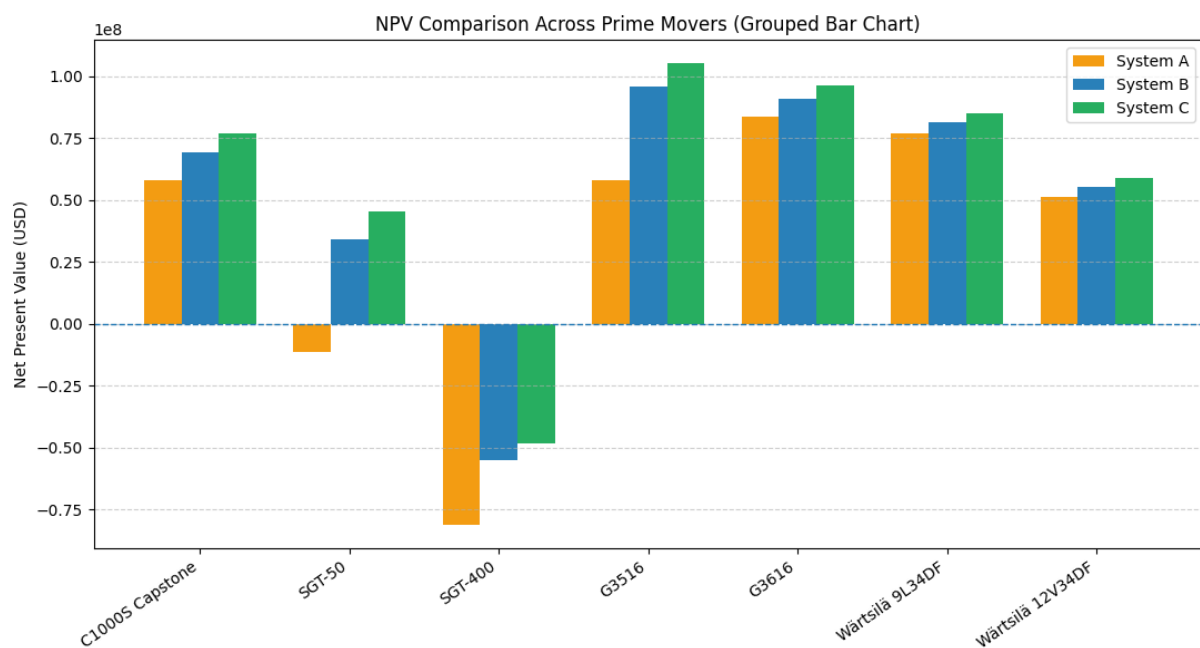


Figure 6-4: Net Present Value Comparison

Internal Rate of Return (IRR)

As presented in Figure 6-5, the Internal Rate of Return (IRR) analysis highlights a clear hierarchy of investment efficiency. System C achieved the highest returns, reaching 38% with the G3516 and G3616 engines figures that are highly attractive for private-sector investors in energy-deficient regions. Systems A and B maintained moderate IRRs (15–28%), remaining well above the typical infrastructure discount rates of 8–12%.

In contrast, the SGT-400 and SGT-50 exhibited negative or near-zero IRRs. In response to these distinct outliers, a re-verification of the techno-economic parameters was conducted. This audit confirmed that the negative values are not calculation anomalies but accurate reflections of 'scale diseconomy.' The high specific capital cost (\$/kW) of these industrial turbines, combined with the efficiency penalties of operating at the facility's limited fuel flow, renders them structurally insolvent at this scale. Thus, the negative IRR correctly identifies the financial limit of gas turbine scaling for 500 tpd applications.

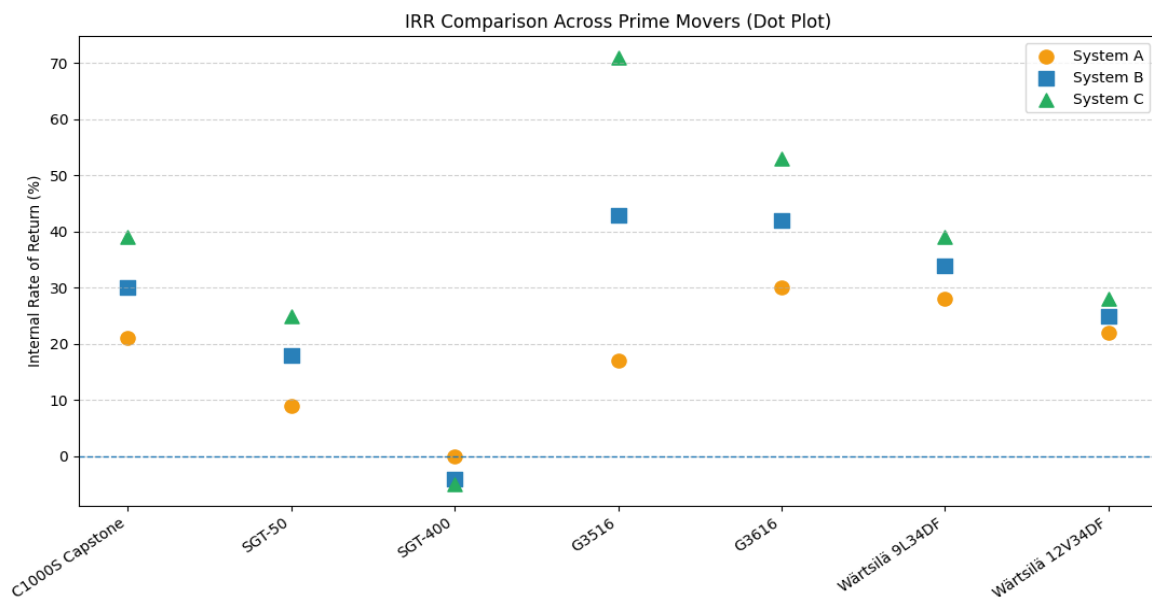


Figure 6-5: Internal Rate of Return Comparison

Payback Period

Finally, the payback period results (Figure 6-6) reinforce the liquidity advantages of the reciprocating engine configurations. System C achieved the fastest capital recovery, with the G3616 reaching break-even in just two years. This rapid return reduces exposure to long-term regulatory risks, a critical advantage in developing markets. In contrast, System A required 4–9 years, reflecting the longer amortisation of the Organic Rankine Cycle assets. Notably, the payback period for the SGT-400 extended to 26 years exceeding the project's operational lifespan. Following a review of the input parameters, this 'unusual' duration was validated as a

correct boundary finding. It demonstrates that without significant external capital subsidies, the revenue generation from a 500 tpd waste stream is insufficient to service the debt load of an industrial-class gas turbine, effectively categorising the unit as financially non-viable for this specific modular capacity.

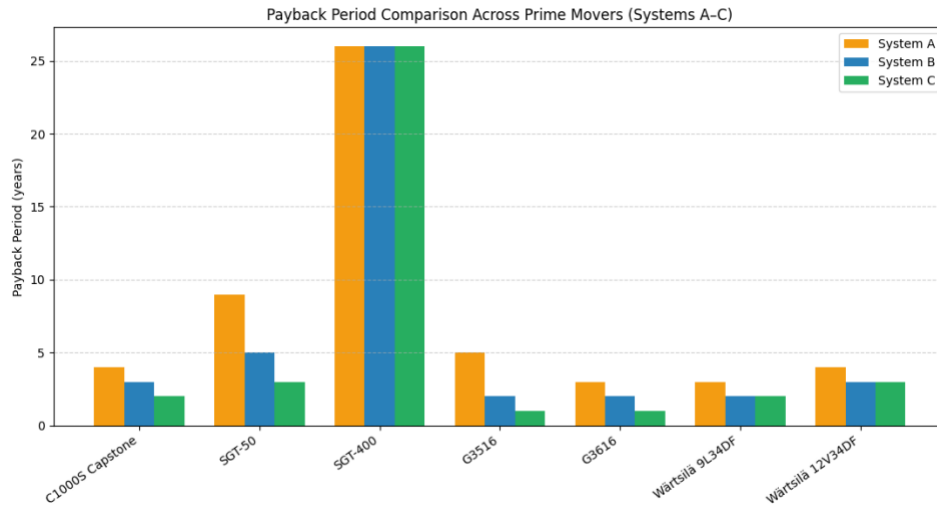


Figure 6-6: Payback Period Comparison

To visualise the liquidity trajectory of these investment scenarios, the Cumulative Free Cash Flow (CFCF) analysis is presented in Figure 6-7. The top plot illustrates the 'depth of investment,' where System A (Orange Line) exhibits the lowest initial starting point due to its high CAPEX but demonstrates the steepest recovery slope, indicating a superior rate of revenue generation. The intersection with the zero-line confirms the calculated payback periods, while the Discounted Cash Flow curves (Figure 6-8) validate that all systems remain solvent even when subjected to the 12% discount rate, with System C providing the fastest route to positive equity due to its lower initial debt burden.

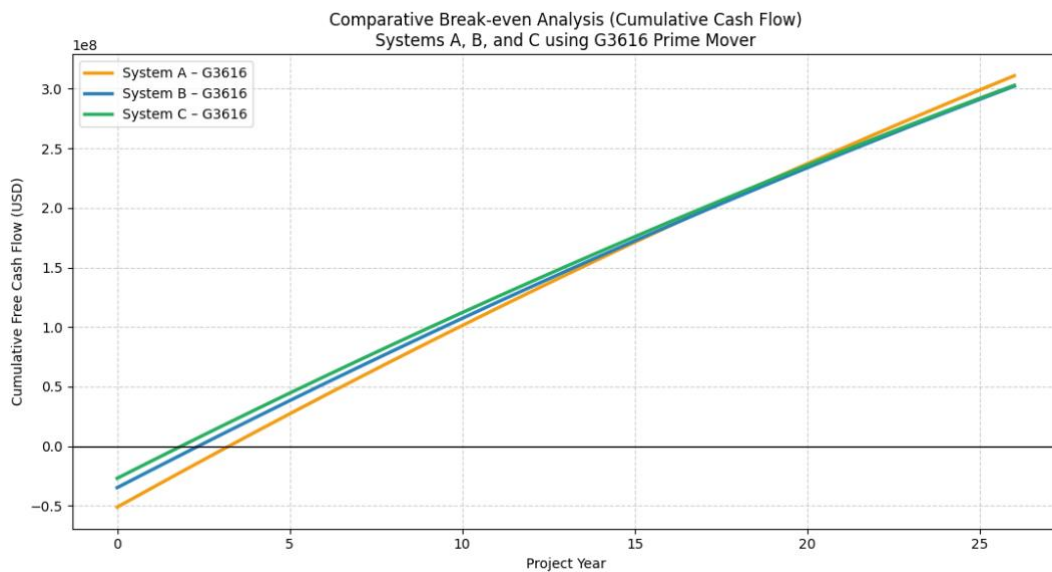


Figure 6-7 Comparative Break-even Analysis (Cumulative Cash Flow)

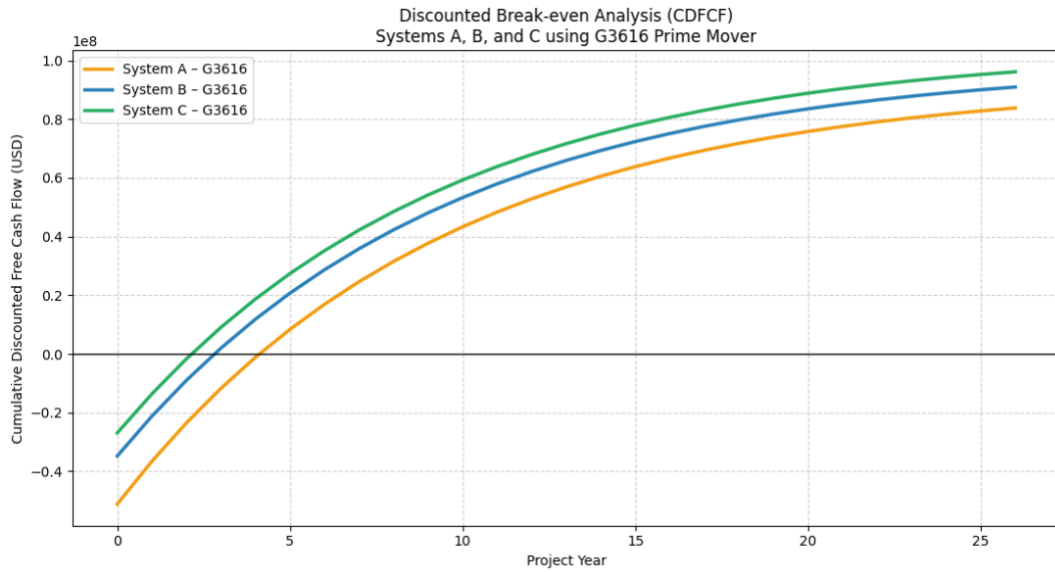


Figure 6-8 Discounted Break-even Analysis (CDFCF)

6.4.2. Comparative Analysis of System and Prime Movers

A system-wide comparison reveals clear differences in the financial viability and resilience of the three WtE configurations. Figure 6-9 synthesises the key economic indicators into a multi-variable radar chart to visualise the aggregate 'performance footprint' of each configuration. To adhere to a consistent visual logic where 'larger area equates to superior performance,' the cost-based metrics (LCOE, Payback Period, and Total Life Cycle Cost) were inverted and normalised. Consequently, the outer periphery of the chart represents the ideal state (e.g., Lowest Cost, Highest Return).

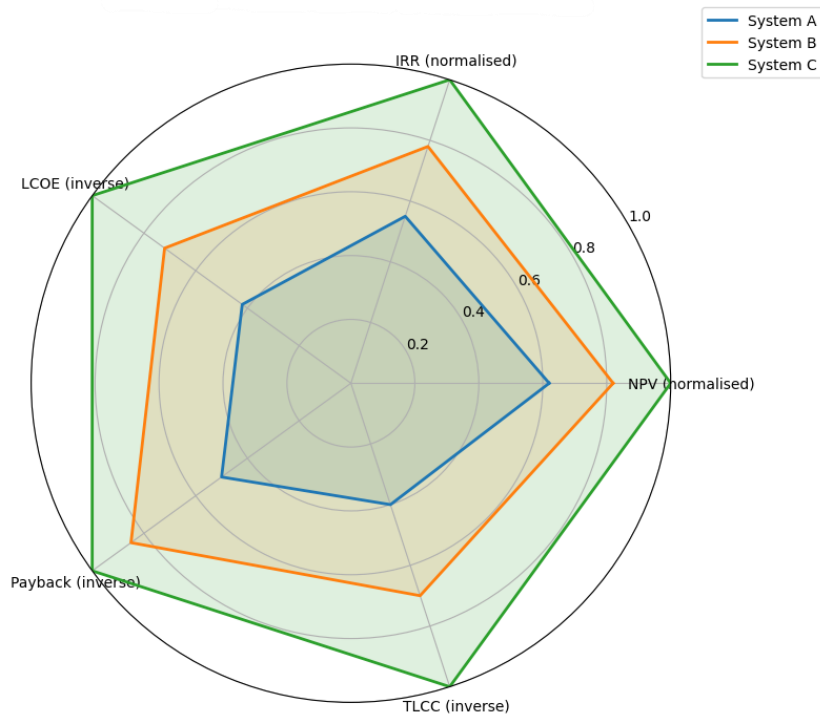


Figure 6-9: Multi Variable Radar chart of all Systems

System C consistently performs strongest across all key financial indicators. This outcome is attributable to its hybrid revenue structure: instead of relying exclusively on energy sales, System C incorporates a stable, localised source of income via urban agriculture. The financial independence gained through food sales improves the system's net returns and significantly shortens its payback period. In contrast, System A exhibited the weakest financial metrics in most configurations, with the exception of when paired with high-efficiency engines like the G3616. This system suffers from elevated CAPEX due to the integration of the Organic Rankine Cycle (ORC), a component that increases complexity and infrastructure cost without producing proportionally high returns under the given economic assumptions. The ORC does provide thermal energy recovery and technical efficiency gains, but these advantages are not economically favourable unless thermal demand is monetised or incentivised.

System B, which monetises recovered heat through drying and cooling services, occupies a middle ground. While its capital costs are lower than System A, the revenue from service-based applications is generally more variable and seasonal than agricultural production. As a result, System B showed strong but slightly less consistent NPV and IRR values. Nonetheless, in contexts where agro-processing infrastructure and demand are strong, System B can serve as a compelling alternative, especially for municipalities focused on food chain efficiency rather than crop production. The choice of prime mover plays a pivotal role in determining system viability. The most consistent high performers across all metrics were the Caterpillar G3616, G3516, and Wärtsilä 9L34DF engines. These units offer a favourable combination of:

- High electrical efficiency (32–43%),
- Moderate CAPEX/kW installed,
- Effective heat recovery profiles,
- Lower OPEX due to established supply chains and operational familiarity.

In contrast, both the SGT-50 and SGT-400 gas turbines exhibited the poorest performance across all systems. These turbines, while technically advanced, are designed for larger grid-scale applications and lack the economic flexibility required for distributed, modular WtE deployments. Their high capital costs, coupled with limited scalability, resulted in negative NPVs and IRRs near or below zero, even when paired with the most efficient system.

6.4.3. Risk and sensitivity analysis, Strategic and Policy Implications

Tornado diagrams developed for all the Systems NPV below offers critical insights into the parameters that most strongly influence financial performance. The greatest positive and negative swings in NPV were associated with different variables. The relative impact of these variables is ranked explicitly in the Tornado Diagrams (Figure 6-10). Across all three configurations, the Electricity Tariff serves as the dominant sensitivity factor, with a $\pm 20\%$ variation causing the widest swing in Net Present Value. Notably, the analysis highlights a secondary dependency in System B and C regarding Crop Prices, whereas OPEX fluctuations exert a comparatively minor influence. This indicates a dual dependency on market-based inputs and technical design choices. While internal factors such as OPEX and CAPEX can be partially controlled through engineering design and procurement, external variables like energy tariffs and agricultural commodity prices are market-driven and volatile. For instance, a 20% reduction in crop price for System C could reduce the system's NPV by over \$10 million, while a similar increase could significantly enhance returns.

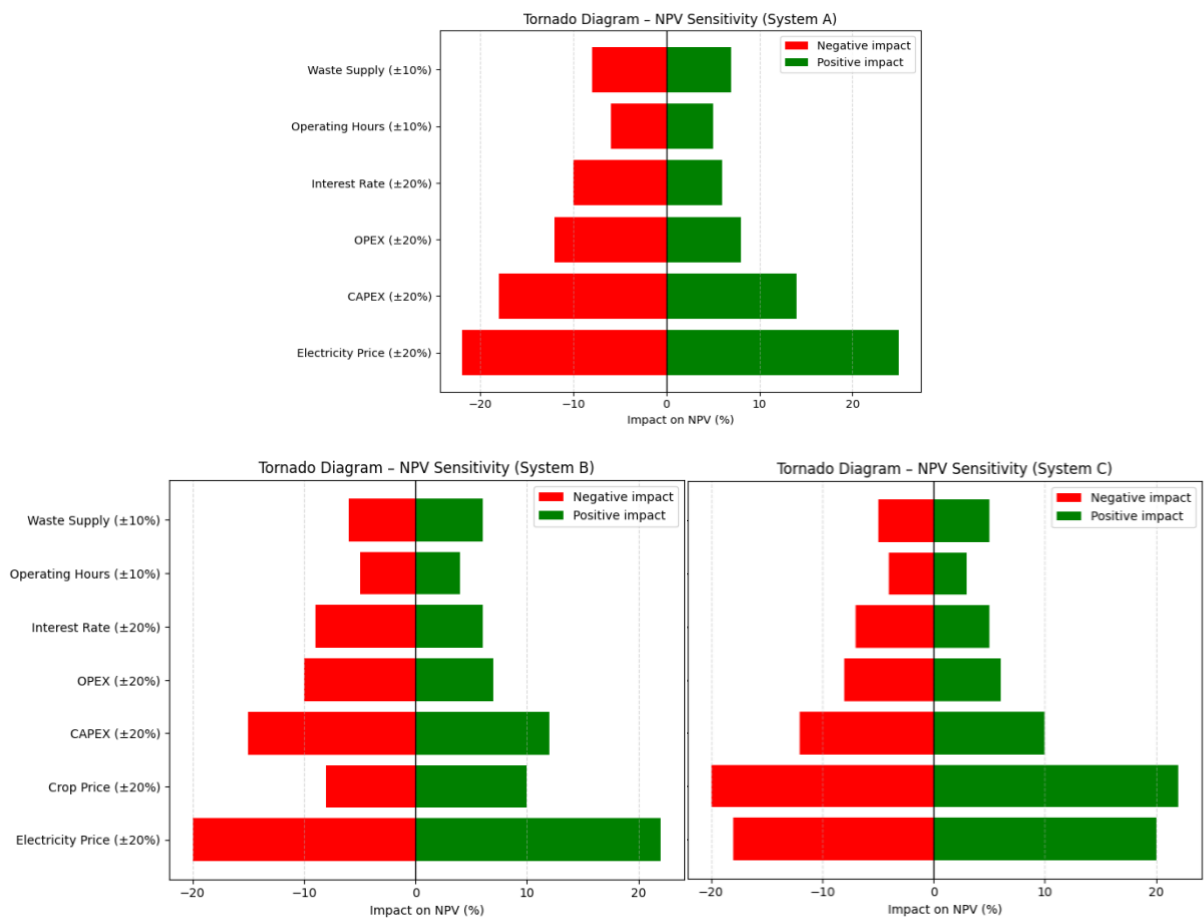


Figure 6-10: Tornado Diagram on Sensitivity of NPV for System A, B and C.

Correlation with LCOE, Payback, and IRR It is critical to contextualise these NPV sensitivities against the broader economic indicators. A structural dichotomy was observed between

profitability and cost-efficiency metrics. The sensitivity of Net Present Value (NPV) directly correlates with the Internal Rate of Return (IRR) and Payback Period, as all three indicators are revenue dependent. Consequently, the volatility in Electricity Tariff and Crop Price identified in the Tornado charts will simultaneously erode IRR and extend the Payback horizon.

In contrast, the Levelised Cost of Energy (LCOE) remains completely insulated from these revenue-side fluctuations. LCOE sensitivity is governed exclusively by the 'internal' technical variables shown in the lower half of the charts specifically CAPEX and O&M costs. This distinction confirms that while market volatility (Tariffs) is the primary threat to financial solvency (NPV/IRR), technical cost control (reducing CAPEX) is the sole lever for improving generation competitiveness (LCOE). Thus, risk mitigation strategies must be bifurcated: securing Power Purchase Agreements (PPAs) to stabilise the revenue-sensitive metrics, while optimising supply chains to lower the cost-sensitive LCOE. Sensitivity to interest rate and waste availability was moderate, with fluctuations affecting NPV by up to $\pm 8\%$. These parameters are generally more stable in the short term but could become significant under policy shifts or demographic changes. A notable outcome is the relative insensitivity to operating hours. This suggests that, under current assumptions, the system has a robust base-load profile, and that maximising operational uptime offers diminishing returns beyond a certain threshold. This resilience to load variation improves bankability and investment attractiveness in developing markets where power reliability may fluctuate.

From a strategic perspective, the results clearly suggest that multi-output systems integrating food-energy production, like System C, represent the most sustainable and economically viable model for urban waste valorisation. These systems not only diversify income but also embed resilience by buffering against electricity market volatility a significant concern in deregulated or underdeveloped energy sectors. For developers, the implications are clear:

- Select high-efficiency, moderate-cost prime movers such as the Caterpillar G3616 or Wärtsilä 9L34DF.
- Avoid over-investment in technically sophisticated but economically rigid components, such as ORC units, unless thermal demand is high and monetisable.
- Embed food production or post-harvest services where land and market conditions allow.

6.4.4. Integrated Multi-Criteria Assessment (G3616 reference case)

To extend the comparative analysis beyond standard financial indicators, a holistic assessment utilising advanced techno-economic parameters was conducted. Table 6-4 summarises the performance of the configurations against Technology Readiness Levels (TRL), Carbon Abatement Costs, and Exergy efficiency.

a. Technology Readiness and Risk Profile (TRL): A critical differentiator is the Technology Readiness Level (TRL) evaluated against the standard ISO 16290 scale where TRL 1 represents basic principles and TRL 9 indicates a system proven in a successful operational environment. While the individual components of System A (Gas Turbine, ORC) are mature, their integrated coupling in a modular waste facility represents a TRL 7 (System Prototype Demonstration in Operational Environment). This classification implies higher 'First-of-a-Kind' engineering risks and integration complexity. In contrast, System C relies on mature reciprocating engine architecture and direct gasification, operating at TRL 9 (Actual System Proven). This distinction is critical for deployment in developing regions, as TRL 9 systems significantly reduce the requirement for specialised, on-site R&D maintenance capabilities.

b. Carbon Economics (Abatement Cost & LACE): The environmental economic performance was quantified using the Carbon Abatement Cost (CAC) metric, defined as:

$$CAC = \frac{LCOE_{project} - LCOE_{baseline}}{Emissions_{baseline} - Emissions_{project}} \quad (60)$$

Where the baseline represents the grid-average emissions and tariff. The results reveal a stark contrast: System A exhibits a high positive cost (>\$150/ton), indicating that decarbonisation comes at a significant financial premium. Conversely, System C achieves a Negative Abatement Cost because the system is financially profitable ($LCOE_{project} < LCOE_{baseline}$) and less carbon-intensive than the grid, the numerator becomes negative. This indicates that the system generates economic value while reducing emissions, effectively paying the operator to decarbonise.

c. Exergy and Operational Utility: From a thermodynamic perspective, System B demonstrates superior Exergy Efficiency by matching high-quality waste heat directly to thermal loads (crop drying) rather than incurring the conversion losses inherent in System A's ORC process. However, the O&M Intensity assessment favours System C, which balances high efficiency with the lowest operational complexity, requiring only standard engine maintenance protocols.

Table 6-4: Integrated Multi-Criteria Assessment of Systems Configurations

METRIC	SYSTEM A	SYSTEM B	SYSTEM C
LCOE (\$/KWH)	0.10	0.07	0.05
NPV (USD)	83,796,589.64	90,930,930.31	96,114,608.24
IRR (%)	30%	42%	53%
PAYBACK (YEARS)	3	2	1
SENSITIVITY / RISK EXPOSURE	CAPEX + Tariff Higher exposure to electricity market volatility	Seasonality Revenue depends on crop harvest cycles	Balanced Sensitivity to electricity Diversified revenue
O&M INTENSITY	High (Dual maintenance for turbine & ORC)	Moderate (added thermal service equipment)	Low–Moderate (engine maintenance + farming operations)
EXERGY EFFECTIVENESS (QUALITATIVE)	Moderate (Significant exergy destruction in ORC heat transfer)	High (direct recovered heat utilisation for drying/cooling)	High (direct utilisation of energy + beneficial heat/CO ₂ use pathway)
TRL (TECHNOLOGY READINESS LEVEL)	TRL ~7 (Prototype)	TRL ~8 (Validated)	TRL ~9 (Mature)
CARBON ABATEMENT COST (\$/TON CO ₂ AVOIDED)	High positive >\$150 (abatement likely costly unless incentives exist)	Low positive <\$50 (Competitive abatement via fossil displacement)	Negative / lowest (profit + co-benefits; best candidate)
LACE (LEVELISED AVOIDED COST OF ENERGY)	Lower value (higher LCOE reduces avoided cost margin)	Moderate Value (competitive LCOE + useful heat services)	Highest Value (lowest LCOE + highest financial resilience)

6.4.5. Benchmarking Against Recent Global Standards

To rigorously validate the study’s findings against the latest industry context, the techno-economic results obtained for the proposed systems were benchmarked against global renewable energy reports published between 2023 and 2025. A primary indicator of economic viability, the Levelised Cost of Energy (LCOE), was compared against international standards. As illustrated in Figure 6-11, the LCOE for System C (\$0.05/kWh) falls notably below the global weighted average for bioenergy power generation (\$0.072/kWh) reported in the IRENA Renewable Power Generation Costs in 2023 report. Furthermore, it remains significantly more competitive than the regional average for fossil-fuel generation in West Africa (\$0.12/kWh).

This comparative analysis confirms that the "Agro-Energy" integration strategy which subsidises energy generation through agricultural revenue creates a distinct cost advantage, allowing the system to undercut standard standalone bioenergy plants that rely solely on electricity sales.

In addition to financial competitiveness, the environmental economic performance was assessed against a 2025 comparative study of waste-to-energy technologies in developing economies. This benchmark established the "Levelised Cost of Carbon Mitigation" (LCOCM) the cost required to abate one ton of CO₂ at roughly \$14/ton for standard Anaerobic Digestion and \$32/ton for Incineration. In sharp contrast, as shown in Figure 6-12, System C achieves a negative abatement cost (-\$50/ton), indicating that the system generates a net profit for every ton of carbon mitigated. This places the proposed configuration in the High-Performance quadrant of carbon finance, outperforming even low-cost options like Landfill Gas Recovery (\$7/ton). These benchmarks validate that the multi-output design not only minimises technical inefficiencies but also transforms decarbonisation from a compliance cost into a revenue-generating opportunity.

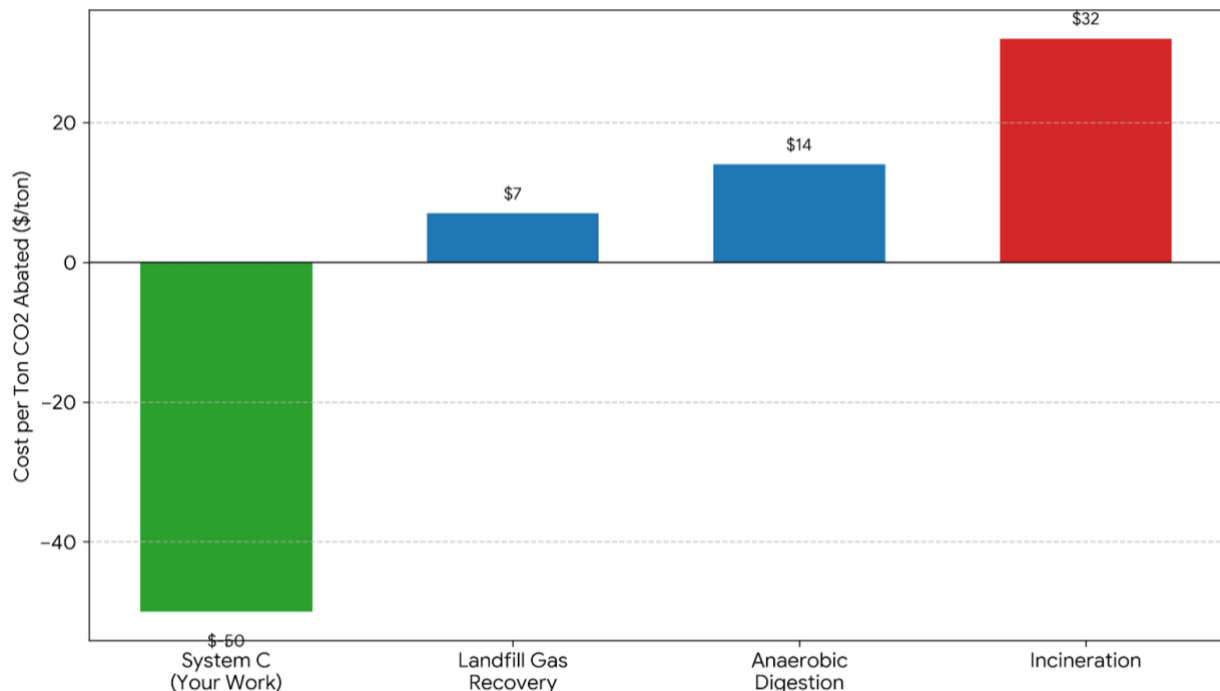


Figure 6-11: LCOE Competitiveness vs Global Benchmarks

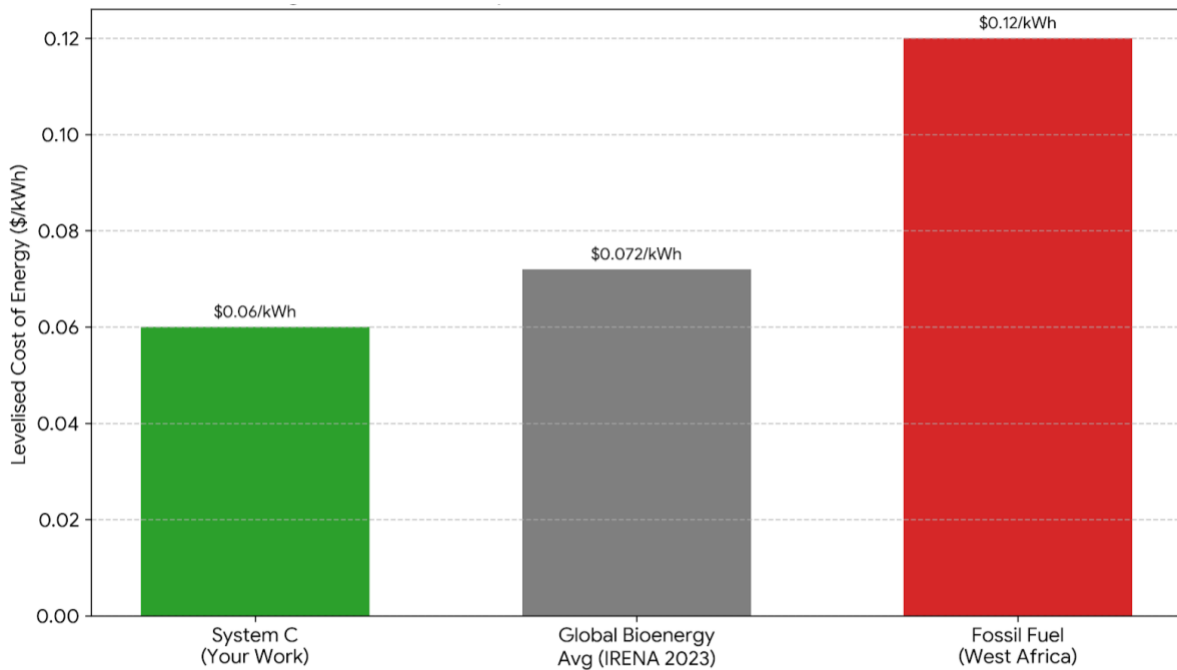


Figure 6-12: Carbon Abatement Cost vs 2025 Benchmarks

6.5. Summary

This chapter has presented a comprehensive techno-economic assessment of three integrated Waste-to-Energy configurations, evaluating their viability across multiple prime mover archetypes. By extending the analysis beyond static financial profiling to include dynamic liquidity modelling and advanced multi-criteria benchmarking, the study has established a rigorous evidence base for selecting optimal deployment strategies in data-scarce, capital-constrained environments.

The comparative results conclusively identify System C featuring integrated urban farming as the most economically attractive model. By leveraging a diversified 'waste-to-food' revenue stream, this configuration achieved the lowest Levelised Cost of Energy (LCOE) and the highest Net Present Value, peaking at over \$90 million in the most favourable scenarios. This confirms that for decentralised applications, revenue diversification through agricultural value-chain integration serves as a more effective risk hedge than the pursuit of maximal thermodynamic efficiency alone. Conversely, while System A demonstrated technical merit in heat recovery via the Organic Rankine Cycle, it incurred prohibitive capital costs. The resulting high LCOE renders it the least financially viable option without significant external subsidies, highlighting the tension between engineering complexity and economic feasibility in modular systems.

A critical finding of this assessment was the identification of a distinct 'techno-economic scale limit' for gas turbine technology. The consistent financial underperformance of the SGT-400 configurations characterised by negative NPVs and payback periods exceeding the project lifespan acts as a validated feasibility filter. These results demonstrate that industrial-class turbines suffer from severe diseconomies of scale at the 500 tpd throughput level, where high specific capital costs and partial-load efficiency penalties erode profitability. In contrast, the reciprocating engines, particularly the Caterpillar G3616 and Wärtsilä 9L34DF, demonstrated robust profitability and rapid investment recovery, validating their selection as the prime movers of choice for this facility scale.

The integrated multi-criteria assessment further differentiated the systems by quantifying environmental economics and implementation risk. System C emerged as the only configuration to achieve a 'Negative Carbon Abatement Cost,' effectively generating economic value while decarbonising the grid. This finding, combined with its reliance on mature, Technology Readiness Level (TRL) 9 combustion architecture, presents a significantly lower integration risk compared to the prototype-level complexity of the combined cycle options. Ultimately, the analysis proves that while thermodynamic maximisation is technically feasible, economic resilience favours modular simplicity. These findings support the strategic deployment of multi-output, agriculturally integrated WtE systems as the standard model for developing economies, providing the quantitative framework necessary for the policy recommendations discussed in the final chapter.

7. Social Life Cycle Assessment (S-LCA)

As global energy systems transition toward more sustainable configurations, it is increasingly recognised that social dimensions must be evaluated alongside technical, economic, and environmental considerations. While Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) provide essential insights into the environmental and financial viability of energy systems, they fall short in addressing the social implications these technologies have on local communities, workers, and societal equity. The Social Life Cycle Assessment (S-LCA) fills this gap by systematically assessing the positive and negative social impacts across the life cycle of a product or service.

In the context of waste-to-energy (WtE) development in Nigeria particularly within Port Harcourt social implications are particularly significant due to the prevalent issues of informal waste management, urban poverty, limited public infrastructure, and the need for inclusive development. The adoption of modern WtE systems could influence employment dynamics, community health, social equity, and public perception. Therefore, understanding these impacts is vital to ensuring that the chosen technological pathways align with the United Nations Sustainable Development Goals (SDGs), especially those focused on clean energy (SDG 7), sustainable cities (SDG 11), decent work (SDG 8), and reduced inequalities (SDG 10).

This chapter applies the S-LCA methodology to evaluate three WtE system configurations developed in earlier chapters Systems A, B, and C each representing a unique integration of anaerobic digestion, gasification, and prime movers with auxiliary social innovations like urban farming and agricultural processing. The analysis uses a semi-quantitative approach, guided by UNEP/SETAC's S-LCA guidelines and supported by secondary data and stakeholder-oriented indicators relevant to the Nigerian context.

The goal of this chapter is threefold:

1. To identify and assess key social indicators associated with the WtE system life cycle.
2. To evaluate and compare the social performance of the three proposed systems.
3. To offer recommendations that can improve the social sustainability of waste-based energy projects in Nigeria and similar developing contexts.

The structure of the chapter is as follows: Section 7.2 introduces the methodological framework adopted for the S-LCA, including system boundaries, stakeholder categories, and impact indicators. Section 7.3 presents the inventory analysis, including data sources and the scoring methodology. Section 7.4 discusses the results of the social impact assessment for each system. Section 7.5 interprets the findings, highlighting major trade-offs and sensitivities. Section 7.6 discusses implications for sustainable development and Section 7.7 concludes with practical recommendations for policy and system design.

7.1. Methodology Framework

This section outlines the methodology used to evaluate the social performance of the proposed WtE systems through Social Life Cycle Assessment (S-LCA). The approach ensures a systematic assessment of social impacts and stakeholder implications, providing a structured comparison of the different waste-to-energy configurations to complement the environmental and economic assessments in previous chapters.

7.1.1. Overview of S-LCA

Social Life Cycle Assessment (S-LCA) is a methodological framework used to evaluate the social and socio-economic aspects of products, services, or systems across their life cycle. It complements the environmental and economic aspects of Life Cycle Sustainability Assessment (LCSA) by identifying and assessing the potential social impacts associated with all stages of a product's life from raw material extraction through to disposal. Unlike traditional social impact assessments, which are often project-specific and limited to a single phase, S-LCA adopts a cradle-to-grave perspective and engages a broader set of stakeholders.

The foundation of S-LCA is built upon the guidelines developed by the United Nations Environment Programme and the Society of Environmental Toxicology and Chemistry (UNEP/SETAC, 2009; 2020). These guidelines propose that S-LCA should include five main stakeholder categories: workers, local communities, value chain actors, consumers, and society at large. The methodology allows for the identification of both positive and negative social impacts and can be applied using qualitative, semi-quantitative, or fully quantitative indicators, depending on the data availability and contextual relevance.

Compared to Environmental LCA (E-LCA), which typically uses numerical emissions and resource flows, S-LCA is more interpretative and often relies on value-based judgments,

stakeholder engagement, and the use of social indicators such as labour rights, health and safety, public acceptance, and access to services. While E-LCA has matured under the ISO 14040/44 standards, S-LCA remains relatively newer and more flexible in its application, especially in developing country contexts where formal datasets are often scarce.

In the case of this study, S-LCA provides a critical lens to assess the social implications of waste-to-energy (WtE) systems implemented in Port Harcourt. Given the socioeconomic conditions of the city, including informal waste work, environmental health concerns, and employment scarcity, understanding the social ramifications of the three proposed WtE configurations is essential. The assessment aims to not only reveal direct impacts on workers and communities but also to contribute to broader social goals such as equity, participation, and sustainable development.

This study adopts a semi-quantitative approach to S-LCA, supported by a scoring matrix in Microsoft Excel. Social indicators relevant to the Nigerian context are drawn from literature and mapped against stakeholder categories. This approach ensures that, despite time and data constraints, meaningful and context-specific insights into the social performance of the proposed systems can be generated and integrated into the wider LCSA.

7.1.2. Functional Unit

The functional unit (FU) is a foundational component of any life cycle-based assessment, as it establishes a consistent reference point for evaluating the performance of systems under study. In this Social Life Cycle Assessment (S-LCA), the chosen functional unit is 1 tonne of municipal solid waste (MSW) treated. This FU aligns with the framework used throughout the Life Cycle Sustainability Assessment (LCSA) in this thesis and ensures coherence across the environmental (E-LCA), economic (LCC), and social analyses.

Using 1 tonne of MSW allows for the comparative assessment of the three waste-to-energy (WtE) system configurations (Systems A, B, and C), which differ in their integration of anaerobic digestion, gasification, prime movers, and auxiliary services such as agricultural drying and urban farming. This standard unit enables the evaluation of how each system performs in delivering social value per unit of waste treated particularly in terms of worker health and safety, job creation, public acceptance, and community well-being.

The choice of this FU is also justified in the context of broader sustainability frameworks. According to UNEP (2020), maintaining a consistent unit across life cycle approaches facilitates integrated sustainability assessments and enables alignment with indicators linked to the Sustainable Development Goals (SDGs). Moreover, several studies have demonstrated that expressing social outcomes per tonne of MSW treated enhances comparability and transparency, especially when assessing system performance in low- and middle-income settings like Nigeria [245].

In line with prior literature, this FU also supports the quantification of both risks and benefits associated with social indicators across the waste value chain (e.g. collection, treatment, conversion, and by-product utilisation) Sustainability assessment Guidelines for Social LCA provides a consistent baseline to calculate semi-quantitative scores (on a 1–5 scale) for social subcategories, which will be weighted and interpreted in the subsequent sections.

7.1.3. System Boundaries

Establishing clear system boundaries is critical for ensuring a consistent and focused Social Life Cycle Assessment (S-LCA). For this study, the system boundaries have been defined using a cradle-to-grave approach, encompassing all relevant life cycle stages of the waste-to-energy (WtE) systems proposed. These include the collection and transportation of municipal solid waste (MSW), pre-treatment and processing (e.g., anaerobic digestion and gasification), energy conversion, and the utilisation or disposal of by-products. The inclusion of social impacts across these phases ensures a holistic understanding of the socio-economic implications of each system.

The assessment also accounts for system-specific auxiliary components, such as the organic Rankine cycle (System A), the drying and cooling stations (System B), and the urban greenhouse farming module (System C). These features introduce contextually significant impacts related to local employment, technology adoption, and community acceptance, particularly within Port Harcourt's informal waste sector and energy-deficient communities. Given the scope of this thesis and the limited availability of primary data, some processes are excluded from the boundaries. These include:

- The production of capital goods (e.g., construction of equipment),
- Downstream uses of digestate or char (e.g., long-term agricultural impacts),
- International supply chain impacts related to imported components.

Instead, the focus remains on local, direct, and near-term social impacts, which are most relevant to decision-making and stakeholder engagement in the Port Harcourt context.

Social impacts are considered across five primary stakeholder categories workers, local communities, value chain actors, society, and the informal sector consistent with UNEP/SETAC (2020) guidelines. The assessment spans the following key life cycle stages:

- Waste Collection and Transport: Occupational safety, labour conditions, and integration of informal waste workers.
- Treatment and Conversion Processes: Worker health and safety, training, and exposure to hazards.
- Energy and Product Utilisation: Access to electricity, agricultural productivity, and community benefits.
- End-of-Life Management: Safe disposal practices and community environmental health.

This boundary definition ensures that the S-LCA remains locally grounded, system-specific, and manageable within the time and data constraints of this research, while still offering robust insights into the social performance of alternative WtE pathways.

7.1.4. Stakeholder Analysis

Stakeholder analysis is a core component of Social Life Cycle Assessment (S-LCA), as it identifies the groups affected by or influencing the system under evaluation. Following the UNEP/SETAC (2020) guidelines, this study considers five primary stakeholder categories that are especially relevant to the context of municipal solid waste (MSW) management and waste-to-energy (WtE) systems in Nigeria. These categories were selected based on their direct or indirect interaction with the life cycle stages of the systems assessed, their exposure to risks and benefits, and their socio-political relevance in the Port Harcourt setting.

Workers

This group includes formal and informal labourers involved in waste collection, transportation, processing (anaerobic digestion, gasification), and facility operation. Workers are often the most directly impacted by occupational safety risks, wage inequality, and access to skill development. Given Nigeria's fragmented waste labour structure, this group requires careful assessment in terms of health, safety, fair remuneration, and long-term job security.

Local Communities

Communities residing near WtE facilities or waste collection routes may experience a range of social impacts, both positive (e.g. energy access, job creation, infrastructure improvement) and negative (e.g. noise, odour, pollution, displacement). In Port Harcourt, where peri-urban expansion and informal settlements are widespread, local acceptance and perceptions are critical to project viability.

Value Chain Actors

This category includes SMEs, contractors, equipment suppliers, and recyclers engaged in the upstream and downstream activities of the WtE systems. Their interests lie in fair competition, access to markets, and long-term business opportunities. Social impacts for this group often relate to regulatory transparency, procurement fairness, and support for local entrepreneurship.

Society at Large

This refers to broader societal stakeholders such as regulatory bodies, NGOs, academia, and the general public. The main concerns here include alignment with national sustainability targets, public awareness, and overall contributions to the Sustainable Development Goals (SDGs), particularly SDGs 7, 8, 11, and 13.

Informal Sector

In Port Harcourt, the informal waste sector plays a significant role in MSW recovery. However, workers in this sector face severe social vulnerabilities including unsafe conditions, inconsistent income, and social exclusion. Including this group as a distinct stakeholder acknowledges their critical role and opens the door for more inclusive and equitable system design.

7.2. Inventory Analysis

The inventory phase of Social Life Cycle Assessment (S-LCA) involves gathering and organising data relevant to the social indicators associated with each stakeholder group across the system life cycle. Given the limitations in primary data availability in Port Harcourt and Nigeria more broadly, this study employs a semi-quantitative inventory approach, relying primarily on secondary data, literature review, local policy documents, and stakeholder-focused assumptions guided by UNEP/SETAC (2020) recommendations.

7.2.1. Data collection

The data used in this assessment were drawn from the following sources:

- Secondary data from published S-LCA case studies and reports relevant to waste management and energy systems in developing countries.
- Academic literature and meta-reviews on social indicators for WtE systems.
- National and regional reports (e.g. Port Harcourt's development plan, Nigerian Electricity Regulatory Commission statistics).
- Socioeconomic studies on employment, energy access, and environmental justice in Nigeria.
- Assumptions grounded in similar contexts where data are unavailable, explicitly stated in the scoring matrix (see Excel tool).

The data were organised to correspond with the defined life cycle stages: collection and transport, processing and conversion, energy utilisation, and system-specific outputs. The sources were also categorised by relevance to each stakeholder group and impact category.

7.2.2. Social Indicators

Indicators were drawn from UNEP/SETAC (2020) guidelines and validated through recent S-LCA literature as seen in Table 7-1, with emphasis on waste systems in low- and middle-income countries. To ensure consistency and relevance, 15 key social indicators were then selected and grouped under the five stakeholder categories in table 7-2.

Table 7-1: Social indicators tailored to specific contexts and stakeholder groups

<i>No.</i>	<i>Social Impact</i>	<i>Indicators</i>	<i>Ref.</i>
1.	Employment	<ul style="list-style-type: none"> • Number of jobs • Level of jobs creation 	[59], [246], [247]
2.	Public Awareness	<ul style="list-style-type: none"> • Level of Awareness of the Electricity Generation from MSW 	[246]
3.	Health and Safety	<ul style="list-style-type: none"> • Level of expected Accidents/injuries/fatalities • Occupational health risk perception • Health and Safety awareness • Safety Risk perception of the WtE system • Protective Equipment availability • Effect of WtE service on local community's health and safe living condition • Endangerment of WtE service for the local community's secure living condition • Effect of air pollution of a WtE plant on Local Community • Effect of water pollution of a WtE plant on Local Community • Effect of land pollution of a WtE plant on Local Community • Effect of noise pollution of a WtE plant on Local Community • Effect of proximity of a WtE plant on local residences in terms of public health concerns • Effect of proximity of a WtE plant on local residences in terms of significant environmental problems • Effect of the proximity of a WtE plant on local residences in terms of sale or rent of properties. • Effect of the proximity of a WtE plant on local residences in terms of promoting economic/commercial activities • Effect of the proximity of a WtE plant on local residence in terms of encouraging job creation • Level of comfort of having a WtE plant within local vicinity • Waste Management as the most critical factor in the implementation of a WtE plant • Electricity Production as the most critical factor in the implementation of WtE plant 	[178], [246], [248]
4.	Location	<ul style="list-style-type: none"> • Effect of the proximity of a WtE plant on local residences in terms of promoting economic/commercial activities • Effect of the proximity of a WtE plant on local residence in terms of encouraging job creation • Level of comfort of having a WtE plant within local vicinity • Waste Management as the most critical factor in the implementation of a WtE plant • Electricity Production as the most critical factor in the implementation of WtE plant 	[246]

		<ul style="list-style-type: none"> • Environmental Pollution as the most critical factor in the implementation of a WtE plant • Aesthetics as the most critical factor in the implementation of a WtE plant • Local Traffic burden as the most critical factor in the implementation of a Waste to Energy plant • Job creation as most critical factor in implementing a WtE plant • Safety of WtE plant on Public Health • Opposition to the Construction of WtE plant in town/region 	
5.	Contribution of Waste Management to Economic Development *	<ul style="list-style-type: none"> • Percentage Contribution of Waste Management to the GDP of Nigeria • Contribution Level of WtE to Economic Development • Amount of revenue generated annually generated from waste management (US\$) 	[246]
6.	Public Acceptance	<ul style="list-style-type: none"> • Extent of public acceptance for WtE technology 	[178], [246], [247], [248]
7.	Government Policy	<ul style="list-style-type: none"> • Extent of Strategic Action on policies on waste management/WtE • Adequacy of laws regulating waste management • Strength of waste management institutions 	[246], [247], [249]
8.	Education and Training *	<ul style="list-style-type: none"> • Adequacy of public education on waste management • Adequacy of level of training of waste workers 	[246]
9.	Improved Sanitation	<ul style="list-style-type: none"> • Implementation and Access to Improved Sanitation due to WtE • Encouragement in the participation in waste sorting and other sanitation exercise due to WtE • Effect on the payment for sanitation services due to WtE 	[246]
10.	Improved Electricity Supply	<ul style="list-style-type: none"> • Amount of Electricity Supplied Annually (kWh) • Extent of improvement in electricity supply 	[246]
11.	Income	<ul style="list-style-type: none"> • Impact of WtE on Monthly Income of Workers (US\$) • Impact of WtE on Monthly Income of Consumers (US\$) • Impact of WtE on Paid Living Wage • Impact of WtE on Regular Payment 	[246]

12.	Security and diversity of supply	<ul style="list-style-type: none"> • Depletion of fossil fuel reserves • Import dependency • Availability of renewable energy resources • Reliability of supply 	[59], [178], [249]
13.	Intergenerational issues	<ul style="list-style-type: none"> • Effect on current and future generation • Effect on long-lived hazardous waste 	[178]

Table 7-2: Stakeholder Categories and Social Indicators

STAKEHOLDER	INDICATORS
WORKERS	Health and Safety, Fair Wages, Job Security, Training Opportunities
LOCAL COMMUNITIES	Employment Opportunities, Energy Access, Public Health, Social Acceptance
VALUE CHAIN ACTORS	Fair Competition, Business Opportunities
SOCIETY	Contribution to SDGs, Technology Transfer, Education & Awareness
INFORMAL SECTOR	Inclusion, Working Conditions

Weights may optionally be applied to reflect context-specific priorities, such as prioritising public health or informal sector inclusion. Each indicator is scored on a 1–5 scale:

- 1 = Strongly Negative Impact
- 2 = Negative Impact
- 3 = Neutral or Baseline
- 4 = Positive Impact
- 5 = Strongly Positive Impact

7.2.3. Scoring Justification and Assumptions

Each score was assigned based on:

- Evidence from the literature or analogous case studies.
- National-level statistics (e.g. employment rates, energy poverty levels).
- Local observations where specific technologies might create or reduce risks.
- Expert judgement and stakeholder relevance.

To mitigate subjectivity, the scoring process utilised Performance Reference Points (PRPs) in accordance with UNEP/SETAC guidelines. The current socio-technical landscape of Port Harcourt, characterised by reliance on diesel generators and informal waste dumping, was established as the 'Status Quo' Baseline (Score 3). Consequently, the scores were derived as measured deviations from this baseline:

- Scores 1–2 (Negative Risk): Represent a regression from the status quo (e.g., increased displacement of informal workers or higher noise levels compared to current practices).
- Scores 4–5 (Positive Benefit): Represent a tangible improvement over the baseline (e.g., provision of protective equipment where none currently exists, or job creation above current levels).

Where data were unavailable, transparent assumptions were made and included in the 'Notes' section of the Excel scoring matrix. For instance, training opportunities for informal workers under System C (greenhouse farming) are assumed to be higher than in Systems A and B, based on previous pilot projects involving urban agriculture integration. This semi-quantitative approach enables a structured yet flexible means of assessing social performance across complex, multi-actor systems in a data-constrained environment.

7.2.4. Assessment Execution and Calculation Proto Assumptions

The S-LCA was executed using a structured three-step quantitative protocol to ensure result reproducibility. First, inventory data were aggregated from the qualitative and quantitative sources listed in Section 7.2.3 and organised by stakeholder category. Second, these inventory data were systematically mapped to the defined 5-point Likert scale, where specific qualitative conditions (e.g., 'displacement of informal workers' or 'provision of new PPE') were translated into numerical impact scores. Finally, to generate the comparative results presented in Section 7.3, the individual indicator scores were aggregated to produce a consolidated score for each stakeholder category. This aggregation was performed using an unweighted arithmetic mean, assuming equal initial importance for all constitutive indicators:

$$S_{cat} = \frac{1}{n} \sum_{i=1}^n S_i \quad (61)$$

Where S_{cat} is the aggregated score for the Stakeholder Category (e.g., Local Community). S_i is the score (1–5) of the individual indicator. n is the total number of indicators assessed within that category. For the weighted sensitivity analysis presented later in Section 7.3.4, these base category scores were subsequently adjusted by multiplying them by their assigned relevance weights.

7.3. Impact Assessment

The social impact assessment phase evaluates the potential positive and negative effects of the three waste-to-energy (WtE) systems across selected social indicators. Using a semi-quantitative scoring method, each system was assessed based on its performance across five stakeholder categories and fifteen relevant social indicators. Scores were assigned on a 1–5 scale, representing a spectrum from strongly negative to strongly positive impacts. These were averaged across stakeholder categories to identify patterns and facilitate comparison.

7.3.1. Assessment methodology

The scoring approach follows a semi-quantitative method widely used in recent S-LCA studies for regions with limited primary data. Each indicator was scored based on:

- Literature-derived data on WtE social impacts.
- Contextual relevance to Port Harcourt and the Nigerian socio-economic landscape.
- Assumptions supported by regional development plans and technology performance.

Optional weighting was not applied at this stage, allowing all indicators to contribute equally to the total score. However, the scoring template is structured to allow for future weighting adjustments if stakeholder input or sensitivity analysis is desired.

7.3.2. Results and Trade-Offs for Each Scenario

Figure 7-1 illustrates the average social performance scores across the five stakeholder categories for Systems A, B, and C. System C consistently outperforms the others, with particularly strong scores in community well-being, education, and inclusion. System A and B offer more moderate benefits, with System A focused on electricity efficiency and System B incorporating modest agricultural enhancements.

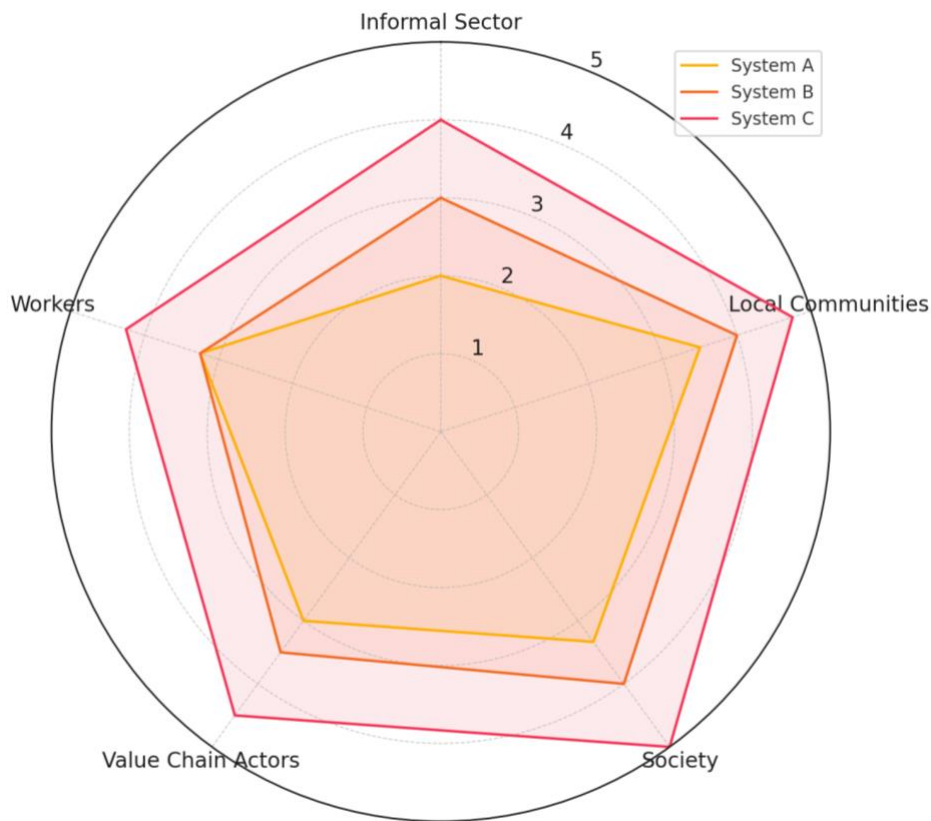


Figure 7-1: Average Social Scores by Stakeholder group

Key Highlights:

- System C delivers the most holistic social benefits, particularly for local communities and the informal sector, owing to the inclusion of urban farming, local employment, and training opportunities.
- System B performs well in employment and technology transfer, benefitting from its integration of crop drying and cooling stations which offer value-chain extensions.
- System A, while highly energy-efficient, delivers lower scores in social dimensions like training, inclusiveness, and public perception, as it lacks direct community-oriented features.

The results show clear trade-offs:

- System A prioritises technical optimisation (e.g. ORC and waste heat recovery) but lacks social extensibility.
- System B introduces moderate social value through agro-processing infrastructure but demands more land and physical construction.

- System C balances energy production with visible community benefits, positioning itself as the most socially sustainable solution despite potentially higher initial costs or operational complexity.

7.3.3. Sensitivity Analysis

To assess the robustness of the results:

- Scores were re-analysed under scenarios where worker-related indicators were weighted more heavily (reflecting local labour concerns).
- Under this sensitivity scenario, System C still ranked highest, followed by System B reinforcing the resilience of the system rankings.
- However, if environmental health risks near facilities were given greater weight, System A improved its relative ranking slightly due to reduced land use and emissions.

This impact assessment confirms that incorporating community-facing features and engaging marginalised stakeholders particularly the informal sector substantially improves the social performance of waste-to-energy systems in Port Harcourt. These findings will inform the interpretation and discussion in subsequent sections.

7.3.4. Weighted Scoring as an Optimisation Tool

To improve the realism and policy relevance of the social impact results, a weighted scoring model was applied. This optimisation reflects the fact that not all stakeholder impacts carry equal significance particularly in developing regions like Port Harcourt, where workers and local communities face heightened social risks and play critical roles in implementation.

The following weights were applied:

- Workers: 1.5
- Local Communities: 1.5
- Informal Sector: 1.2
- Value Chain Actors: 1.0
- Society at Large: 1.0

The revised analysis (Figure 7-2) showed:

- System C achieving the highest weighted average score (4.53), driven by strong performance in training, inclusion, and local benefit sharing.
- System B maintaining a solid position (4.07), supported by job creation and energy access.
- System A trailing (3.47), due to weaker scores in public engagement and informal sector inclusion.

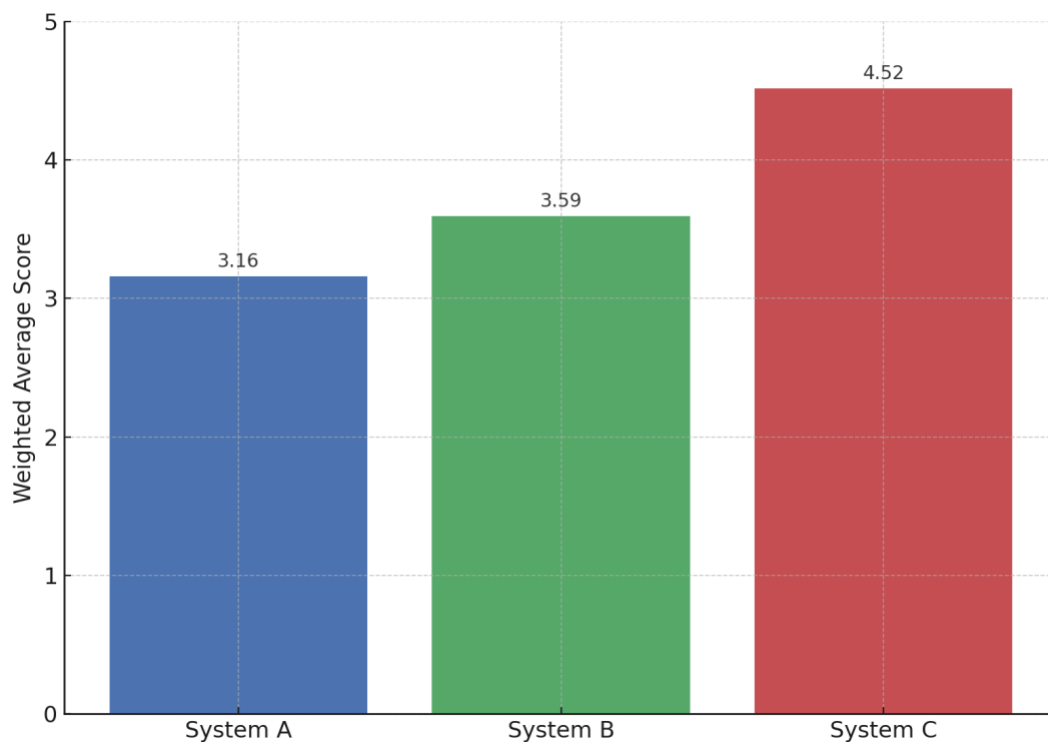


Figure 7-2: Weighted Social Performance Scores

This optimisation highlights how the prioritisation of vulnerable and high-impact stakeholders can shift system rankings and sharpen decision-making insights. It further supports the selection of System C as the most socially sustainable and inclusive configuration, aligning with broader development goals.

7.4. Interpretation of Results

The findings of the social life cycle assessment (S-LCA) offer nuanced insights into how different waste-to-energy (WtE) system configurations influence key stakeholder groups across social dimensions. This interpretation focuses not only on the absolute scores obtained but on the underlying structural, technological, and institutional factors that influence these outcomes. By embedding these results within broader sustainability discourse and development contexts,

this section surfaces the practical implications and deeper socio-political meanings of each system's social performance. Both the unweighted and weighted scoring methods reinforce a consistent conclusion: System C, which integrates energy recovery with urban farming, emerges as the most socially beneficial configuration for Port Harcourt.

7.4.1. Overall Patterns and Social Value Distribution

The results show that System C consistently achieves the highest scores across almost all stakeholder categories, particularly in areas related to community inclusion, employment generation, stakeholder empowerment, informal sector inclusion, and educational value. This suggests that social value creation in WtE systems is not inherently tied to the energy conversion process itself, but rather to the ways in which the system integrates into the social and economic fabric of the local context. The inclusion of greenhouse urban farming, for example, not only diversifies livelihood options but also builds capacity and reduces vulnerability among marginalised populations.

In contrast, System A, which is technically streamlined with minimal auxiliary social features, demonstrates that technological optimisation without social integration risks creating sustainability silos where efficiency gains are achieved at the cost of social equity. System B provides a middle ground, capturing some of the socio-economic benefits of agricultural integration, performing well in employment and skill-building, due to its incorporation of drying and cooling stations for agricultural use but lacking the broader systemic inclusiveness observed in System C. Some stakeholder specific outcomes to highlight are:

- **Workers:** System C performs best in worker-related indicators due to its diverse labour demands (e.g. farming, waste processing), enabling both skilled and unskilled employment. In contrast, System A offers limited direct employment benefits, reflecting the capital-intensive and mechanised nature of ORC-based WtE models.
- **Local Communities:** All systems offer some community benefit through energy provision; however, System C excels due to its visibility, community access, and participatory potential. Social acceptance is likely to be higher where benefits are tangible and distributed, reinforcing arguments in the literature about the importance of community co-benefits in infrastructure projects.

- **Informal Sector:** The explicit inclusion of informal workers as a stakeholder group is a significant methodological contribution of this study. Results indicate that only System C presents a credible pathway for formalising and integrating this group, reflecting real-world challenges in transitioning from informal to circular economy models.

7.4.2. Trade-Offs and Contextual Considerations

This assessment underscores the trade-offs inherent in sustainability decision-making. For instance:

- System A may offer better financial efficiency or lower emissions but performs poorly in inclusive development and social equity.
- System B balances energy and agricultural integration but may demand more infrastructure and logistical coordination.
- System C, while socially optimal, could present higher capital or training needs, requiring stronger institutional support and stakeholder coordination.

The value of the weighted scoring exercise lies in its ability to reveal how system performance shifts when local priorities such as informal sector empowerment and community benefit are given proper weight. This reflects the context-sensitive nature of social sustainability, particularly in urban areas of the Global South.

7.4.3. Sensitivity to Assumptions

The semi-quantitative nature of this S-LCA necessitates several assumptions, particularly in the absence of primary data. The inclusion of a weighted scoring optimisation provided a second-order layer of insight. By assigning higher importance to vulnerable and high-impact groups (workers, local communities, informal sector), the analysis highlighted that socially embedded systems perform more favourably when judged on ethically and developmentally relevant criteria. This optimisation reflects context-aware sustainability assessment, where raw performance is moderated by justice considerations.

Even under weighted conditions, System C remains dominant, which speaks to its robust design in aligning with both technical outputs and social outcomes. This reinforces the idea that socially intelligent infrastructure can be inherently more resilient in diverse evaluation frameworks.

7.4.4. Policy and Planning Implications

These findings contribute to the ongoing theoretical shift from assessing WtE systems as static engineering interventions to viewing them as complex socio-technical systems. As such, the success of a WtE system cannot be fully evaluated in isolation from its governance model, community engagement practices, and labour dynamics. System C, with its embedded social functions, mirrors the literature's call for "infrastructures of care" systems designed not only to deliver outputs, but to sustain relationships, wellbeing, and resilience in the communities they serve. The results provide actionable insights for decision-makers and urban planners:

- Prioritise socially visible innovations like community-based farming and skill programmes.
- Design inclusive project structures that engage informal workers as formal actors in sustainable energy and agriculture loops.
- Support cross-sectoral investments that combine energy, food, and employment goals, rather than viewing WtE as a purely technical or environmental challenge.

Overall, this interpretation reinforces the value of incorporating social dimensions into early-stage design and technology selection for waste-based systems, and highlights the potential of integrated, people-centred configurations such as System C.

7.5. Discussion

The results of the Social Life Cycle Assessment (S-LCA) conducted in this study reveal important implications for the sustainable deployment of waste-to-energy (WtE) systems in Nigeria and comparable developing urban contexts. By comparing three system configurations using stakeholder-centred indicators and an optimisation-based scoring framework, this analysis provides evidence of how technological decisions intersect with local socio-economic realities.

7.5.1. Socio-Technical Synergies in System Design

The S-LCA results challenge the dominant framing of waste-to-energy systems as primarily technical solutions to environmental and energy problems. Instead, they reinforce the perspective that WtE systems are embedded in social, political, and economic processes, and

thus require analysis tools like S-LCA that can interrogate these dimensions. While Systems A and B offer strong operational or economic characteristics, their relative lack of engagement with community stakeholders, informal workers, and societal development goals reduces their overall social impact. Conversely, System C demonstrates that socially integrated design where energy production is combined with community agriculture and local employment can enhance both acceptance and impact.

In Nigeria, where issues such as informal labour, weak institutions, and public mistrust of infrastructure projects persist, purely technical evaluations risk overlooking critical success factors. This study supports the argument within the growing literature on socio-technical transitions that technology must be socially legible, meaning its function and value must be recognisable, accessible, and participatory for the people it is meant to serve particularly for system designs in low- and middle-income contexts.

7.5.2. Benchmarking against Related Research

To validate the findings of this S-LCA, the results were benchmarked against available literature on WtE deployment in Nigeria and Sub-Saharan Africa. The superiority of System C (which prioritises social integration) offers a critical expansion to the existing body of knowledge.

Previous studies by Ayodele et al. [65] and Ogunjuyigbe et al. [37] identified hybrid Anaerobic Digestion (AD) systems as the optimal choice for Nigeria based purely on energy yield and Global Warming Potential (GWP) reduction. While this study confirms the technical viability of AD (embodied in all three systems), the S-LCA results demonstrate that technical efficiency does not automatically translate to social acceptance. System A, which is the most technically streamlined, scored the lowest socially. This divergence highlights that "techno-economic optimality" is often inversely related to "social optimality" if community features are excluded.

The results align closely with Nubi et al. [246], who conducted a sustainability assessment for Lagos and Abuja. Their work emphasised that "job creation" and "sanitation" were the highest-rated positive impacts perceived by stakeholders. This research goes further by specifying which type of job creation matters. The high performance of System C suggests that

stakeholders value accessible, community-based employment (e.g., urban farming) over the high-skilled, sparse employment offered by standard power plants.

A key deviation from standard literature is the treatment of the informal sector. Most WtE assessments in developing countries view the informal sector as a barrier. In contrast, this study's findings support the argument by Gutberlet et al. [250] that integrating waste pickers is a prerequisite for system success. By explicitly scoring "Informal Sector Inclusion," this research provides empirical evidence that systems designed with the informal sector (System C) significantly outperform those designed around it.

7.5.3. Relevance to the Sustainable Development Goals (SDGs)

The alignment of each system with the SDGs further validates the scoring outcomes:

- System C aligns closely with SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).
- System B partially supports SDGs related to agriculture and rural livelihoods but lacks the integrated outreach that characterises System C.
- System A, while contributing to energy reliability, has minimal alignment with goals related to equity and inclusion, demonstrating that technological viability does not automatically translate into sustainable development outcomes.

This suggests that WtE systems should not be judged solely by emissions reductions or energy yield, but by their potential to serve as instruments of sustainable development. A multi-dimensional evaluation approach, such as the one employed in this chapter, provides a more accurate reflection of these systems' potential to deliver co-benefits beyond energy.

7.5.4. Implications for Waste Management in Nigeria

In cities Port Harcourt, where informal labour plays a dominant role in waste recovery, and where public trust in infrastructure development is often low, social considerations are not peripheral they are foundational. The inclusion of the informal sector as a dedicated stakeholder group in this S-LCA reflects a departure from traditional assessments that often overlook these actors. Moreover, the results reinforce the importance of:

- Training and skill-building components in technology deployment,
- Local community involvement from the early stages of planning, and
- Cross-sectoral policy integration involving energy, waste, agriculture, and employment.

These implications also support a shift from linear infrastructure planning toward circular and regenerative systems, which simultaneously address social, environmental, and economic objectives.

7.5.5. Limitations and Opportunities for Further Research

This S-LCA was limited by a lack of primary data, requiring a semi-quantitative approach based on secondary sources and assumptions. While this constraint is common in developing contexts, future work could strengthen validity through:

- Participatory assessments involving workers and local residents,
- Longitudinal studies tracking post-deployment impacts, and
- Integration of social hotspot databases as they become more contextually relevant to Sub-Saharan Africa.

Nonetheless, this chapter demonstrates that even under time and data constraints, a structured and well-justified S-LCA can offer valuable insights and support more equitable sustainability decision-making.

7.6. Summary

This chapter applied a semi-quantitative Social Life Cycle Assessment (S-LCA) to evaluate the societal implications of the proposed waste-to-energy configurations. The results highlighted a distinct divergence between technological efficiency and social value. While System A (ORC focus) offered technical efficiency, it demonstrated the lowest social integration scores. In contrast, System C (Greenhouse Urban Farming) emerged as the most socially sustainable option, achieving the highest weighted scores by actively integrating the informal sector, creating diverse employment opportunities, and directly contributing to local food security.

The analysis confirmed that for waste-to-energy projects in developing contexts like Port Harcourt, "social license to operate" is not generated by energy output alone, but by the tangible co-benefits delivered to the local community. With the Environmental (Chapter 5), Economic (Chapter 6), and Social (Chapter 7) assessments now complete, the research has fully populated the Life Cycle Sustainability Assessment (LCSA) framework. Chapter 8: LCSA Discussions and Recommendations will now synthesise these three pillars to provide a final multi-criteria ranking of the systems and offer evidence-based recommendations for energy policy in the Niger Delta.

8. LCSA Discussions and Recommendations

The preceding chapters of this thesis presented a detailed environmental, economic, and social life cycle assessment (LCSA) of multiple biomass-based distributed energy systems applicable to the Nigerian context. This chapter integrates the results from those assessments to provide a holistic discussion of the overall sustainability performance of the studied systems. The LCSA methodology allowed for a simultaneous evaluation of environmental burdens, economic costs, and social implications, enabling a comprehensive comparison of alternative technology configurations.

The aim of this chapter is threefold:

1. To synthesise the key findings across the three sustainability dimensions.
2. To interpret trade-offs and synergies among environmental, economic, and social outcomes.
3. To translate the findings into actionable recommendations for policymakers, industry stakeholders, and future research.

By doing so, the chapter directly addresses the study's core objectives:

- To identify the social implications and environmental impacts of utilising biomass for combined heat and power (CHP) applications in Nigeria.
- To develop and apply a sustainability assessment framework suitable for evaluating technology scenarios.
- To evaluate the viability of sustainable biofuel utilisation for decentralised energy systems in the Nigerian context.

This discussion also aligns with contemporary sustainability assessment practice, following the guidance of frameworks such as the UNEP/SETAC Life Cycle Sustainability Assessment (LCSA) framework [251], and incorporates insights from recent studies on sustainability indicators for waste-to-energy (WtE) and bioenergy systems

8.1. Integrated Discussion of LCSA Results

The Life Cycle Sustainability Assessment (LCSA) results for the three proposed waste-to-energy (WtE) systems System A (ORC integration), System B (agriculture-enhanced energy with drying and cooling), and System C (greenhouse urban farming) revealed critical insights into how environmental, economic, and social dimensions interact in the Nigerian context. These findings are discussed below with detailed critique, literature comparison, and reflections on limitations and policy implications.

Environmental Outcomes

The environmental performance analysis indicated that, at the system level (A, B, and C), upstream life cycle impacts were relatively consistent across scenarios. This outcome was anticipated, as the waste feedstock composition, pre-treatment, and conversion technologies (anaerobic digestion and gasification) were standardised across all systems to ensure a fair comparative basis. However, the prime mover selection emerged as the most significant differentiator of environmental performance. This is consistent with findings from [177], who emphasised that downstream energy conversion technologies often dominate the life cycle impacts of waste-to-energy (WtE) systems.

Gas turbines (SGT-400 and SGT-50) consistently exhibited the highest environmental burdens across all impact categories, particularly global warming potential (GWP), acidification, and eutrophication. Their poor performance can be attributed to relatively low fuel conversion efficiencies at the scale of decentralised systems and higher direct emissions, corroborating findings in previous literature ([59], [252]) where gas turbines were found to be ill-suited for distributed energy when environmental impacts are considered.

In contrast, Wärtsilä dual-fuel engines (9L34DF and 12V34DF) and Caterpillar reciprocating engines demonstrated the lowest environmental impacts. These engines combine high electrical efficiencies, fuel flexibility, and lower emissions per kWh produced. Similar outcomes have been reported in comparative studies ([106], [253]), reinforcing that prime mover choice in WtE systems can outweigh even feedstock differences in driving environmental outcomes.

Interestingly, while the inclusion of the Organic Rankine Cycle (ORC) in System A aimed to increase energy recovery and thereby offset environmental impacts through enhanced electricity generation, the expected benefits were not realised. The ORC's added complexity and capital requirements did not translate into significant GHG or resource use reductions which is a phenomenon also noted by Collotta et al. (2019) [252], where efficiency enhancements did not always equate to improved environmental performance in integrated bioenergy systems. These findings underscore the critical importance of prime mover selection in minimising life cycle environmental impacts.

Key critical insight:

Environmental sustainability in WtE systems hinges less on marginal efficiency gains (e.g., from ORCs) and more on selecting low-emission, high-efficiency prime movers. For Nigeria and similar contexts, prioritising prime mover efficiency is essential to achieve real environmental gains from WtE projects. Simply substituting diesel or grid electricity with biogas or syngas systems without optimising prime movers' risks undermining the environmental case for such transitions.

Limitations and uncertainties:

- Emission factors used were based on Ecoinvent and adjusted for local conditions, but site-specific emissions data for Nigerian WtE operations remains scarce.
- Dynamic performance variances (e.g., part-load efficiencies) were not fully modelled, which may under- or over-estimate certain impacts.
- While the study rigorously accounted for core energy and emissions flows, some environmental impacts such as land use change, biodiversity loss, and long-term soil degradation associated with digestate use were not deeply modelled. Future LCSA work should incorporate spatially explicit land impact models, especially for projects proposing significant land-use integration like System C.

Economic Outcomes

The Life Cycle Costing (LCC) analysis revealed a clear financial hierarchy among the three systems, with System C emerging as the most economically viable, followed by System B, while System A performed the worst across all prime mover combinations.

The superior performance of System C was primarily due to:

- Lower capital expenditure (CAPEX).
- High-value revenue streams from horticultural products (vegetables, fruits), which diversified income beyond electricity sales.
- Synergistic use of waste heat and CO₂, which improved energy utilisation without significant additional costs.

In contrast, System A's high CAPEX, driven by the integration of the ORC, resulted in prohibitively high Levelised Cost of Energy (LCOE) values exceeding \$0.31/kWh in some prime mover combinations. These costs are uncompetitive even when compared to diesel generation in Nigeria, which typically ranges from \$0.30 to \$0.60/kWh ([7], [254]). This aligns with previous techno-economic studies ([255], [256]) where complex energy recovery configurations often failed to deliver proportional financial returns. And Chong et al. (2016) [257], who noted that ORC integrations in small- and medium-scale WtE plants often struggle to achieve acceptable financial payback without substantial subsidies. Despite theoretical gains in energy efficiency, the capital intensity and modest additional electricity revenue made the ORC unjustifiable in this study's context. System B, integrating agricultural drying and cooling services achieved moderate LCC and LCOE outcomes. While its CAPEX and OPEX were higher than System C, particularly due to drying and cooling infrastructure, it still offered viable payback periods when paired with efficient prime movers like Wärtsilä and Caterpillar.

Critical financial drivers:

- Prime mover choice again proved decisive. Efficient ICEs dramatically reduced LCOE compared to gas turbines.
- Economies of scale were limited by the distributed system design, confirming observations in literature that decentralised WtE faces inherent cost scaling challenges [253].

Uncertainties:

- The LCC calculations assumed static future revenue for electricity, agricultural products and other by products, an assumption that may underestimate risks and vulnerabilities given Nigeria's history of currency devaluation and inflation. A stochastic economic analysis would provide a more nuanced understanding of financial risks affect long-term economic viability - a factor noted in Diaz-Trujillo et al. (2018) [258] for similar projects.

Social Outcomes

The Social Life Cycle Assessment (S-LCA) clearly positioned System C as the best performer. Its strengths lay in:

- Job creation, both skilled (system operation) and unskilled (greenhouse farming).
- Community engagement, offering food security benefits and social inclusion.
- Training and educational opportunities through the agricultural components.

These results resonate with the S-LCA findings in within the literature, where argued that WtE systems that valorise outputs beyond energy (such as compost, food, or materials) generally deliver higher net social value. System B also provided respectable social value, particularly in employment generation and technology transfer (e.g., skills in drying and cooling technologies). However, its infrastructure demands limited its flexibility, susceptible to seasonal variability. and scalability in certain urban contexts. System A, despite its technical sophistication, struggled to deliver social benefits beyond basic employment for plant operations. Its technological complexity, coupled with high automation, limited opportunities for broad community engagement a finding aligned with Nubi et al. (2022) [62] who cautioned against 'technological elitism' in WtE projects

Critical insight:

While the S-LCA methodology provided important comparative insights, it was constrained by the qualitative and semi-quantitative nature of much of the data, introducing subjectivity especially regarding informal sector workers and gendered impacts. Future studies would benefit from participatory approaches, such as social impact workshops with local communities, to validate assumptions.

Social benefits in WtE systems are not an automatic by-product of technical or economic success. They must be intentionally designed into the system configuration. This finding resonates with the UNEP/SETAC 2011 guidelines and is consistent with empirical observations in Southeast Asia and Latin America, where bioenergy systems integrating community-scale agriculture or cooperative models yielded higher social sustainability outcomes. Sustainable WtE solutions for Nigeria must directly address social justice and inclusion, not merely employment metrics. Systems that contribute simultaneously to clean energy, local food systems, and community development offer the best prospects for durable social acceptance.

Overall Sustainability Trade-Offs

The LCSA results highlighted the trade-offs inherent in each system design:

- System A prioritised technical and thermal efficiency but suffered from poor economic and social outcomes.
- System B offered a balance between moderate social and economic performance without the technical complexity of System A.
- System C emerged as the most sustainable option, delivering strong environmental, economic, and social performance, primarily due to its diversified revenue model and community-focused design.

Cross-analysis of the LCSA important insights:

1. Technological complexity does not guarantee sustainability. System A, despite having the highest theoretical energy efficiency (due to the ORC), was environmentally and economically unsustainable and socially limited.
2. Prime mover selection is a primary lever for sustainability gains, often outweighing incremental gains from other system components.
3. Scale and integration are crucial. The economies of scope (multi-output systems) were more significant than economies of scale (large single-purpose plants), supporting a move towards decentralised, modular energy systems for developing contexts.
4. Environmental benefits are constrained by technology efficiencies and regional contexts. For example, water consumption in greenhouse farming (System C) would need careful management in water-scarce regions.
5. The most sustainable solutions are those which align environmental, economic, and social benefits, rather than maximising any single pillar.

Unexpected finding:

- The magnitude of environmental impact variation between prime movers was larger than anticipated, suggesting that even relatively small-scale technology choices can have outsized effects.
- The superior social performance of greenhouse farming (System C) exceeded even optimistic projections, underscoring the latent social capital potential in urban agriculture projects when combined with clean energy.

This holistic assessment underscores that technical optimisation alone is insufficient for sustainable WtE development. Systems that integrate social value and financial resilience such as System C are more likely to succeed in the Nigerian context. These findings are not only applicable to Port Harcourt or Nigeria. They offer a valuable blueprint for sustainable WtE design in resource-constrained developing country contexts, where decentralised energy systems must deliver multi-dimensional benefits to be viable.

8.2. Cross-Pillar Trade-offs and Synergies

The preceding assessments of environmental, economic, and social outcomes for the three WtE system configurations have highlighted both synergies, areas where improvements in one sustainability pillar reinforced gains in others, and trade-offs, where gains in one dimension compromised performance in another. These interactions are now critically examined to provide an integrated understanding of the LCSA results.

8.2.1. Environmental-Economic Trade-offs

A clear trade-off was observed between energy efficiency gains (and associated environmental benefits) and financial viability. While System A incorporated the Organic Rankine Cycle (ORC) to improve overall energy recovery, the additional capital and operational costs introduced by this complexity outweighed the environmental advantages. Although the ORC reduced the marginal GWP per unit of energy produced, the financial burden resulted in prohibitively high Levelised Cost of Energy (LCOE) particularly when paired with less efficient prime movers. This reflects a wider trend noted by Karellas et al. (2010) and Aziz et al. (2018) [255], [256], who found that technological enhancements aimed at maximising environmental performance often led to diminishing economic returns in small and medium-scale WtE plants. In developing country contexts, where capital cost constraints are significant, such trade-offs become especially pronounced.

Conversely, System C demonstrated a rare synergy between environmental and economic performance. By integrating greenhouse agriculture, the system achieved revenue diversification that not only improved financial outcomes but also contributed to the circular economy by utilising waste heat and CO₂ emissions to enhance plant growth. This model aligns

with findings by Ceraso et al. (2024) [177], who identified integrated bioenergy-agriculture systems as particularly promising for sustainable development in emerging economies

8.2.2. Environmental-Social Trade-offs

Environmental performance and social outcomes were, in some cases, synergistic but also exhibited notable tensions. System C's low environmental impacts (when coupled with efficient prime movers) aligned with high social benefits, particularly in employment, education, and food security. The incorporation of greenhouse urban farming fostered community engagement and local capacity building, an example of socio-technical synergy recommended in recent sustainability frameworks ([66], [160]).

However, the higher water consumption associated with greenhouse operations introduced an environmental-social trade-off. While promoting food security and employment, water use could strain local resources in water-scarce areas. Similar tensions have been noted in other integrated systems studied by Collotta et al. (2019) and Chong et al. (2016) [252], [257], where land and water use intensity increased as social and economic co-benefits were added to energy systems. In System B, while the introduction of agricultural services (drying and cooling) provided social value, it increased resource consumption and environmental impacts, albeit to a lesser extent than System A's ORC integration.

8.2.3. Economic-Social Synergies and Trade-offs

From an economic-social perspective, System C excelled due to its diversified revenue streams supporting both financial resilience and social inclusion. Agricultural activities not only provided revenue but also enabled job creation, training opportunities, and enhanced food security. This multi-dimensional benefit profile supports the argument made by Aberilla et al. (2020) and Díaz-Trujillo et al. (2019) [253], [258], that decentralised systems delivering multiple community services are more socially sustainable and financially robust in developing.

In contrast, System A's financial burdens constrained social outcomes. High capital and operational costs restricted potential for wider community engagement, capacity building, or affordable energy provision. This finding underscores the importance of cost-social performance coupling; a concept well-established in recent LCSA literature but rarely applied in Nigerian or West African WtE contexts. System B demonstrated moderate synergies, with

agricultural service integration supporting employment and local value addition without prohibitive costs. However, the lack of revenue diversification beyond energy and agricultural drying limited the extent of social benefits compared to System C.

8.2.4. Prime Mover Influence Across Pillars

The selection of prime movers emerged as the most influential cross-pillar factor. High-efficiency, low-emission internal combustion engines (ICEs) such as the Wärtsilä dual-fuel engines consistently supported better environmental, economic, and social outcomes across all system configurations. Gas turbines (SGT-400 and SGT-50), despite their theoretical suitability for CHP applications, underperformed across all three dimensions. Their high environmental burdens and operational costs exacerbated financial and social challenges, particularly in decentralised contexts where efficiency losses at partial loads further undermined performance. This confirms the assertion made by Collotta et al. (2019) and Chong et al. (2016) [252], [257] that prime mover selection can overwhelm other system-level design factors in determining sustainability outcomes. It also highlights a critical area for policy intervention: supporting the adoption of prime movers optimised for distributed, small- to medium-scale WtE applications rather than relying on equipment designed for large, centralised plants.

8.2.5. Macro-Environmental Strategic Trade-offs (PESTEL Synthesis)

Beyond the internal trade-offs discussed previously, the feasibility of real-world deployment is governed by external macro-environmental constraints. To synthesise these broader implications, a PESTEL risk assessment was conducted (see Figure 8-1), revealing a critical divergence between 'Technical Optimality' and 'Contextual Suitability.' The analysis highlights the broader need for multi-functional, socially integrated WtE systems in developing countries. Systems designed purely for technical efficiency or maximum energy output, as exemplified by System A, may underperform in real-world settings where financial and social factors are equally critical. System C's success reflects the growing consensus in sustainability science that circular economy principles and community co-benefits should be integral to energy system design [160], [177].

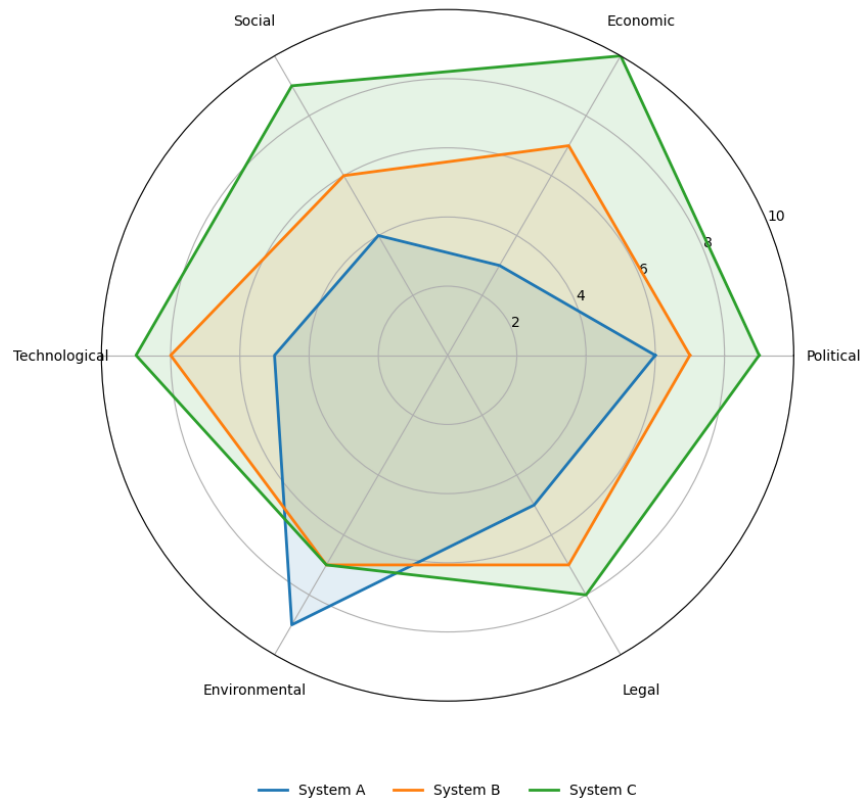


Figure 8-1: Comparative PESTEL Suitability Analysis (1-10 scale)

A significant trade-off was identified between Technological Complexity and Social Inclusivity, termed here as the "Techno-Political Paradox." This is best exemplified by the contrast between System A and System C. System A, designed for maximum electrical output via an Organic Rankine Cycle (ORC), creates a "technological enclave" that relies on automation and highly skilled technicians. While efficient, this approach limits social inclusivity by offering few accessible employment opportunities, reflected in its low PESTEL Social alignment (Score: 3/10). Conversely, System C accepts the high operational complexity of managing a biological subsystem (urban farming) alongside energy generation. The study demonstrates that by accepting this burden of complexity, the project secures superior social inclusivity (PESTEL Social Score: 9/10), creating a broad base of low-skilled agricultural jobs and directly addressing food security. This "Social License to Operate" acts as a critical de-risking mechanism in the Niger Delta context.

Furthermore, a distinct negative trade-off was observed between Environmental Optimisation and Financial Viability. The pursuit of maximum thermodynamic efficiency in System A, achieved through the addition of the ORC unit, resulted in a disproportionate increase in Capital Expenditure (CAPEX). This "efficiency premium" severely compromised the project's economic attractiveness, extending the payback period to over 9 years. The PESTEL analysis

contextualises this as a fatal Economic Risk (Score: 3/10), indicating that strictly pursuing the highest technical efficiency can actively undermine the financial viability required for project implementation.

In contrast, System C prioritised "Scope Economies" over strict thermodynamic optimisation. By foregoing the expensive ORC unit and instead diversifying revenue streams through the greenhouse, System C achieved the shortest payback period (~2 years) and the lowest Levelised Cost of Energy (LCOE). Consequently, the PESTEL analysis serves as the final arbiter, identifying System C as the 'Macro-Environmental Ideal.' It demonstrates that sustainability trade-offs are not inherent to WtE systems; rather, they are design dependent. Systems that prioritise technology-centric optimisation without considering the socio-economic macro-environment will likely face sustainability barriers, particularly in emerging economies.

8.3. Relevance to Sustainable Development Goals

The Life Cycle Sustainability Assessment (LCSA) conducted in this study not only evaluated the environmental, economic, and social dimensions of the proposed WtE systems but also explored their alignment with broader global development objectives. The United Nations' Sustainable Development Goals (SDGs), adopted in 2015 as part of the 2030 Agenda, provide a comprehensive framework for addressing interconnected challenges in energy, environment, social well-being, and economic growth. This section examines how each system particularly System C, identified as the most sustainable contributes to key SDGs relevant to Nigeria's development trajectory.

8.3.1. SDG 7: Affordable and Clean Energy

All three systems addressed SDG 7, which seeks to ensure access to affordable, reliable, sustainable, and modern energy. By converting municipal solid waste into usable energy, the systems provided a decentralised, renewable energy solution that can reduce reliance on Nigeria's overburdened and unreliable centralised grid. However, System C offered the strongest contribution by delivering low LCOE values, especially when paired with efficient prime movers. Its diversified revenue streams enhanced financial resilience, increasing the likelihood that energy services could be delivered sustainably and affordably over the long term a critical factor in low-income and energy-poor communities. System A, by contrast, struggled to meet affordability targets, with LCOE values exceeding those of conventional diesel generation, thereby conflicting with the affordability aspect of SDG 7.

8.3.2. SDG 11: Sustainable Cities and Communities

System C also made significant progress towards SDG 11, which promotes inclusive, safe, resilient, and sustainable cities. The integration of greenhouse-based urban farming aligned with this goal by:

- Providing local food production, reducing food miles and associated emissions.
- Supporting community engagement and social cohesion through urban agriculture.
- Enhancing urban green infrastructure, which contributes to resilience and climate adaptation.

System B's contribution to SDG 11 was moderate, primarily through its support of agricultural drying and cooling services. System A contributed the least in this dimension, offering few co-benefits beyond energy provision.

8.3.3. SDG 12: Responsible Consumption and Production

All systems promoted SDG 12 by implementing waste-to-energy solutions that divert municipal solid waste from landfills and reduce reliance on fossil fuels. By closing material and energy loops, especially in System C, the systems embodied circular economy principles.

The valorisation of digestate, biochar, and CO₂ in System C contributed directly to resource efficiency. This circular approach is essential in urban centres like Port Harcourt, where waste management challenges and resource scarcity coexist. However, the systems also highlighted challenges: increased water consumption in System C's greenhouse operations and potential infrastructure demands in System B could create new resource pressures, underscoring the need for integrated resource management strategies.

8.3.4. SDG 13: Climate Action

By reducing greenhouse gas (GHG) emissions through methane capture, fossil fuel substitution, and avoided landfill emissions, all systems contributed to SDG 13. System C, when paired with efficient prime movers, demonstrated the lowest global warming potential (GWP) per unit of energy and highest emissions offset potential. These outcomes align with IPCC recommendations emphasising the role of bioenergy with carbon recycling in climate mitigation pathways. Nevertheless, the emissions intensity of prime movers (particularly gas

turbines) introduced significant variability. This finding reinforces the importance of technology choice in determining a system's net climate impact; a key consideration for SDG 13 implementation in Nigeria and similar contexts.

8.3.5. SDG 8: Decent Work and Economic Growth

Systems B and C both supported SDG 8, promoting sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work.

System C excelled in job creation, offering skilled and unskilled employment opportunities in both energy generation and urban agriculture. These jobs not only provided income but also supported capacity building and technological upskilling, critical for socio-economic development in Nigeria.

System B also provided employment through agricultural services but on a smaller scale and with more limited community engagement. System A, due to its capital-intensive and technically specialised nature, offered fewer employment opportunities, restricting its contribution to SDG 8.

8.3.6. Cross-Cutting SDG Synergies

The study's findings reveal that sustainability synergies, such as those achieved by System C, are most likely when systems integrate multi-sectoral benefits. System C addressed:

- Energy access (SDG 7).
- Urban sustainability and resilience (SDG 11).
- Resource efficiency and circular economy (SDG 12).
- Climate mitigation (SDG 13).
- Economic growth and employment (SDG 8).

These results affirm the conclusions of Menikpura et al. (2017) and UNEP/SETAC (2011), which suggest that multi-functional, community-integrated systems offer the highest potential for sustainable development in low- and middle-income countries.

8.3.7. Limitations and Considerations

While the systems demonstrated clear SDG contributions, certain limitations were identified:

- Data gaps in social performance measurement may understate or overstate contributions to SDG 8.
- Dynamic factors (e.g., policy changes, energy price fluctuations, technology learning curves) could alter sustainability and SDG alignment over time.
- Regional variability in resource availability (e.g., water scarcity) could constrain the replicability of System C's social and environmental benefits.

These considerations suggest that while the proposed systems offer robust pathways towards SDG achievement, adaptive management and site-specific design customisation are essential for sustained impact.

8.4. Policy, Integrated Discussion of LCSA Results

The outcomes of the LCSA provide a robust evidence base for formulating recommendations aimed at facilitating the sustainable deployment of WtE systems in Nigeria. The following recommendations are structured across three main categories: policy, technology adoption, and planning and stakeholder engagement.

8.4.1. Policy Recommendations

a. Incentivise Distributed WtE Systems

Given the demonstrated environmental, economic, and social benefits particularly for System C, national and local governments should establish targeted incentives for decentralised waste-to-energy plants. These incentives should include Feed-in Tariffs (FIT) for biomass electricity and tax holidays for projects integrating circular economy principles like urban farming. This recommendation directly supports the Renewable Energy Master Plan (REMP), which sets specific targets for increasing the contribution of biomass to the national electricity mix (aiming for 400 MW of biomass power). It also aligns with the Rural Electrification Strategy and Implementation Plan (RESIP), which prioritises decentralised, off-grid solutions for energy-poor communities. Such policies would align with international best practices as recommended by Chong et al. (2016) and the World Bank (2022) for promoting renewable energy adoption in developing economies.

b. Promote Prime Mover Optimisation

The results clearly showed that prime mover selection critically affects sustainability performance. Policies should encourage the import and deployment of high-efficiency, dual-fuel Internal Combustion Engines (ICEs) while discouraging inefficient legacy gas turbines for small-scale applications. Promoting high-efficiency equipment supports the National Energy Policy (NEP) objective of ensuring energy efficiency and conservation across the supply chain. It also supports the Nationally Determined Contributions (NDCs) under the Paris Agreement by reducing the carbon intensity of new energy generation capacity.

c. Integrate WtE into National and Local Waste Management Plans

WtE should be recognised not only as an energy solution but also as a waste management strategy. Planning regulations must mandate source separation frameworks to ensure high-quality feedstock for anaerobic digestion and gasification. This is consistent with the National Policy on Solid Waste Management, which explicitly advocates for a shift from "waste-as-trash" to a "Waste-to-Wealth" paradigm. It also supports Vision 20:2020 goals regarding environmental sustainability and the elimination of hazardous open dumpsites.

d. Foster Social Co-benefit Integration

Policies should introduce a "Social Value" premium or grant for WtE systems that deliver verifiable co-benefits, such as the food security and job creation demonstrated by System C's greenhouse integration. This aligns with the Economic Recovery and Growth Plan (ERGP), which focuses on restoring growth through economic diversification (agriculture) and investing in people (job creation). It ties energy infrastructure investment directly to the National Food Security agenda.

8.4.2. Technology Deployment Guidance

a. Prioritise Multi-Functional System Designs

Technical designs should aim to deliver multiple value streams beyond energy, such as food production, waste-derived products (e.g., biochar, digestate), and social services. The success of System C confirms that such diversification improves both sustainability outcomes and financial resilience.

b. Modular and Scalable Infrastructure

Given capital constraints and demand variability in Nigerian urban areas:

- Systems should adopt modular designs that can be scaled incrementally.
- Modular configurations allow for technology upgrades over time without prohibitive upfront costs, as recommended by Collotta et al. (2019) and Ceraso et al. (2024) [177], [252].

c. Efficiency Optimisation through Prime Mover Selection

Technology developers and project planners must prioritise prime mover efficiency and emissions performance in system design. The LCSA demonstrated that engine choice can override even feedstock variability in determining environmental and economic performance.

d. Valorisation of By-products

Where feasible, systems should incorporate:

- Digestate valorisation for agricultural fertiliser markets.
- Biochar production for soil amendment or industrial applications.
- Carbon capture or utilisation of CO₂ in controlled-environment agriculture (CEA), as successfully demonstrated in System C.

8.4.3. Planning and stakeholder engagement

a. Early and Inclusive Stakeholder Engagement

Community acceptance is critical to project success. Developers should engage stakeholders, including informal waste collectors, residents, and agricultural partners, from the earliest planning stages. Collaborative design approaches increase social acceptability and can improve system design through local knowledge.

b. Capacity Building and Training

The deployment of advanced WtE systems requires local capacity for design, operation, and maintenance. Public-private partnerships should invest in:

- Training programmes for engineers, operators, and agricultural specialists.
- Partnerships with educational institutions to develop relevant curricula.

c. Data Collection and Transparency

The LCSA process highlighted data gaps, especially in social performance and local emissions factors. Policymakers and researchers should:

- Establish national data repositories for WtE performance metrics.
- Promote data transparency to facilitate continual improvement and stakeholder confidence.

d. Financial Innovation and Risk Mitigation

Financial models should explore:

- Public-private partnerships to share capital risks.
- Performance-based financing, where returns are linked to environmental and social outcomes.
- Green bonds or impact investment instruments targeting sustainability goals.

8.5. Research Gaps and Recommendations for Future Work

While this study provides a comprehensive Life Cycle Sustainability Assessment (LCSA), the research process was confronted with significant data-related challenges inherent to the Nigerian context. These challenges directly influenced the methodological approach, interpretation, and validation of the findings, and they frame the recommendations for future work.

8.5.1. Environmental Assessment Gaps

a. Site-Specific Emissions Data

A primary challenge was the scarcity of reliable, site-specific environmental data. Waste composition data for Port Harcourt is often inconsistent, aggregated, or outdated, making precise feedstock characterisation difficult. Furthermore, a significant gap exists in local emissions factors for WtE technologies operating within Nigeria.

b. Dynamic Operational Modelling

To interpret and validate the models, this research relied on cross-referencing data from international databases like Ecoinvent and peer-reviewed literature from similar developing regions. While this is a standard approach, it introduces uncertainties. The technical performance of prime movers was based on manufacturer data under ideal conditions, as real-

world operational data at partial loads in a Nigerian environment is not available. Future studies should incorporate dynamic simulation models that reflect realistic load profiles and part-load operational efficiencies of prime movers, gasifiers, and digesters.

8.5.2. Economic Assessment Gaps

a. Market Volatility Sensitivity

The Levelised Cost of Energy (LCOE) and Life Cycle Costing (LCC) analyses used static assumptions for energy prices, CAPEX, OPEX, and by-product revenues. Yet, in the Nigerian context, high market volatility particularly exchange rate fluctuations, inflation, and energy policy changes can have a significant impact. Future research should conduct Monte Carlo simulations or probabilistic sensitivity analyses to better understand how economic uncertainty affects financial viability.

b. Financing Models

The current study did not explicitly model alternative financing mechanisms such as public-private partnerships (PPPs), micro-financing, or green bonds. Future work should explore how innovative financing approaches can reduce upfront capital burdens and improve the bankability of decentralised WtE projects.

8.5.3. Social Assessment Gaps

a. Social Life Cycle Assessment (S-LCA) Data Limitations

The social assessment (S-LCA) presented the most complex data challenges. Social impacts are often qualitative, subjective, and difficult to quantify. A major hurdle which is a critical stakeholder group, was the lack of formal data on the informal waste sector, notably:

- The impacts on informal waste sector workers were difficult to quantify.
- Gender-based impacts and equity considerations require deeper analysis.
- Long-term social outcomes (e.g., skills development, health improvements) were assessed qualitatively but lacked empirical measurement.

To overcome this, a semi-quantitative, literature-based methodology was adopted. Data was interpreted by mapping it to established stakeholder categories and indicators from the UNEP/SETAC guidelines. Validation was then achieved by using a weighted scoring system (Section 7.3.4) to reflect local socio-economic priorities, such as informal sector inclusion and community health.

b. Stakeholder Acceptance Modelling

Social acceptability is a crucial determinant of WtE project success but was not quantitatively modelled in this study. Future work should integrate social acceptance modelling, possibly using agent-based models or discrete choice experiments, to predict community responses to different WtE system designs.

8.5.4. Methodological Advancements

a. Multi-Objective Optimisation

While the LCSA framework provided valuable insights, multi-objective optimisation models could further refine system design by balancing trade-offs across environmental, economic, and social objectives simultaneously.

b. Geographic and Sectoral Expansion

The current study focused on Port Harcourt as a representative case. Expanding the analysis to: Other Nigerian cities with differing waste profiles, energy demands, and social contexts. Other sectors, such as industrial or agricultural waste streams, could broaden the applicability of the findings.

8.5.5. Key Limitations Critical Next steps

Despite achieving a robust comparative sustainability assessment, the study has three key limitations that define the trajectory for future research. First, the techno-economic assessment is based on desktop modelling and simulated data, necessitated by the scarcity of publicly available, audited operational data for complex WtE plants in Nigeria. Second, the environmental and social Life Cycle Assessments rely on international Life Cycle Inventory (LCI) databases (e.g., Ecoinvent) and literature-derived qualitative metrics for social impact, introducing inherent uncertainties due to geographical and contextual differences. Third, the current scope is limited to three predefined poly-generation configurations.

The critical next steps must therefore prioritise the validation of the model's findings. The immediate next step is to conduct a site-specific pilot study and detailed pre-feasibility analysis for the most viable configuration, System C. This requires securing local operational data to build a Nigeria-specific LCI database reflecting Nigerian operational realities and executing an

in-depth stakeholder engagement survey to refine the social impact metrics. Further comparative analysis should also be extended to include other feedstock sources (e.g., agricultural residue) to fully harness Nigeria's biomass potential.

8.6. Final Remarks

This research was motivated by the urgent need to resolve the dual crisis of energy poverty and inefficient waste management in Nigeria. Through a comprehensive Life Cycle Sustainability Assessment (LCSA), this study evaluated three distinct waste-to-energy (WtE) configurations; System A (ORC integration), System B (Agricultural drying/cooling), and System C (Greenhouse urban farming), to determine the most viable pathway for distributed energy generation in Port Harcourt.

The study moves beyond standard technical assessments to demonstrate that sustainability in developing contexts depends heavily on how well technical systems integrate with local socio-economic needs. The final conclusions, quantitative evidence, and future outlook are summarised below.

8.6.1. Key Conclusions

- **System C as the Optimal Configuration:** System C (Anaerobic Digestion + Gasification + Greenhouse Urban Farming) consistently outperformed other configurations across environmental, economic, and social dimensions. It serves as a model for "infrastructures of care," delivering food security and employment alongside energy.
- **Criticality of Prime Mover Selection:** The choice of prime mover proved more improved sustainability outcomes than even the choice of conversion technology. High-efficiency Internal Combustion Engines (ICEs) (e.g., Wärtsilä/Caterpillar) offered superior economic and environmental performance compared to micro-gas turbines, which suffered from high capital costs, lower electrical efficiencies at this scale and high acidification potentials due to high exhaust mass flow rates.
- **Limits of Technical Complexity:** System A demonstrated that maximising thermodynamic efficiency via Organic Rankine Cycles (ORC) does not guarantee sustainability. The high capital expenditure required for ORC integration rendered it economically unviable compared to a simpler, multi-functional approach of System C.

- **Social License to Operate:** Social viability was strongest in systems that provided visible community benefits. System C's inclusion of urban farming created a "social value premium" that System A's electricity-only focus lacked.

8.6.2. Summary of Quantitative Findings

The following metrics underscore the superior performance of the integrated poly-generation approach (System C) compared to the alternatives:

- **Energy Performance:** System C achieved an overall CHP utilisation of approximately 80%. It generated 1.376 MWh of electricity per tonne of MSW, satisfying the full demand of a 1,000 m² greenhouse while exporting 177–240 GWh/year of electricity and 1.24–4.66 GWh/year of surplus heat to expand utilisation.
- **Economic Viability (LCOE & LCC):** System C achieved the lowest Life Cycle Cost (LCC), more than 60% lower than the worst-case turbine configurations. It delivered a Levelised Cost of Electricity (LCOE) range of \$0.05–\$0.07/kWh with efficient engines. In contrast, System A (ORC) recorded an LCOE of \$0.31–\$0.46/kWh using gas turbines.
- **Social Impact (S-LCA):** On a weighted 5-point social impact scale, System C ranked highest with a score of 4.53, compared to 4.07 for System B and 3.47 for System A. This reflects superior job creation, community inclusion, and support for food security.
- **Environmental Impact:** System C achieved a negative Carbon Abatement Cost (-\$50/ton CO₂), meaning it generates profit while decarbonising, unlike standard incineration which costs ~\$32/ton to abate carbon. Global Warming Potential (GWP) was minimised to <90 kg CO₂-eq/ton when using efficient dual-fuel engines.

8.6.3. Recommendations for Future Research

To bridge the gap between this academic assessment and practical implementation, future work should focus on the following key areas:

- **Pilot-Scale Validation:** Conduct a site-specific pilot study for System C to validate the modelled "Waste-to-Wealth" synergies. This includes securing real-world operational data to replace simulated inputs and building a Nigeria-specific Life Cycle Inventory (LCI) database.

- **Dynamic Modelling:** Move from steady-state models to dynamic simulations that account for the realistic part-load performance of prime movers and the daily fluctuation of municipal waste streams in Nigeria.
- **Economic Sensitivity Analysis:** Perform probabilistic risk assessments (e.g., Monte Carlo simulations) to model the impact of Nigeria's market volatility specifically inflation rates, fuel subsidies, and currency fluctuation on the long-term bankability of these projects.
- **Feedstock Expansion:** Extend the comparative analysis to include agricultural residues and market waste, maximizing the potential of Nigeria's biomass resources beyond municipal solid waste.
- **Social Acceptance Modelling:** Execute comprehensive stakeholder engagement surveys to quantify "social acceptance" and better understand the informal waste sector's role in the supply chain.

In conclusion, this thesis has contributed to both theoretical and practical understanding by demonstrating how LCSA can be applied in the Nigerian context to inform sustainable energy decision-making. The findings provide a blueprint for policymakers, industry stakeholders, and researchers seeking to implement waste-to-energy solutions that are not only technically and economically viable but also socially inclusive and environmentally responsible. As Nigeria and other developing nations pursue their energy transitions and sustainable development agendas, integrated approaches such as the one presented in this study will be essential for navigating complex trade-offs and delivering systems that are resilient, adaptable, and equitable.

Bibliography

- [1] UN. Secretary-General and World Commission on Environment and Development, “Report of the World Commission on Environment and Development: Our Common Future,” New York, 1987.
- [2] United Nations Department of Economic and Social Affairs/Population Division, “World Population Prospects 2019, Volume II: Demographic Profiles,” USA, 2019. Accessed: Feb. 02, 2023. [Online]. Available: <https://tinyurl.com/uxul8hc>.
- [3] IPCC, “Climate Change 2014, Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects.,” Cambridge, 2014.
- [4] Arne Dalfelt, “Climate Change and Sub-Saharan Africa: Issues and Opportunities,” Washington, 1998. Accessed: Feb. 02, 2023. [Online]. Available: <http://hdl.handle.net/10986/9882>.
- [5] World Health Organization, “Burning opportunity: clean household energy for health, sustainable development, and wellbeing of women and children.,” 2016. Accessed: Feb. 02, 2023. [Online]. Available: <https://apps.who.int/iris/handle/10665/204717>
- [6] IEA, “Nigeria - Countries & Regions,” IEA. Accessed: Feb. 02, 2023. [Online]. Available: <https://www.iea.org/countries/nigeria#analysis>
- [7] World Bank, “Nigeria on the Move : A Journey to Inclusive Growth.,” Washington , 2020. Accessed: Feb. 02, 2023. [Online]. Available: <https://openknowledge.worldbank.org/handle/10986/33347>
- [8] A. Ochieng, “Nigeria’s Generator Addiction Is An Opportunity in Disguise.” Accessed: Feb. 02, 2023. [Online]. Available: <https://emerge85.io/Insights/nigerias-generator-addiction-is-an-opportunity-in-disguise/>
- [9] B. Ugwoke, O. Gershon, C. Becchio, S. P. Corgnati, and P. Leone, “A review of Nigerian energy access studies: The story told so far,” 2020. doi: 10.1016/j.rser.2019.109646.
- [10] United Nations, “Chapter XXVII: Paris Agreement, United Nations Treaty Collection,” 2021. Accessed: Feb. 02, 2023. [Online]. Available: <https://tinyurl.com/xdesadf2>
- [11] I. A. Tajudeen, “Examining the role of energy efficiency and non-economic factors in energy demand and CO2 emissions in Nigeria: Policy implications,” *Energy Policy*, vol. 86, 2015, doi: 10.1016/j.enpol.2015.07.014.
- [12] Y. S. Mohammed, M. W. Mustafa, N. Bashir, M. A. Ogundola, and U. Umar, “Sustainable potential of bioenergy resources for distributed power generation development in Nigeria,” 2014. doi: 10.1016/j.rser.2014.03.018.
- [13] S. Kaza, L. C. Yao, P. Bhada-Tata, and F. Van Woerden, *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*. Washington, DC: World Bank, 2018. doi: 10.1596/978-1-4648-1329-0.
- [14] IEA, “Nigeria Renewable Energy Master Plan,” IEA/IRENA Renewables Policies Database.
- [15] E. I. Ohimain, “Can the Nigerian biofuel policy and incentives (2007) transform Nigeria into a biofuel economy?,” *Energy Policy*, vol. 54, 2013, doi: 10.1016/j.enpol.2012.11.051.
- [16] A. Ozier *et al.*, “Building a consumer market for ethanol-methanol cooking fuel in Lagos, Nigeria,” *Energy for Sustainable Development*, vol. 46, 2018, doi: 10.1016/j.esd.2018.06.007.
- [17] A. Giwa, A. Alabi, A. Yusuf, and T. Olukan, “A comprehensive review on biomass and solar energy for sustainable energy generation in Nigeria,” 2017. doi: 10.1016/j.rser.2016.11.160.

- [18] J. Ben-Iwo, V. Manovic, and P. Longhurst, "Biomass resources and biofuels potential for the production of transportation fuels in Nigeria," Sep. 01, 2016, *Elsevier Ltd.* doi: 10.1016/j.rser.2016.05.050.
- [19] A. Tursi, "A review on biomass: Importance, chemistry, classification, and conversion," 2019. doi: 10.18331/BRJ2019.6.2.3.
- [20] F. Cherubini, "The biorefinery concept: Using biomass instead of oil for producing energy and chemicals," *Energy Convers Manag*, vol. 51, no. 7, 2010, doi: 10.1016/j.enconman.2010.01.015.
- [21] Y. S. Mohammed, M. W. Mustafa, N. Bashir, and I. S. Ibrahim, "Existing and recommended renewable and sustainable energy development in Nigeria based on autonomous energy and microgrid technologies," 2017. doi: 10.1016/j.rser.2016.11.062.
- [22] N. V. Emodi and K. J. Boo, "Sustainable energy development in Nigeria: Current status and policy options," 2015. doi: 10.1016/j.rser.2015.06.016.
- [23] O. J. Ogorure, C. O. C. Oko, E. O. Diemuodeke, and K. Owebor, "Energy, exergy, environmental and economic analysis of an agricultural waste-to-energy integrated multigeneration thermal power plant," *Energy Convers Manag*, vol. 171, 2018, doi: 10.1016/j.enconman.2018.05.093.
- [24] R. A. Ibikunle, I. F. Titiladunayo, A. F. Lukman, S. O. Dahunsi, and E. A. Akeju, "Municipal solid waste sampling, quantification and seasonal characterization for power evaluation: Energy potential and statistical modelling," *Fuel*, vol. 277, 2020, doi: 10.1016/j.fuel.2020.118122.
- [25] R. A. Ibikunle, I. F. Titiladunayo, B. O. Akinnuli, S. O. Dahunsi, and T. M. A. Olayanju, "Estimation of power generation from municipal solid wastes: A case Study of Ilorin metropolis, Nigeria," *Energy Reports*, vol. 5, 2019, doi: 10.1016/j.egyr.2019.01.005.
- [26] *Improving Solid Waste and Plastics Management in Lagos State: A Way Forward.* 2024. doi: 10.1596/42374.
- [27] K. Alanne and A. Saari, "Distributed energy generation and sustainable development," 2006. doi: 10.1016/j.rser.2004.11.004.
- [28] N. Fumo, P. J. Mago, and L. M. Chamra, "Emission operational strategy for combined cooling, heating, and power systems," *Appl Energy*, vol. 86, no. 11, 2009, doi: 10.1016/j.apenergy.2009.03.007.
- [29] H. Cho, A. D. Smith, and P. Mago, "Combined cooling, heating and power: A review of performance improvement and optimization," 2014. doi: 10.1016/j.apenergy.2014.08.107.
- [30] S. Carley, "Distributed generation: An empirical analysis of primary motivators," *Energy Policy*, vol. 37, no. 5, 2009, doi: 10.1016/j.enpol.2009.01.003.
- [31] A. D. Hawkes and M. A. Leach, "Cost-effective operating strategy for residential micro-combined heat and power," *Energy*, vol. 32, no. 5, 2007, doi: 10.1016/j.energy.2006.06.001.
- [32] M. Burer, K. Tanaka, D. Favrat, and K. Yamada, "Multi-criteria optimization of a district cogeneration plant integrating a solid oxide fuel cell-gas turbine combined cycle, heat pumps and chillers," *Energy*, vol. 28, no. 6, 2003, doi: 10.1016/S0360-5442(02)00161-5.
- [33] M. Bianchi, F. Cherubini, A. De Pascale, A. Peretto, and B. Elmegaard, "Cogeneration from poultry industry wastes: Indirectly fired gas turbine application," *Energy*, vol. 31, no. 10–11, 2006, doi: 10.1016/j.energy.2005.05.028.
- [34] S. N. Uddin and L. Barreto, "Biomass-fired cogeneration systems with CO₂ capture and storage," *Renew Energy*, vol. 32, no. 6, 2007, doi: 10.1016/j.renene.2006.04.009.

- [35] R. Madlener and M. Bachhiesl, "Socio-economic drivers of large urban biomass cogeneration: Sustainable energy supply for Austria's capital Vienna," *Energy Policy*, vol. 35, no. 2, 2007, doi: 10.1016/j.enpol.2006.01.022.
- [36] G. Qiu, Y. Shao, J. Li, H. Liu, and S. B. Riffat, "Experimental investigation of a biomass-fired ORC-based micro-CHP for domestic applications," *Fuel*, vol. 96, 2012, doi: 10.1016/j.fuel.2012.01.028.
- [37] A. S. O. Ogunjuyigbe, T. R. Ayodele, and M. A. Alao, "Electricity generation from municipal solid waste in some selected cities of Nigeria: An assessment of feasibility, potential and technologies," 2017. doi: 10.1016/j.rser.2017.05.177.
- [38] F. Brizi, J. L. Silveira, U. Desideri, J. A. Dos Reis, C. E. Tuna, and W. D. Q. Lamas, "Energetic and economic analysis of a Brazilian compact cogeneration system: Comparison between natural gas and biogas," 2014. doi: 10.1016/j.rser.2014.05.088.
- [39] International Energy Agency, "Evaluating the benefits of greater global investment," *Combined Heat and Power*, 2008.
- [40] G. Chicco and P. Mancarella, "Distributed multi-generation: A comprehensive view," 2009. doi: 10.1016/j.rser.2007.11.014.
- [41] E. Masood and A. Keshavarz, *Combined Cooling, Heating and Power: Decision-Making, Design and Optimization*. 2014. doi: 10.1016/C2013-0-18763-6.
- [42] M. Jradi and S. Riffat, "Tri-generation systems: Energy policies, prime movers, cooling technologies, configurations and operation strategies," 2014. doi: 10.1016/j.rser.2014.01.039.
- [43] Y. Huang, Y. D. Wang, S. Rezvani, D. R. McIlveen-Wright, M. Anderson, and N. J. Hewitt, "Biomass fuelled trigeneration system in selected buildings," *Energy Convers Manag*, vol. 52, no. 6, 2011, doi: 10.1016/j.enconman.2010.12.053.
- [44] E. Gholamian, V. Zare, and S. M. Mousavi, "Integration of biomass gasification with a solid oxide fuel cell in a combined cooling, heating and power system: A thermodynamic and environmental analysis," *Int J Hydrogen Energy*, vol. 41, no. 44, 2016, doi: 10.1016/j.ijhydene.2016.07.217.
- [45] H. Ozcan and I. Dincer, "Performance evaluation of an SOFC based trigeneration system using various gaseous fuels from biomass gasification," *Int J Hydrogen Energy*, vol. 40, no. 24, 2015, doi: 10.1016/j.ijhydene.2014.11.109.
- [46] M. Puig-Arnavat, J. C. Bruno, and A. Coronas, "Modeling of trigeneration configurations based on biomass gasification and comparison of performance," *Appl Energy*, vol. 114, 2014, doi: 10.1016/j.apenergy.2013.09.013.
- [47] N. S. Bentsen, C. Felby, and B. J. Thorsen, "Agricultural residue production and potentials for energy and materials services," 2014. doi: 10.1016/j.peccs.2013.09.003.
- [48] K. Jana, A. Ray, M. M. Majoumerd, M. Assadi, and S. De, "Polygeneration as a future sustainable energy solution – A comprehensive review," 2017. doi: 10.1016/j.apenergy.2017.05.129.
- [49] Z. H. Tabriz, L. Khani, M. Mohammadpourfard, and G. G. Akkurt, "Biomass driven polygeneration systems: A review of recent progress and future prospects," *Process Safety and Environmental Protection*, vol. 169, pp. 363–397, Jan. 2023, doi: 10.1016/j.psep.2022.11.029.
- [50] E. Gholamian, P. Hanafizadeh, A. Habibollahzade, and P. Ahmadi, "Evolutionary based multi-criteria optimization of an integrated energy system with SOFC, gas turbine, and hydrogen production via electrolysis," *Int J Hydrogen Energy*, vol. 43, no. 33, 2018, doi: 10.1016/j.ijhydene.2018.06.130.
- [51] F. Safari and I. Dincer, "Development and analysis of a novel biomass-based integrated system for multigeneration with hydrogen production," *Int J Hydrogen Energy*, vol. 44, no. 7, 2019, doi: 10.1016/j.ijhydene.2018.12.101.

- [52] K. Jana and S. De, “Sustainable polygeneration design and assessment through combined thermodynamic, economic and environmental analysis,” *Energy*, vol. 91, 2015, doi: 10.1016/j.energy.2015.08.062.
- [53] M. Malik, I. Dincer, and M. A. Rosen, “Development and analysis of a new renewable energy-based multi-generation system,” *Energy*, vol. 79, no. C, 2015, doi: 10.1016/j.energy.2014.10.057.
- [54] C. Lythcke-Jørgensen and F. Haglind, “Design optimization of a polygeneration plant producing power, heat, and lignocellulosic ethanol,” *Energy Convers Manag*, vol. 91, 2015, doi: 10.1016/j.enconman.2014.12.028.
- [55] E. Sevinchan, I. Dincer, and H. Lang, “Energy and exergy analyses of a biogas driven multigenerational system,” *Energy*, vol. 166, 2019, doi: 10.1016/j.energy.2018.10.085.
- [56] Z. Bai, Q. Liu, J. Lei, H. Li, and H. Jin, “A polygeneration system for the methanol production and the power generation with the solar-biomass thermal gasification,” *Energy Convers Manag*, vol. 102, 2015, doi: 10.1016/j.enconman.2015.02.031.
- [57] H. Æ. Sigurjonsson and L. R. Clausen, “Solution for the future smart energy system: A polygeneration plant based on reversible solid oxide cells and biomass gasification producing either electrofuel or power,” *Appl Energy*, vol. 216, 2018, doi: 10.1016/j.apenergy.2018.02.124.
- [58] J. Rogelj *et al.*, “Scenarios towards limiting global mean temperature increase below 1.5 °c,” *Nat Clim Chang*, vol. 8, no. 4, 2018, doi: 10.1038/s41558-018-0091-3.
- [59] Y. T. Chong, K. M. Teo, and L. C. Tang, “A lifecycle-based sustainability indicator framework for waste-to-energy systems and a proposed metric of sustainability,” 2016. doi: 10.1016/j.rser.2015.11.036.
- [60] C. Achillas, C. Vlachokostas, N. Moussiopoulos, G. Baniyas, G. Kafetzopoulos, and A. Karagiannidis, “Social acceptance for the development of a waste-to-energy plant in an urban area,” *Resour Conserv Recycl*, vol. 55, no. 9–10, 2011, doi: 10.1016/j.resconrec.2011.04.012.
- [61] M. Takata, K. Fukushima, N. Kino-Kimata, N. Nagao, C. Niwa, and T. Toda, “The effects of recycling loops in food waste management in Japan: Based on the environmental and economic evaluation of food recycling,” *Science of the Total Environment*, vol. 432, 2012, doi: 10.1016/j.scitotenv.2012.05.049.
- [62] O. Nubi, S. Morse, and R. J. Murphy, “A prospective social life cycle assessment (Slca) of electricity generation from municipal solid waste in nigeria,” *Sustainability (Switzerland)*, vol. 13, no. 18, 2021, doi: 10.3390/su131810177.
- [63] S. Ascher, I. Watson, X. Wang, and S. You, “Township-based bioenergy systems for distributed energy supply and efficient household waste re-utilisation: Techno-economic and environmental feasibility,” *Energy*, vol. 181, 2019, doi: 10.1016/j.energy.2019.05.191.
- [64] W. R. Chang, J. J. Hwang, and W. Wu, “Environmental impact and sustainability study on biofuels for transportation applications,” 2017. doi: 10.1016/j.rser.2016.09.020.
- [65] T. R. Ayodele, A. S. O. Ogunjuyigbe, and M. A. Alao, “Life cycle assessment of waste-to-energy (WtE) technologies for electricity generation using municipal solid waste in Nigeria,” *Appl Energy*, vol. 201, 2017, doi: 10.1016/j.apenergy.2017.05.097.
- [66] J. M. Aberilla, A. Gallego-Schmid, and A. Azapagic, “Environmental sustainability of small-scale biomass power technologies for agricultural communities in developing countries,” *Renew Energy*, vol. 141, 2019, doi: 10.1016/j.renene.2019.04.036.
- [67] S. N. Ofori, J. N. Fobil, and O. J. Odia, “Household biomass fuel use, blood pressure and carotid intima media thickness; a cross sectional study of rural dwelling women in Southern Nigeria,” *Environmental Pollution*, vol. 242, 2018, doi: 10.1016/j.envpol.2018.06.102.

- [68] K. H. Chuang, C. H. Lu, J. C. Chen, and M. Y. Wey, "Reuse of bottom ash and fly ash from mechanical-bed and fluidized-bed municipal incinerators in manufacturing lightweight aggregates," *Ceram Int*, vol. 44, no. 11, 2018, doi: 10.1016/j.ceramint.2018.04.070.
- [69] Z. Yang, S. Tian, L. Liu, X. Wang, and Z. Zhang, "Recycling ground MSWI bottom ash in cement composites: Long-term environmental impacts," *Waste Management*, vol. 78, 2018, doi: 10.1016/j.wasman.2018.07.002.
- [70] J. Hu *et al.*, "Economic, environmental and social assessment of briquette fuel from agricultural residues in China - A study on flat die briquetting using corn stalk," *Energy*, vol. 64, 2014, doi: 10.1016/j.energy.2013.10.028.
- [71] V. Nabavi, M. Azizi, A. Tarmian, and C. D. Ray, "Feasibility study on the production and consumption of wood pellets in Iran to meet return-on-investment and greenhouse gas emissions targets," *Renew Energy*, vol. 151, 2020, doi: 10.1016/j.renene.2019.10.140.
- [72] R. Tauro, C. A. García, M. Skutsch, and O. Masera, "The potential for sustainable biomass pellets in Mexico: An analysis of energy potential, logistic costs and market demand," 2018. doi: 10.1016/j.rser.2017.09.036.
- [73] T. R. Ayodele, A. S. O. Ogunjuyigbe, and M. A. Alao, "Economic and environmental assessment of electricity generation using biogas from organic fraction of municipal solid waste for the city of Ibadan, Nigeria," *J Clean Prod*, vol. 203, 2018, doi: 10.1016/j.jclepro.2018.08.282.
- [74] W. Huang and H. Fooladi, "Economic and environmental estimated assessment of power production from municipal solid waste using anaerobic digestion and landfill gas technologies," *Energy Reports*, vol. 7, 2021, doi: 10.1016/j.egy.2021.07.036.
- [75] S. Abdelhady, D. Borello, and A. Shaban, "Techno-economic assessment of biomass power plant fed with rice straw: Sensitivity and parametric analysis of the performance and the LCOE," *Renew Energy*, vol. 115, 2018, doi: 10.1016/j.renene.2017.09.040.
- [76] F. Tambone, P. Genevini, G. D'Imporzano, and F. Adani, "Assessing amendment properties of digestate by studying the organic matter composition and the degree of biological stability during the anaerobic digestion of the organic fraction of MSW," *Bioresour Technol*, vol. 100, no. 12, 2009, doi: 10.1016/j.biortech.2009.02.012.
- [77] L. Luning, E. H. M. Van Zundert, and A. J. F. Brinkmann, "Comparison of dry and wet digestion for solid waste," in *Water Science and Technology*, 2003. doi: 10.2166/wst.2003.0210.
- [78] G. Ali, M. K. Bashir, H. Ali, and M. H. Bashir, "Utilization of rice husk and poultry wastes for renewable energy potential in Pakistan: An economic perspective," 2016. doi: 10.1016/j.rser.2016.03.014.
- [79] H. Y. Yap and J. D. Nixon, "A multi-criteria analysis of options for energy recovery from municipal solid waste in India and the UK," *Waste Management*, vol. 46, 2015, doi: 10.1016/j.wasman.2015.08.002.
- [80] United Nations Environment Programme (UNEP), "Waste To Energy: Considerations for Informed Decision-Making," 2019.
- [81] L. Appels *et al.*, "Anaerobic digestion in global bio-energy production: Potential and research challenges," 2011. doi: 10.1016/j.rser.2011.07.121.
- [82] L. Yang, F. Xu, X. Ge, and Y. Li, "Challenges and strategies for solid-state anaerobic digestion of lignocellulosic biomass," 2015. doi: 10.1016/j.rser.2015.01.002.
- [83] O. P. Karthikeyan and C. Visvanathan, "Bio-energy recovery from high-solid organic substrates by dry anaerobic bio-conversion processes: A review," 2013. doi: 10.1007/s11157-012-9304-9.

- [84] M. A. Alao, T. R. Ayodele, A. S. O. Ogunjuyigbe, and O. M. Popoola, "Multi-criteria decision based waste to energy technology selection using entropy-weighted TOPSIS technique: The case study of Lagos, Nigeria," *Energy*, vol. 201, 2020, doi: 10.1016/j.energy.2020.117675.
- [85] N. B. Klinghoffer and M. J. Castaldi, *Waste to Energy Conversion Technology*. 2013. doi: 10.1533/9780857096364.
- [86] T. Malkow, "Novel and innovative pyrolysis and gasification technologies for energy efficient and environmentally sound MSW disposal," *Waste Management*, vol. 24, no. 1, 2004, doi: 10.1016/S0956-053X(03)00038-2.
- [87] G. Lopez, M. Artetxe, M. Amutio, J. Alvarez, J. Bilbao, and M. Olazar, "Recent advances in the gasification of waste plastics. A critical overview," 2018. doi: 10.1016/j.rser.2017.09.032.
- [88] A. A. Ahmad, N. A. Zawawi, F. H. Kasim, A. Inayat, and A. Khasri, "Assessing the gasification performance of biomass: A review on biomass gasification process conditions, optimization and economic evaluation," 2016. doi: 10.1016/j.rser.2015.09.030.
- [89] V. Belgiorno, G. De Feo, C. Della Rocca, and R. M. A. Napoli, "Energy from gasification of solid wastes," *Waste Management*, vol. 23, no. 1, 2003, doi: 10.1016/S0956-053X(02)00149-6.
- [90] S. Consonni and F. Viganò, "Waste gasification vs. conventional Waste-To-Energy: A comparative evaluation of two commercial technologies," *Waste Management*, vol. 32, no. 4, 2012, doi: 10.1016/j.wasman.2011.12.019.
- [91] A. Demirbas, "Progress and recent trends in biodiesel fuels," *Energy Convers Manag*, vol. 50, no. 1, 2009, doi: 10.1016/j.enconman.2008.09.001.
- [92] G. C. Young, *Municipal Solid Waste to Energy Conversion Processes: Economic, Technical, and Renewable Comparisons*. 2010. doi: 10.1002/9780470608616.
- [93] O. O. Ayodele and F. A. Dawodu, "Production of biodiesel from Calophyllum inophyllum oil using a cellulose-derived catalyst," *Biomass Bioenergy*, vol. 70, 2014, doi: 10.1016/j.biombioe.2014.08.028.
- [94] F. Ishola *et al.*, "Biodiesel production from palm olein: A sustainable bioresource for Nigeria," *Heliyon*, vol. 6, no. 4, 2020, doi: 10.1016/j.heliyon.2020.e03725.
- [95] O. C. Okeh, C. O. Onwosi, and F. J. C. Odibo, "Biogas production from rice husks generated from various rice mills in Ebonyi State, Nigeria," *Renew Energy*, vol. 62, 2014, doi: 10.1016/j.renene.2013.07.006.
- [96] S. O. Oyedepo, "Towards achieving energy for sustainable development in Nigeria," 2014. doi: 10.1016/j.rser.2014.03.019.
- [97] S. Sri Shalini, K. Palanivelu, and A. Ramachandran, "Biochar Pyrolyzed from Municipal Solid Waste—Properties, Activation, Applications and Climate Benefits," in *Energy, Environment, and Sustainability*, 2022. doi: 10.1007/978-981-16-8682-5_14.
- [98] A. V. Bridgwater, D. Meier, and D. Radlein, "An overview of fast pyrolysis of biomass," *Org Geochem*, vol. 30, no. 12, 1999, doi: 10.1016/S0146-6380(99)00120-5.
- [99] U. Arena, "Process and technological aspects of municipal solid waste gasification. A review," *Waste Management*, vol. 32, no. 4, 2012, doi: 10.1016/j.wasman.2011.09.025.
- [100] L. Lombardi, E. Carnevale, and A. Corti, "A review of technologies and performances of thermal treatment systems for energy recovery from waste," *Waste Management*, vol. 37, 2015, doi: 10.1016/j.wasman.2014.11.010.
- [101] IRENA, "A International Renewable Energy Agency RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES, Biomass for Power Generation," *International Renewable Energy Agency RENEWABLE*, vol. 1, no. 1, 2012.

- [102] J. D. Murphy and E. McKeogh, "Technical, economic and environmental analysis of energy production from municipal solid waste," *Renew Energy*, vol. 29, no. 7, 2004, doi: 10.1016/j.renene.2003.12.002.
- [103] G. McKay, "Dioxin characterisation, formation and minimisation during municipal solid waste (MSW) incineration: Review," *Chemical Engineering Journal*, vol. 86, no. 3, 2002, doi: 10.1016/S1385-8947(01)00228-5.
- [104] C. Mukherjee, J. Denney, E. G. Mbonimpa, J. Slagley, and R. Bhowmik, "A review on municipal solid waste-to-energy trends in the USA," 2020. doi: 10.1016/j.rser.2019.109512.
- [105] A. U. Zaman, "Comparative study of municipal solid waste treatment technologies using life cycle assessment method," *International Journal of Environmental Science and Technology*, vol. 7, no. 2, 2010, doi: 10.1007/BF03326132.
- [106] H. Al Moussawi, F. Fardoun, and H. Louahlia, "Selection based on differences between cogeneration and trigeneration in various prime mover technologies," 2017. doi: 10.1016/j.rser.2017.02.077.
- [107] J. C. Bruno, V. Ortega-López, and A. Coronas, "Integration of absorption cooling systems into micro gas turbine trigeneration systems using biogas: Case study of a sewage treatment plant," *Appl Energy*, vol. 86, no. 6, 2009, doi: 10.1016/j.apenergy.2008.08.007.
- [108] P. A. Pilavachi, "Mini- and micro-gas turbines for combined heat and power," *Appl Therm Eng*, vol. 22, no. 18, 2002, doi: 10.1016/S1359-4311(02)00132-1.
- [109] M. He, X. Zhang, K. Zeng, and K. Gao, "A combined thermodynamic cycle used for waste heat recovery of internal combustion engine," *Energy*, vol. 36, no. 12, 2011, doi: 10.1016/j.energy.2011.10.014.
- [110] Y. Yin, S. Chen, X. Li, B. Jiang, J. R. H. Zhao, and G. Nong, "Comparative analysis of different CHP systems using biogas for the cassava starch plants," *Energy*, vol. 232, 2021, doi: 10.1016/j.energy.2021.121028.
- [111] D. W. Wu and R. Z. Wang, "Combined cooling, heating and power: A review," 2006. doi: 10.1016/j.pecs.2006.02.001.
- [112] A. Boudghene Stambouli and E. Traversa, "Fuel cells, an alternative to standard sources of energy," 2002. doi: 10.1016/S1364-0321(01)00015-6.
- [113] T. Nakata, D. Silva, and M. Rodionov, "Application of energy system models for designing a low-carbon society," 2011. doi: 10.1016/j.pecs.2010.08.001.
- [114] D. Sonar, S. L. Soni, and D. Sharma, "Micro-trigeneration for energy sustainability: Technologies, tools and trends," *Appl Therm Eng*, vol. 71, no. 2, 2014, doi: 10.1016/j.applthermaleng.2013.11.037.
- [115] S. Mekhilef, R. Saidur, and A. Safari, "Comparative study of different fuel cell technologies," 2012. doi: 10.1016/j.rser.2011.09.020.
- [116] C. Bang-Møller, M. Rokni, B. Elmegaard, J. Ahrenfeldt, and U. B. Henriksen, "Decentralized combined heat and power production by two-stage biomass gasification and solid oxide fuel cells," *Energy*, vol. 58, 2013, doi: 10.1016/j.energy.2013.06.046.
- [117] M. Liu, Y. Shi, and F. Fang, "Combined cooling, heating and power systems: A survey," 2014. doi: 10.1016/j.rser.2014.03.054.
- [118] H. A. El-Sattar, S. Kamel, D. Vera, and F. Jurado, "Tri-generation biomass system based on externally fired gas turbine, organic rankine cycle and absorption chiller," *J Clean Prod*, vol. 260, 2020, doi: 10.1016/j.jclepro.2020.121068.
- [119] U. Arena, F. Di Gregorio, and M. Santonastasi, "A techno-economic comparison between two design configurations for a small scale, biomass-to-energy gasification based system," *Chemical Engineering Journal*, vol. 162, no. 2, 2010, doi: 10.1016/j.cej.2010.05.067.

- [120] K. Jana and S. De, "Polygeneration using agricultural waste: Thermodynamic and economic feasibility study," *Renew Energy*, vol. 74, 2015, doi: 10.1016/j.renene.2014.08.078.
- [121] D. Maraver, A. Sin, J. Royo, and F. Sebastián, "Assessment of CCHP systems based on biomass combustion for small-scale applications through a review of the technology and analysis of energy efficiency parameters," *Appl Energy*, vol. 102, 2013, doi: 10.1016/j.apenergy.2012.07.012.
- [122] M. Renzi and C. Brandoni, "Study and application of a regenerative Stirling cogeneration device based on biomass combustion," *Appl Therm Eng*, vol. 67, no. 1–2, 2014, doi: 10.1016/j.applthermaleng.2014.03.045.
- [123] X. Q. Kong, R. Z. Wang, and X. H. Huang, "Energy efficiency and economic feasibility of CCHP driven by Stirling engine," *Energy Convers Manag*, vol. 45, no. 9–10, 2004, doi: 10.1016/j.enconman.2003.09.009.
- [124] S. Murugan and B. Horák, "Tri and polygeneration systems-A review," 2016. doi: 10.1016/j.rser.2016.01.127.
- [125] M. Liu, Y. Shi, and F. Fang, "A new operation strategy for CCHP systems with hybrid chillers," *Appl Energy*, vol. 95, 2012, doi: 10.1016/j.apenergy.2012.02.035.
- [126] A. A. Hassan, A. E. Elwardany, S. Ookawara, M. Ahmed, and I. I. El-Sharkawy, "Integrated adsorption-based multigeneration systems: A critical review and future trends," 2020. doi: 10.1016/j.ijrefrig.2020.04.001.
- [127] J. Deng, R. Z. Wang, and G. Y. Han, "A review of thermally activated cooling technologies for combined cooling, heating and power systems," 2011. doi: 10.1016/j.pecs.2010.05.003.
- [128] R. O. Lamidi, L. Jiang, Y. D. Wang, P. B. Pathare, and A. P. Roskilly, "Techno-economic analysis of a biogas driven poly-generation system for postharvest loss reduction in a Sub-Saharan African rural community," *Energy Convers Manag*, vol. 196, 2019, doi: 10.1016/j.enconman.2019.06.023.
- [129] D. Wu, J. Chen, and A. P. Roskilly, "Phase change material thermal storage for biofuel preheating in micro trigeneration application: A numerical study," *Appl Energy*, vol. 137, 2015, doi: 10.1016/j.apenergy.2014.09.087.
- [130] Y. Fang, S. Kuang, X. Gao, and Z. Zhang, "Preparation and characterization of novel nanoencapsulated phase change materials," *Energy Convers Manag*, vol. 49, no. 12, 2008, doi: 10.1016/j.enconman.2008.06.027.
- [131] B. Zalba, J. M. Marín, L. F. Cabeza, and H. Mehling, "Review on thermal energy storage with phase change: Materials, heat transfer analysis and applications," 2003. doi: 10.1016/S1359-4311(02)00192-8.
- [132] H. J. Alves, C. Bley Junior, R. R. Niklevicz, E. P. Frigo, M. S. Frigo, and C. H. Coimbra-Araújo, "Overview of hydrogen production technologies from biogas and the applications in fuel cells," in *International Journal of Hydrogen Energy*, 2013. doi: 10.1016/j.ijhydene.2013.02.057.
- [133] M. Carmo, D. L. Fritz, J. Mergel, and D. Stolten, "A comprehensive review on PEM water electrolysis," 2013. doi: 10.1016/j.ijhydene.2013.01.151.
- [134] M. H. Taheri, A. H. Mosaffa, and L. G. Farshi, "Energy, exergy and economic assessments of a novel integrated biomass based multigeneration energy system with hydrogen production and LNG regasification cycle," *Energy*, vol. 125, 2017, doi: 10.1016/j.energy.2017.02.124.
- [135] A. Habibollahzade, E. Gholamian, E. Houshfar, and A. Behzadi, "Multi-objective optimization of biomass-based solid oxide fuel cell integrated with Stirling engine and electrolyzer," *Energy Convers Manag*, vol. 171, 2018, doi: 10.1016/j.enconman.2018.06.061.

- [136] Y. E. Yuksel, M. Ozturk, and I. Dincer, "Performance investigation of a combined biomass gasifier-SOFC plant for compressed hydrogen production," *Int J Hydrogen Energy*, vol. 45, no. 60, 2020, doi: 10.1016/j.ijhydene.2020.05.076.
- [137] S. Yilmaz and H. Selim, "A review on the methods for biomass to energy conversion systems design," 2013. doi: 10.1016/j.rser.2013.05.015.
- [138] P. Zhou, B. W. Ang, and K. L. Poh, "Decision analysis in energy and environmental modeling: An update," 2006. doi: 10.1016/j.energy.2005.10.023.
- [139] J. J. Wang, Y. Y. Jing, C. F. Zhang, and J. H. Zhao, "Review on multi-criteria decision analysis aid in sustainable energy decision-making," 2009. doi: 10.1016/j.rser.2009.06.021.
- [140] R. Baños, F. Manzano-Agugliaro, F. G. Montoya, C. Gil, A. Alcayde, and J. Gómez, "Optimization methods applied to renewable and sustainable energy: A review," 2011. doi: 10.1016/j.rser.2010.12.008.
- [141] D. Connolly, H. Lund, B. V. Mathiesen, and M. Leahy, "A review of computer tools for analysing the integration of renewable energy into various energy systems," 2010. doi: 10.1016/j.apenergy.2009.09.026.
- [142] S. Karellas, I. Boukis, and G. Kontopoulos, "Development of an investment decision tool for biogas production from agricultural waste," 2010. doi: 10.1016/j.rser.2009.12.002.
- [143] F. d'Amore and F. Bezzo, "Strategic optimisation of biomass-based energy supply chains for sustainable mobility," *Comput Chem Eng*, vol. 87, 2016, doi: 10.1016/j.compchemeng.2016.01.003.
- [144] T. R. Ayodele, M. A. Alao, and A. S. O. Ogunjuyigbe, "Effect of collection efficiency and oxidation factor on greenhouse gas emission and life cycle cost of landfill distributed energy generation," *Sustain Cities Soc*, vol. 52, 2020, doi: 10.1016/j.scs.2019.101821.
- [145] S. Consonni, M. Giugliano, and M. Grosso, "Alternative strategies for energy recovery from municipal solid waste: Part A: Mass and energy balances," in *Waste Management*, 2005. doi: 10.1016/j.wasman.2004.09.007.
- [146] S. Consonni, M. Giugliano, and M. Grosso, "Alternative strategies for energy recovery from municipal solid waste: Part B: Emission and cost estimates," in *Waste Management*, 2005. doi: 10.1016/j.wasman.2004.09.006.
- [147] A. Hilkiyah Igoni, M. J. Ayotamuno, C. L. Eze, S. O. T. Ogaji, and S. D. Probert, "Designs of anaerobic digesters for producing biogas from municipal solid-waste," *Appl Energy*, vol. 85, no. 6, 2008, doi: 10.1016/j.apenergy.2007.07.013.
- [148] A. Donoso-Bravo, J. Mailier, C. Martin, J. Rodríguez, C. A. Aceves-Lara, and A. Vande Wouwer, "Model selection, identification and validation in anaerobic digestion: A review," 2011. doi: 10.1016/j.watres.2011.08.059.
- [149] S. Fazlollahi and F. Maréchal, "Multi-objective, multi-period optimization of biomass conversion technologies using evolutionary algorithms and mixed integer linear programming (MILP)," in *Applied Thermal Engineering*, 2013. doi: 10.1016/j.applthermaleng.2011.11.035.
- [150] K. Holmgren and A. Gebremedhin, "Modelling a district heating system: Introduction of waste incineration, policy instruments and co-operation with an industry," *Energy Policy*, vol. 32, no. 16, 2004, doi: 10.1016/S0301-4215(03)00168-X.
- [151] M. Luoranen and M. Horttanainen, "Co-generation based energy recovery from municipal solid waste integrated with the existing energy supply system," *Waste Management*, vol. 28, no. 1, 2008, doi: 10.1016/j.wasman.2006.12.014.

- [152] K. Holmgren and D. Henning, "Comparison between material and energy recovery of municipal waste from an energy perspective: A study of two Swedish municipalities," *Resour Conserv Recycl*, vol. 43, no. 1, 2004, doi: 10.1016/j.resconrec.2004.05.001.
- [153] R. Davis *et al.*, "Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons," *National Renewable Energy Laboratory-NREL*, no. October 2013, 2013.
- [154] I. Dincer and M. A. Rosen, *Exergy: Energy, Environment and Sustainable Development*. 2020. doi: 10.1016/B978-0-12-824372-5.09986-3.
- [155] H. Li, E. Larsson, E. Thorin, E. Dahlquist, and X. Yu, "Feasibility study on combining anaerobic digestion and biomass gasification to increase the production of biomethane," *Energy Convers Manag*, vol. 100, 2015, doi: 10.1016/j.enconman.2015.05.007.
- [156] M. Aziz, T. Kurniawan, T. Oda, and T. Kashiwagi, "Advanced power generation using biomass wastes from palm oil mills," *Appl Therm Eng*, vol. 114, 2017, doi: 10.1016/j.applthermaleng.2016.11.031.
- [157] A. Vlysidis, M. Binns, C. Webb, and C. Theodoropoulos, "A techno-economic analysis of biodiesel biorefineries: Assessment of integrated designs for the co-production of fuels and chemicals," *Energy*, vol. 36, no. 8, 2011, doi: 10.1016/j.energy.2011.04.046.
- [158] S. A. Gebrezgabher, M. P. M. Meuwissen, B. A. M. Prins, and A. G. J. M. O. Lansink, "Economic analysis of anaerobic digestion-A case of Green power biogas plant in the Netherlands," *NJAS - Wageningen Journal of Life Sciences*, vol. 57, no. 2, 2010, doi: 10.1016/j.njas.2009.07.006.
- [159] J. Salisu, N. Gao, and C. Quan, "Techno-economic Assessment of Co-gasification of Rice Husk and Plastic Waste as an Off-grid Power Source for Small Scale Rice Milling - an Aspen Plus Model," *J Anal Appl Pyrolysis*, vol. 158, 2021, doi: 10.1016/j.jaap.2021.105157.
- [160] S. Valdivia, C. M. L. Ugaya, G. Sonnemann, and J. Hildenbrand, "Towards a Life Cycle Sustainability Assessment: Making informed choices on products," 2011.
- [161] Z. Zhou, H. Jiang, and L. Qin, "Life cycle sustainability assessment of fuels," *Fuel*, vol. 86, no. 1–2, pp. 256–263, Jan. 2007, doi: 10.1016/j.fuel.2006.06.004.
- [162] W. Kloepffer, "Life cycle sustainability assessment of products," *Int J Life Cycle Assess*, vol. 13, no. 2, 2008, doi: 10.1065/lca2008.02.376.
- [163] D. Costa, P. Quinteiro, and A. C. Dias, "A systematic review of life cycle sustainability assessment: Current state, methodological challenges, and implementation issues," 2019. doi: 10.1016/j.scitotenv.2019.05.435.
- [164] S. N. M. Menikpura, S. H. Gheewala, and S. Bonnet, "Framework for life cycle sustainability assessment of municipal solid waste management systems with an application to a case study in Thailand," *Waste Management and Research*, vol. 30, no. 7, 2012, doi: 10.1177/0734242X12444896.
- [165] E. Ekener, J. Hansson, A. Larsson, and P. Peck, "Developing Life Cycle Sustainability Assessment methodology by applying values-based sustainability weighting - Tested on biomass based and fossil transportation fuels," *J Clean Prod*, vol. 181, 2018, doi: 10.1016/j.jclepro.2018.01.211.
- [166] O. Nubi, S. Morse, and R. J. Murphy, "Life Cycle Sustainability Assessment of Electricity Generation from Municipal Solid Waste in Nigeria: A Prospective Study," *Energies (Basel)*, vol. 15, no. 23, p. 9173, Dec. 2022, doi: 10.3390/en15239173.
- [167] N. Indrawan, B. Simkins, A. Kumar, and R. L. Huhnke, "Economics of distributed power generation via gasification of biomass and municipal solid waste," *Energies (Basel)*, vol. 13, no. 14, 2020, doi: 10.3390/en13143703.

- [168] F. C. Luz *et al.*, “Techno-economic analysis of municipal solid waste gasification for electricity generation in Brazil,” *Energy Convers Manag*, vol. 103, 2015, doi: 10.1016/j.enconman.2015.06.074.
- [169] S. Martinez, G. Michaux, P. Salagnac, and J. L. Bouvier, “Micro-combined heat and power systems (micro-CHP) based on renewable energy sources,” 2017. doi: 10.1016/j.enconman.2017.10.035.
- [170] A. M. Buswell and H. F. Mueller, “Mechanism of Methane Fermentation,” *Ind Eng Chem*, vol. 44, no. 3, pp. 550–552, Mar. 1952, doi: 10.1021/ie50507a033.
- [171] D. Deublein and A. Steinhauser, *Biogas from Waste and Renewable Resources: An Introduction*, 2nd ed. John Wiley & Sons, 2011.
- [172] G. F. Parkin and W. F. Owen, “Fundamentals of Anaerobic Digestion of Wastewater Sludges,” *Journal of Environmental Engineering*, vol. 112, no. 5, 1986, doi: 10.1061/(asce)0733-9372(1986)112:5(867).
- [173] M. A. Alao, O. M. Popoola, and T. R. Ayodele, “Waste-to-energy nexus: An overview of technologies and implementation for sustainable development,” 2022. doi: 10.1016/j.cles.2022.100034.
- [174] A. Chanthakett, M. T. Arif, M. M. K. Khan, and A. M. T. Oo, “Performance assessment of gasification reactors for sustainable management of municipal solid waste,” 2021. doi: 10.1016/j.jenvman.2021.112661.
- [175] M. F. M. A. Zamri *et al.*, “A comprehensive review on anaerobic digestion of organic fraction of municipal solid waste,” 2021. doi: 10.1016/j.rser.2020.110637.
- [176] B. Wang, R. Gupta, L. Bei, Q. Wan, and L. Sun, “A review on gasification of municipal solid waste (MSW): Syngas production, tar formation, mineral transformation and industrial challenges,” 2023. doi: 10.1016/j.ijhydene.2023.03.086.
- [177] A. Ceraso and A. Cesaro, “Life Cycle Sustainability Assessment of municipal solid waste management systems: a review,” Sep. 01, 2024, *Academic Press*. doi: 10.1016/j.jenvman.2024.122143.
- [178] E. Santoyo-Castelazo and A. Azapagic, “Sustainability assessment of energy systems: Integrating environmental, economic and social aspects,” *J Clean Prod*, vol. 80, 2014, doi: 10.1016/j.jclepro.2014.05.061.
- [179] R. E. G. Bohrer, R. BERTICELLI, A. PANDOLFO, and R. F. D. S. Salazar, “Life cycle sustainability assessment and multi-criteria decision analysis: selection of a strategy for municipal solid waste management in Brazil,” *Int J Environ Waste Manag*, vol. 1, no. 1, 2023, doi: 10.1504/ijewm.2023.10048361.
- [180] J. Wang, S. D. Maier, R. Horn, R. Holländer, and R. Aschemann, “Development of an ex-ante sustainability assessment methodology for municipal solid waste management innovations,” *Sustainability (Switzerland)*, vol. 10, no. 9, 2018, doi: 10.3390/su10093208.
- [181] H. W. Hsu *et al.*, “Toward sustainability of Waste-to-Energy: An overview,” Dec. 01, 2024, *Elsevier Ltd*. doi: 10.1016/j.enconman.2024.119063.
- [182] R. K. Foolmaun and T. Ramjeeawon, “Comparative life cycle assessment and life cycle costing of four disposal scenarios for used polyethylene terephthalate bottles in Mauritius,” *Environmental Technology (United Kingdom)*, vol. 33, no. 17, 2012, doi: 10.1080/09593330.2012.655321.
- [183] A. Ramos, J. Berzosa, J. Espí, F. Clarens, and A. Rouboa, “Life cycle costing for plasma gasification of municipal solid waste: A socio-economic approach,” *Energy Convers Manag*, vol. 209, 2020, doi: 10.1016/j.enconman.2020.112508.
- [184] A. Ramos, “Sustainability assessment in waste management: An exploratory study of the social perspective in waste-to-energy cases,” Oct. 10, 2024, *Elsevier Ltd*. doi: 10.1016/j.jclepro.2024.143693.

- [185] C. Visentin, A. W. da S. Trentin, A. B. Braun, and A. Thomé, “Life cycle sustainability assessment: A systematic literature review through the application perspective, indicators, and methodologies,” 2020. doi: 10.1016/j.jclepro.2020.122509.
- [186] M. Hemmati, N. Bayati, and T. Ebel, “Life Cycle Sustainability Assessment of Waste-to-Electricity Plants for 2030 Power Generation Development Scenarios in Western Lombok, Indonesia under Multi-Criteria Decision-Making Approach,” *Journal of Building Engineering*, vol. 95, Oct. 2024, doi: 10.1016/j.job.2024.110335.
- [187] T. Myllyviita, R. Antikainen, and P. Leskinen, “Sustainability assessment tools—their comprehensiveness and utilisation in company-level sustainability assessments in Finland,” *International Journal of Sustainable Development and World Ecology*, vol. 24, no. 3, 2017, doi: 10.1080/13504509.2016.1204636.
- [188] S. Moslehi and T. A. Reddy, “A new quantitative life cycle sustainability assessment framework: Application to integrated energy systems,” *Appl Energy*, vol. 239, 2019, doi: 10.1016/j.apenergy.2019.01.237.
- [189] A. Bernstad and J. la Cour Jansen, “A life cycle approach to the management of household food waste - A Swedish full-scale case study,” *Waste Management*, vol. 31, no. 8, 2011, doi: 10.1016/j.wasman.2011.02.026.
- [190] I. R. Istrate, D. Iribarren, J. L. Gálvez-Martos, and J. Dufour, “Review of life-cycle environmental consequences of waste-to-energy solutions on the municipal solid waste management system,” 2020. doi: 10.1016/j.resconrec.2020.104778.
- [191] L. Q. Luu and A. Halog, “Life Cycle Sustainability Assessment: A Holistic Evaluation of Social, Economic, and Environmental Impacts,” in *Sustainability in the Design, Synthesis and Analysis of Chemical Engineering Processes*, 2016. doi: 10.1016/B978-0-12-802032-6.00014-1.
- [192] W. Chen and N. M. Holden, “Tiered life cycle sustainability assessment applied to a grazing dairy farm,” *J Clean Prod*, vol. 172, 2018, doi: 10.1016/j.jclepro.2017.10.264.
- [193] C. Benoît Norris *et al.*, “Guidelines for SOCIAL LIFE CYCLE ASSESSMENT OF PRODUCTS AND ORGANIZATIONS 2020,” 2020.
- [194] R. Rebolledo-Leiva, M. T. Moreira, and S. González-García, “Progress of social assessment in the framework of bioeconomy under a life cycle perspective,” *Renewable and Sustainable Energy Reviews*, vol. 175, 2023, doi: 10.1016/j.rser.2023.113162.
- [195] A. Ramos, “Sustainability assessment in waste management: An exploratory study of the social perspective in waste-to-energy cases,” Oct. 10, 2024, *Elsevier Ltd*. doi: 10.1016/j.jclepro.2024.143693.
- [196] M. O. Asibey, O. Amponsah, and V. Yeboah, “Solid waste management in informal urban neighbourhoods. Occupational safety and health practices among tricycle operators in Kumasi, Ghana,” *Int J Environ Health Res*, vol. 29, no. 6, 2019, doi: 10.1080/09603123.2019.1569211.
- [197] D. Bleck and W. Wettberg, “Waste collection in developing countries - Tackling occupational safety and health hazards at their source,” *Waste Management*, vol. 32, no. 11, 2012, doi: 10.1016/j.wasman.2012.03.025.
- [198] U.S. Environmental Protection Agency, “Technical Assistance Document for the Reporting of Daily Air Quality – the Air Quality Index (AQI),” 2024.
- [199] M. A. Toko, Shaibu-Imodagbe, Okuofu, and A. Giwa, “Assessment of Groundwater Quality in Port Harcourt, Nigeria using Weighted Arithmetic Water Quality Index ARTICLE INFORMATION ABSTRACT,” 2020.
- [200] A. Grace, I. Innocent, F. Chijioko, and M. Sabainah, “Socio-Economic Effects of Open Waste Dumpsite on Residents of Selected Communities in Rivers State, Nigeria,” 2024. [Online]. Available: www.ijisrt.com

- [201] T. R. Zolnikov, F. Furio, V. Cruvinel, and J. Richards, "A systematic review on informal waste picking: Occupational hazards and health outcomes," 2021. doi: 10.1016/j.wasman.2021.03.006.
- [202] D. A. Okpara, M. Kharlamova, and V. Grachev, "Proliferation of household waste irregular dumpsites in Niger Delta region (Nigeria): unsustainable public health monitoring and future restitution," *Sustainable Environment Research*, vol. 31, no. 1, 2021, doi: 10.1186/s42834-020-00077-1.
- [203] J. M. Ayotamuno and A. E. Gobo, "Municipal solid waste management in Port Harcourt, Nigeria: Obstacles and prospects," 2004. doi: 10.1108/14777830410540135.
- [204] T. C. Ogwueleka, "Municipal solid waste characteristics and management in Nigeria," *Iranian J Environ Health Sci Eng*, vol. 6, no. 3, 2009.
- [205] M. Tawfiq Ladan, "LEAD Law Environment and Development Journal VOLUME 8/1 REVIEW OF NESREA ACT 2007 AND REGULATIONS 2009-2011: A NEW DAWN IN ENVIRONMENTAL COMPLIANCE AND ENFORCEMENT IN NIGERIA." [Online]. Available: www.lead-journal.org
- [206] FEDERAL MINISTRY OF ENVIRONMENT, "NATIONAL ENVIRONMENTAL SANITATION POLICY 2005," 2005.
- [207] D. V. Ogunkan, "Achieving sustainable environmental governance in Nigeria: A review for policy consideration," 2022. doi: 10.1016/j.ugj.2022.04.004.
- [208] M. Melikoglu, "Vision 2023: Assessing the feasibility of electricity and biogas production from municipal solid waste in Turkey," 2013. doi: 10.1016/j.rser.2012.11.017.
- [209] "Nigeria Demographic and Health Survey 2023-24 Key Indicators."
- [210] E. Nnete Gam and C. N. Tom, "Solid Waste Characterisation in PortHarcourt Metropolis, Rivers State, Nigeria," *International Journal of Advances in Engineering and Management*, vol. 7, no. 3, 2025, doi: 10.35629/5252-0703810823.
- [211] A. H. Igoni, M. J. Ayotamuno, S. O. T. Ogaji, and S. D. Probert, "Municipal solid-waste in Port Harcourt, Nigeria," *Appl Energy*, vol. 84, no. 6, 2007, doi: 10.1016/j.apenergy.2006.12.002.
- [212] B. Babatunde *et al.*, "Comparative analysis of municipal solid waste (MSW) composition in three local government areas in Rivers State, Nigeria," *Afr J Environ Sci Tech*, vol. 7, no. 9, 2013.
- [213] S. Achinas and G. J. W. Euverink, "Theoretical analysis of biogas potential prediction from agricultural waste," *Resource-Efficient Technologies*, vol. 2, no. 3, 2016, doi: 10.1016/j.reffit.2016.08.001.
- [214] L. Appels, J. Baeyens, J. Degrève, and R. Dewil, "Principles and potential of the anaerobic digestion of waste-activated sludge," 2008. doi: 10.1016/j.pecs.2008.06.002.
- [215] P. Basu, *Biomass gasification, pyrolysis and torrefaction: Practical design and theory*. 2018. doi: 10.1016/C2016-0-04056-1.
- [216] U. Arena, F. Di Gregorio, C. Amorese, and M. L. Mastellone, "A techno-economic comparison of fluidized bed gasification of two mixed plastic wastes," *Waste Management*, vol. 31, no. 7, 2011, doi: 10.1016/j.wasman.2011.02.004.
- [217] U. Environmental Protection Agency, C. Heat, and P. Partnership, "Catalog of CHP Technologies, Section 1. Introduction," 2015.
- [218] WÄRTSILÄ, "WÄRTSILÄ 34SG BALANCER GAS ENGINE GENERATING SET," 2022.
- [219] Capstone Green Energy, "Smarter Energy for a Cleaner Future," 2025. [Online]. Available: www.capstonegreenenergy.com
- [220] I. Renewable Energy Agency, *Key findings: Renewable power generation costs in 2019*. 2020.

- [221] J. Spaeth and P. Buckley, “I E A B I O E N E R G Y : E X C O : 2 0 2 0 : 0 2 Under the IEA Framework for International Energy Technology Cooperation the Executive Committee of each Technology Collaboration Programme (TCP) must produce an Annual Report for IEA,” 2019.
- [222] Turboden, “Organic Rankine Cycle Solutions for Power Generation with Turbogenerators The,” 2024. [Online]. Available: <https://www.turboden.com/solutions/1051/biomass>
- [223] A. Behzadi, E. Gholamian, E. Houshfar, and A. Habibollahzade, “Multi-objective optimization and exergoeconomic analysis of waste heat recovery from Tehran’s waste-to-energy plant integrated with an ORC unit,” *Energy*, vol. 160, 2018, doi: 10.1016/j.energy.2018.07.074.
- [224] V. Eveloy, P. Rodgers, and L. Qiu, “Performance investigation of a power, heating and seawater desalination poly-generation scheme in an off-shore oil field,” *Energy*, vol. 98, 2016, doi: 10.1016/j.energy.2015.12.113.
- [225] M. A. J. Huijbregts *et al.*, “ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level,” *International Journal of Life Cycle Assessment*, vol. 22, no. 2, 2017, doi: 10.1007/s11367-016-1246-y.
- [226] J. Guinée, “Handbook on life cycle assessment - Operational guide to the ISO standards,” 2001. doi: 10.1007/BF02978784.
- [227] “Climate Change 2021—The Physical Science Basis,” *Chemistry International*, vol. 43, no. 4, 2021, doi: 10.1515/ci-2021-0407.
- [228] Y. Sun, Z. Qin, Y. Tang, T. Huang, S. Ding, and X. Ma, “Techno-environmental-economic evaluation on municipal solid waste (MSW) to power/fuel by gasification-based and incineration-based routes,” *J Environ Chem Eng*, vol. 9, no. 5, 2021, doi: 10.1016/j.jece.2021.106108.
- [229] A. Arias, C. R. Behera, G. Feijoo, G. Sin, and M. T. Moreira, “Unravelling the environmental and economic impacts of innovative technologies for the enhancement of biogas production and sludge management in wastewater systems,” *J Environ Manage*, vol. 270, 2020, doi: 10.1016/j.jenvman.2020.110965.
- [230] O. J. Ogorure, C. O. C. Oko, E. O. Diemuodeke, and K. Owebor, “Energy, exergy, environmental and economic analysis of an agricultural waste-to-energy integrated multigeneration thermal power plant,” *Energy Convers Manag*, vol. 171, 2018, doi: 10.1016/j.enconman.2018.05.093.
- [231] X. Kan, D. Zhou, W. Yang, X. Zhai, and C. H. Wang, “An investigation on utilization of biogas and syngas produced from biomass waste in premixed spark ignition engine,” *Appl Energy*, vol. 212, 2018, doi: 10.1016/j.apenergy.2017.12.037.
- [232] W. Short, D. Packey, and T. Holt, “A manual for the economic evaluation of energy efficiency and renewable energy technologies,” *Renew Energy*, vol. 95, no. March, 1995, doi: NREL/TP-462-5173.
- [233] Y. Yang, J. Wang, K. Chong, and A. V. Bridgwater, “A techno-economic analysis of energy recovery from organic fraction of municipal solid waste (MSW) by an integrated intermediate pyrolysis and combined heat and power (CHP) plant,” *Energy Convers Manag*, vol. 174, 2018, doi: 10.1016/j.enconman.2018.08.033.
- [234] M. M. Azis, J. Kristanto, and C. W. Purnomo, “A techno-economic evaluation of municipal solid waste (Msw) conversion to energy in indonesia,” *Sustainability (Switzerland)*, vol. 13, no. 13, 2021, doi: 10.3390/su13137232.
- [235] L. A. Hadidi and M. M. Omer, “A financial feasibility model of gasification and anaerobic digestion waste-to-energy (WTE) plants in Saudi Arabia,” *Waste Management*, vol. 59, 2017, doi: 10.1016/j.wasman.2016.09.030.

- [236] V. P. Paixão, L. F. M. Franco, and J. V. H. Dangelo, “Thermoeconomic analysis of conventional and recuperative ORC for heat recovery of exothermic reactions,” *Thermal Science and Engineering Progress*, vol. 33, 2022, doi: 10.1016/j.tsep.2022.101347.
- [237] IRENA, “Renewable Energy in District Heating and Cooling: A Sector Roadmap for REmap.”
- [238] X. Luo, J. Wang, M. Dooner, and J. Clarke, “Overview of current development in electrical energy storage technologies and the application potential in power system operation,” *Appl Energy*, vol. 137, 2015, doi: 10.1016/j.apenergy.2014.09.081.
- [239] J. Vourdoubas, “Economic and Environmental Assessment of the Use of Renewable Energies in Greenhouses: A Case Study in Crete-Greece,” *Journal of Agricultural Science*, vol. 7, no. 10, 2015, doi: 10.5539/jas.v7n10p48.
- [240] T. Compennolle, N. Witters, S. Van Passel, and T. Thewys, “Analyzing a self-managed CHP system for greenhouse cultivation as a profitable way to reduce CO₂-emissions,” *Energy*, vol. 36, no. 4, 2011, doi: 10.1016/j.energy.2010.02.045.
- [241] *Renewable Energy and Agri-food Systems: Advancing Energy and Food Security towards Sustainable Development Goals*. 2021. doi: 10.4060/cb7433en.
- [242] IRENA (International Renewable Energy Agency), “Renewable Power Generation Costs in 2018,” 2019.
- [243] K. Van Den Berg and T. C. Duong, “Solid and Industrial Hazardous Waste Management Assessment - Options and action area to implement the national strategy,” *The World Bank*, 2018.
- [244] D. Olukanni, O. Akinyinka, A. Ede, I. Akinwumi, and K. Ajanaku, “Appraisal of Municipal Solid Waste Management, Its Effect and Resource Potential in a Semi-Urban City: a Case Study,” *Journal of South African Business Research*, pp. 1–13, Oct. 2014, doi: 10.5171/2014.705695.
- [245] J. C. Solarte-Toro, M. Laghezza, S. Fiore, F. Berruti, K. Moustakas, and C. A. Cardona Alzate, “Review of the impact of socio-economic conditions on the development and implementation of biorefineries,” *Fuel*, vol. 328, 2022, doi: 10.1016/j.fuel.2022.125169.
- [246] O. Nubi, S. Morse, and R. J. Murphy, “A Prospective Social Life Cycle Assessment (sLCA) of Electricity Generation from Municipal Solid Waste in Nigeria,” *Sustainability*, vol. 13, no. 18, p. 10177, Sep. 2021, doi: 10.3390/su131810177.
- [247] A. I. Chatzimouratidis and P. A. Pilavachi, “Multicriteria evaluation of power plants impact on the living standard using the analytic hierarchy process,” *Energy Policy*, vol. 36, no. 3, 2008, doi: 10.1016/j.enpol.2007.11.028.
- [248] F. Cavallaro and L. Ciruolo, “A multicriteria approach to evaluate wind energy plants on an Italian island,” *Energy Policy*, vol. 33, no. 2, 2005, doi: 10.1016/S0301-4215(03)00228-3.
- [249] O. Renn, “Social assessment of waste energy utilization scenarios,” *Energy*, vol. 28, no. 13, 2003, doi: 10.1016/S0360-5442(03)00113-0.
- [250] J. Gutberlet, “Grassroots waste picker organizations addressing the UN sustainable development goals,” *World Dev*, vol. 138, 2021, doi: 10.1016/j.worlddev.2020.105195.
- [251] M. Finkbeiner, E. M. Schau, A. Lehmann, and M. Traverso, “Towards life cycle sustainability assessment,” *Sustainability*, vol. 2, no. 10, 2010, doi: 10.3390/su2103309.
- [252] M. Collotta, P. Champagne, G. Tomasoni, M. Alberti, L. Busi, and W. Mabee, “Critical indicators of sustainability for biofuels: An analysis through a life cycle sustainability assessment perspective,” *Renewable and Sustainable Energy Reviews*, vol. 115, 2019, doi: 10.1016/j.rser.2019.109358.

- [253] J. M. Aberilla, A. Gallego-Schmid, L. Stamford, and A. Azapagic, "Design and environmental sustainability assessment of small-scale off-grid energy systems for remote rural communities," *Appl Energy*, vol. 258, 2020, doi: 10.1016/j.apenergy.2019.114004.
- [254] M. Kojima and J. J. Han, *Electricity Tariffs for Nonresidential Customers in Sub-Saharan Africa*. 2017. doi: 10.1596/26571.
- [255] M. Aziz, T. Kurniawan, T. Oda, and T. Kashiwagi, "Advanced power generation using biomass wastes from palm oil mills," *Appl Therm Eng*, vol. 114, 2017, doi: 10.1016/j.applthermaleng.2016.11.031.
- [256] S. Karellas, I. Boukis, and G. Kontopoulos, "Development of an investment decision tool for biogas production from agricultural waste," 2010. doi: 10.1016/j.rser.2009.12.002.
- [257] Y. T. Chong, K. M. Teo, and L. C. Tang, "A lifecycle-based sustainability indicator framework for waste-to-energy systems and a proposed metric of sustainability," 2016. doi: 10.1016/j.rser.2015.11.036.
- [258] L. A. Díaz-Trujillo and F. Nápoles-Rivera, "Optimization of biogas supply chain in Mexico considering economic and environmental aspects," *Renew Energy*, vol. 139, 2019, doi: 10.1016/j.renene.2019.03.027.

Appendix

Chapter 4:

Product ratio	SI Unit	Results
CH4	kg/ton	228.23
CO2	kg/ton	547.69
NH3	kg/ton	4.48
H2S	kg/ton	1.00
Actual methane yield		
Used organic matter (%)	%	80%
AD waste per day	kg/day	394,056.23
OOFMSW flow rate	kg/s	5.70
Methane per kg of msw	m ³ /kg	0.144
LHV of Methane	MJ/kg	50
Methane CH4	kg/year	31,263.74
Volume of biogas	m ³ /year	43,603.54
Fertilizer	ton/year	34,245.36

Figure 0-1: Snapshot of the Anaerobic Digestion modelling interface showing the stoichiometric yield calculations module based in the Buswell-Mueller equation.

Chapter 5: Emissions for MSW collection and transport

The emissions from diesel combustion during the waste collection and transportation is calculated using:

$$\text{Emissions (kg/l)} = \text{Diesel Fuel Used (L/t)} * \text{Emission Factor (kg/l)} \quad (62)$$

Assuming the total diesel consumed each waste collection trip is 100 L of diesel and the tonnage for a trip is 9 tonnes of MSW the diesel consumption in L/t is calculated as

$$\text{Diesel Fuel Used (L/t)} = 100 \text{ L} / Xt \quad (63)$$

Chapter 5: Methodology for Calculating Life Cycle Impact Characterisation Results

For the main system (excluding prime movers), emissions per tonne of municipal solid waste (MSW) were calculated based on the Life Cycle Inventory (LCI) data compiled in Chapter 5. The following key steps were applied:

Step 1: Convert annual emissions to kg/tonne MSW

$$E_{kg/ton} = \frac{E_{annual} (ton) \times 1000}{\text{Annual Throughput (tonnes)}} \quad (64)$$

Where $E_{annual} (ton)$ is annual emission in tonnes and *Annual Throughput (tonnes)* is 20,000 tonnes MSW per year (as assumed in this study).

Step 2: Apply characterisation factors

For each pollutant, characterisation factors (CF) were applied to convert inventory flows to impact category equivalents.

$$Impact = E_{kg/ton} \times CF \quad (65)$$

Characterisation factors used:

- GWP (IPCC 2021):
 - CO₂ = 1.0 kg CO₂-eq/kg.
 - CH₄ = 27.2 kg CO₂-eq/kg.
 - CO = 1.57 kg CO₂-eq/kg.
- Acidification:
 - NO_x = 0.7 kg SO₂-eq/kg.
 - NH₃ = 1.88 kg SO₂-eq/kg.
- Eutrophication:
 - NO_x = 0.13 kg PO₄³⁻-eq/kg.
 - NH₃ = 0.35 kg PO₄³⁻-eq/kg.
- PM Formation:
 - PM₁₀ = 1.0 kg PM₁₀-eq/kg.
- Fossil Depletion:
 - Diesel = 38.6 MJ per litre consumed.
- Photochemical Ozone Formation (POF):
 - CO = 0.022 kg NMVOC-eq/kg.
 - NO_x = 0.007 kg NMVOC-eq/kg.

Prime Mover Emissions

For each prime mover, emissions were calculated based on engine-specific exhaust flow rates, pollutant concentrations (ppm), and electricity output per tonne MSW.

Step 1: Convert exhaust mass flow to volume flow

$$Q_{Nm^3/s} = \frac{Q_{kg/s}}{\rho_{gas}} \quad (66)$$

Where $Q_{kg/s}$ is exhaust mass flow and ρ_{gas} is exhaust gas density (assumed 1.25 kg/Nm³).

Step 2: Determine runtime per tonne MSW

$$t_{hours/MSW} = \frac{1}{\eta} \quad (67)$$

Where η is the prime mover efficiency.

Step 3: Calculate total exhaust volume per tonne MSW

$$V_{Nm^3/tonne\ MSW} = Q_{Nm^3/s} \times 3600 \times t_{hours/MSW} \quad (68)$$

Step 4: Convert ppm to mg/Nm³

$$C_{mg/Nm^3} = \frac{C_{ppm} \times MW \times 1000}{24.45} \quad (69)$$

Where C_{ppm} is concentration in ppm and MW is molecular weight (CO = 28.01 g/mol; NO_x = 46 g/mol).

Step 5: Calculate total emissions per tonne MSW

$$E_{kg/ton} = C_{mg/Nm^3} \times V_{Nm^3/tonne\ MSW} \times 10^{-6} \quad (70)$$

Step 6: Apply characterisation factors

$$Impact = E_{kg/ton} \times CF \quad (71)$$

Production with G3516													
Capacity factor	%	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Electrical Production	MWh/yr	207,445,540.69	208,364,532.79	208,364,532.79	208,364,532.79	208,364,532.79	208,364,532.79	208,364,532.79	208,364,532.79	208,364,532.79	208,364,532.79	208,364,532.79	208,364,532.79
Char Yield	ton/yr	21,444,948.24	21,871,844.50	21,871,844.50	21,765,689.27	21,652,889.83	21,544,614.43	21,434,893.24	21,329,708.87	21,223,062.21	21,116,945.03	21,011,360.80	20,904,604.50
Char Yield	ton/yr	23,980.95	21,871.84	21,871.84	21,765.69	21,652.89	21,544.61	21,434.89	21,329.71	21,223.06	21,116.94	21,011.36	20,904.61
Fertilizer Yield	ton/yr	23,108.56	20,993.82	20,993.82	20,888.09	20,782.36	20,676.63	20,570.90	20,465.17	20,359.44	20,253.71	20,147.98	20,042.25
UNIT	SOURCE	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
CAPEX													
Initial Investment	\$	10,521,320.20	20,321,320.20	20,321,320.20	20,321,320.20	20,321,320.20	20,321,320.20	20,321,320.20	20,321,320.20	20,321,320.20	20,321,320.20	20,321,320.20	20,321,320.20
Depreciation	\$	6156.40	6156.40	6156.40	6156.40	6156.40	6156.40	6156.40	6156.40	6156.40	6156.40	6156.40	6156.40
Accumulated depreciation	\$	6156.40	12312.79	18469.19	24625.58	30781.98	36938.38	43094.77	49251.17	55407.56	61563.96	67720.36	73876.75
CAPEX (net)	\$	20,515,163.80	20,327,376.60	20,305,448.80	20,187,911.01	20,070,438.62	19,952,966.23	19,835,493.84	19,718,021.45	19,600,549.06	19,483,076.67	19,365,604.28	19,248,131.89
OPER													
TOTAL OPER	\$	8,993,414.97	8,361,414.97	8,361,414.97	8,361,414.97	8,361,414.97	8,361,414.97	8,361,414.97	8,361,414.97	8,361,414.97	8,361,414.97	8,361,414.97	8,361,414.97
PRE CASH FLOW													
Electricity revenue	\$	27,277,000.34	27,277,000.34	27,277,000.34	27,277,000.34	27,277,000.34	27,277,000.34	27,277,000.34	27,277,000.34	27,277,000.34	27,277,000.34	27,277,000.34	27,277,000.34
Fertilizer revenue	\$	1,134,339.79	1,134,339.79	1,134,339.79	1,134,339.79	1,134,339.79	1,134,339.79	1,134,339.79	1,134,339.79	1,134,339.79	1,134,339.79	1,134,339.79	1,134,339.79
Slag/Char revenue	\$	1,899,047.40	1,899,047.40	1,899,047.40	1,899,047.40	1,899,047.40	1,899,047.40	1,899,047.40	1,899,047.40	1,899,047.40	1,899,047.40	1,899,047.40	1,899,047.40
Cryst. Sales revenue	\$	38,625.00	38,625.00	38,625.00	38,625.00	38,625.00	38,625.00	38,625.00	38,625.00	38,625.00	38,625.00	38,625.00	38,625.00
Net Income before interest and taxes	\$	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62
Less: Income Tax 10%	\$	-2,122,840.96	-2,122,840.96	-2,122,840.96	-2,122,840.96	-2,122,840.96	-2,122,840.96	-2,122,840.96	-2,122,840.96	-2,122,840.96	-2,122,840.96	-2,122,840.96	-2,122,840.96
Plus: Depreciation	\$	4,156.40	4,156.40	4,156.40	4,156.40	4,156.40	4,156.40	4,156.40	4,156.40	4,156.40	4,156.40	4,156.40	4,156.40
Free cash flow	\$	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06
Cumulative Free-cash flow	\$	19,109,725.06	38,219,450.12	57,329,175.18	76,438,900.24	95,548,625.30	114,658,350.36	133,768,075.42	152,877,800.48	171,987,525.54	191,097,250.60	210,206,975.66	229,316,700.72
Payback year	year		1										
Discounted PRE CASH FLOW													
Free cash flow	\$	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06	19,109,725.06
Discount factor	%	0.91	0.83	0.75	0.68	0.60	0.53	0.46	0.40	0.34	0.29	0.24	0.19
Sum of present value	\$	17,399,850.81	15,848,100.81	14,438,293.81	13,148,486.81	11,978,680.81	10,918,874.81	9,969,068.81	9,119,262.81	8,369,456.81	7,719,650.81	7,169,844.81	6,719,038.81
Less: CAPEX	\$	(10,521,320.20)	(20,321,320.20)	(20,321,320.20)	(20,321,320.20)	(20,321,320.20)	(20,321,320.20)	(20,321,320.20)	(20,321,320.20)	(20,321,320.20)	(20,321,320.20)	(20,321,320.20)	(20,321,320.20)
Income Statement													
Net Income	\$	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62	21,228,409.62
Levelized Cost of Energy	\$	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Net Present Value	\$	105,205,934.54	105,205,934.54	105,205,934.54	105,205,934.54	105,205,934.54	105,205,934.54	105,205,934.54	105,205,934.54	105,205,934.54	105,205,934.54	105,205,934.54	105,205,934.54
IRR	%	71%	71%	71%	71%	71%	71%	71%	71%	71%	71%	71%	71%
Payback period	years		1										

Figure 0-2: Sample Economic Calculations

Data Category	Value (Example)	Units	Relevance	Relevance	Relevance	Notes/Assumptions
			System A	System B	System C	
Waste Composition	Organics 50–60%	% by weight	Yes	Yes	Yes	Based on local MSW studies (Port Harcourt)
Waste Generation Rate		086 kg/capita/day	Yes	Yes	Yes	From World Bank or national studies
Transportation Distance	15	km	Yes	Yes	Yes	To be measured from local routes
Diesel Consumption		1111 L/tonne MSW	Yes	Yes	Yes	Estimate from field study or vehicle logs
Electricity for Sorting	34.02	kWh/tonne MSW	Yes	Yes	Yes	From literature (e.g., Table 9)
Electricity for AD	0.77	kWh/tonne MSW	Yes	Yes	Yes	From literature (e.g., Table 9)
Electricity for Gasification	4.50	kWh/tonne MSW	Yes	Yes	Yes	From literature (e.g., Table 9)
Electricity for Chiller (System B)	4.72	kWh/tonne MSW	No	Yes	No	System B only component
Biogas Yield (AD)	228.12 m ³	m ³ /tonne MSW	Yes	Yes	Yes	Calculated using Buswell's Equation
Syngas Yield (Gasification)	3.2 Nm ³ /kg	Nm ³ /tonne MSW	Yes	Yes	Yes	From gasifier performance data
Electricity Output (C1000S)	101619	kWh/tonne MSW	Yes	Yes	Yes	Based on efficiency of chosen prime mover
Electricity Output (SGT-50)	80064	kWh/tonne MSW	Yes	Yes	Yes	Based on efficiency of chosen prime mover
Electricity Output (SGT-400)	107162	kWh/tonne MSW	Yes	Yes	Yes	Based on efficiency of chosen prime mover
Electricity Output (G3516)	116092	kWh/tonne MSW	Yes	Yes	Yes	Based on efficiency of chosen prime mover
Electricity Output (G3616)	127486	kWh/tonne MSW	Yes	Yes	Yes	Based on efficiency of chosen prime mover
Electricity Output (Wärtsilä 9L34DF)	137648	kWh/tonne MSW	Yes	Yes	Yes	Based on efficiency of chosen prime mover
Electricity Output (Wärtsilä 12V34DF)	137648	kWh/tonne MSW	Yes	Yes	Yes	Based on efficiency of chosen prime mover
Heat Output (ORC/System B)	ORC + System B	MJ/tonne MSW	Yes	Yes	Yes	ORC or heat recovery station data
Digestate Output	28739	kg/tonne MSW	Yes	Yes	Yes	Used as fertiliser (System A and C)
Biochar Output	20525	kg/tonne MSW	Yes	Yes	Yes	Used as soil enhancer (System A and B)
CO ₂ Emissions (Transport)	30	kg CO ₂ /tonne MSW	Yes	Yes	Yes	Table 11 emission factors
NO _x Emissions (Transport)	002622	kg NO _x /tonne MSW	Yes	Yes	Yes	Vehicle emission factor
Particulate Matter Emissions	000689	kg PM10/tonne MSW	Yes	Yes	Yes	From transport & combustion sources
Water Use (Cleaning/Cooling)	variable	litres/tonne MSW	Yes	Yes	Yes	Facility operational water need
Chemical Use (Chiller)	lithium bromide	kg/tonne MSW	No	Yes	No	Absorption chiller chemical needs
Anaerobic Digestion Efficiency	80%	%	Yes	Yes	Yes	From Excel data
Gasification Efficiency	75%	%	Yes	Yes	Yes	From Excel data
ORC Efficiency (High Temp)	25%	%	Yes	No	No	From Excel data
ORC Efficiency (Medium Temp)	15%	%	Yes	No	No	From Excel data
ORC Efficiency (Low Temp)	8%	%	Yes	No	No	From Excel data
Prime Mover Efficiency (Capstone C1000S)	33%	%	Yes	Yes	Yes	From Excel data
Prime Mover Efficiency (SGT-50)	26%	%	Yes	Yes	Yes	From Excel data
Prime Mover Efficiency (SGT-400)	348%	%	Yes	Yes	Yes	From Excel data
Prime Mover Efficiency (G3516)	377%	%	Yes	Yes	Yes	From Excel data
Prime Mover Efficiency (G3616)	414%	%	Yes	Yes	Yes	From Excel data
Prime Mover Efficiency (Wärtsilä 9L34DF)	447%	%	Yes	Yes	Yes	From Excel data
Prime Mover Efficiency (Wärtsilä 12V34DF)	447%	%	Yes	Yes	Yes	From Excel data
Grid Emission Factor (Nigeria)	0.59 kg CO ₂ /kWh	kg CO ₂ /kWh	Yes	Yes	Yes	IEA Nigeria estimate
Carbon Sequestration (Biochar)	~0.35 tCO ₂ /tonne MSW	tCO ₂ /t MSW	Yes	Yes	Yes	Assumed sequestration factor from biochar literature
Fertiliser Offset (Digestate)	~50 kg NPK/t	kg/t	Yes	Yes	Yes	Based on digestate composition and application
Leachate Generation from AD	To be estimated	litres/tonne MSW	Yes	Yes	Yes	May vary based on retention time
CH ₄ Emissions (AD)	149	ton/year	Yes	Yes	Yes	From Excel AD gas composition
CO ₂ Emissions (AD)	357	ton/year	Yes	Yes	Yes	From Excel AD gas composition
NH ₃ Emissions (AD)	003	ton/year	Yes	Yes	Yes	From Excel data
H ₂ S Emissions (AD)	0000018	ton/year	Yes	Yes	Yes	From Excel data
H ₂ Composition (G)	4546	ton/year	Yes	Yes	Yes	From corrected gasification composition table
CO Composition (G)	6641	ton/year	Yes	Yes	Yes	From corrected gasification composition table
CH ₄ Composition (G)	2238	ton/year	Yes	Yes	Yes	From corrected gasification composition table
CO ₂ Composition (G)	8552	ton/year	Yes	Yes	Yes	From corrected gasification composition table
N ₂ Composition (G)	34741	ton/year	Yes	Yes	Yes	From corrected gasification composition table
C ₂ H ₄ Composition (G)	459	ton/year	Yes	Yes	Yes	From corrected gasification composition table
C ₂ H ₆ Composition (G)	029	ton/year	Yes	Yes	Yes	From corrected gasification composition table
C ₂ H ₂ Composition (G)	046	ton/year	Yes	Yes	Yes	From corrected gasification composition table
C ₆ H ₆ Composition (G)	143	ton/year	Yes	Yes	Yes	From corrected gasification composition table
CO Emissions (C1000S)	18	ppm	Yes	Yes	Yes	Capstone datasheet
NO _x Emissions (C1000S)	9	ppm	Yes	Yes	Yes	Capstone datasheet
CO Emissions (SGT-50)	30	ppm	Yes	Yes	Yes	Estimated based on similar turbine class
NO _x Emissions (SGT-50)	35	ppm	Yes	Yes	Yes	Estimated based on similar turbine class
CO Emissions (SGT-400)	25	ppm	Yes	Yes	Yes	Manufacturer datasheet
NO _x Emissions (SGT-400)	28	ppm	Yes	Yes	Yes	Manufacturer datasheet
CO Emissions (G3516)	15	ppm	Yes	Yes	Yes	Manufacturer datasheet
NO _x Emissions (G3516)	20	ppm	Yes	Yes	Yes	Manufacturer datasheet
CO Emissions (G3616)	12	ppm	Yes	Yes	Yes	Manufacturer datasheet
NO _x Emissions (G3616)	18	ppm	Yes	Yes	Yes	Manufacturer datasheet
CO Emissions (Wärtsilä 9L34DF)	10	ppm	Yes	Yes	Yes	Manufacturer datasheet
NO _x Emissions (Wärtsilä 9L34DF)	50	ppm	Yes	Yes	Yes	Manufacturer datasheet
CO Emissions (Wärtsilä 12V34DF)	9	ppm	Yes	Yes	Yes	Manufacturer datasheet
NO _x Emissions (Wärtsilä 12V34DF)	50	ppm	Yes	Yes	Yes	Manufacturer datasheet
Exhaust Mass Flow Rate (C1000S)	67	kg/s	Yes	Yes	Yes	Manufacturer datasheet
Exhaust Mass Flow Rate (SGT-50)	95	kg/s	Yes	Yes	Yes	Manufacturer datasheet
Exhaust Mass Flow Rate (SGT-400)	342	kg/s	Yes	Yes	Yes	Manufacturer datasheet
Exhaust Mass Flow Rate (G3516)	577	kg/s	Yes	Yes	Yes	Manufacturer datasheet
Exhaust Mass Flow Rate (G3616)	631	kg/s	Yes	Yes	Yes	Manufacturer datasheet
Exhaust Mass Flow Rate (Wärtsilä 9L34DF)	59	kg/s	Yes	Yes	Yes	Manufacturer datasheet
Exhaust Mass Flow Rate (Wärtsilä 12V34DF)	89	kg/s	Yes	Yes	Yes	Manufacturer datasheet

Figure 0-3: LCI Data Sheet

Millions of tonnes of oil equivalent

Nigeria BALANCE (2020)

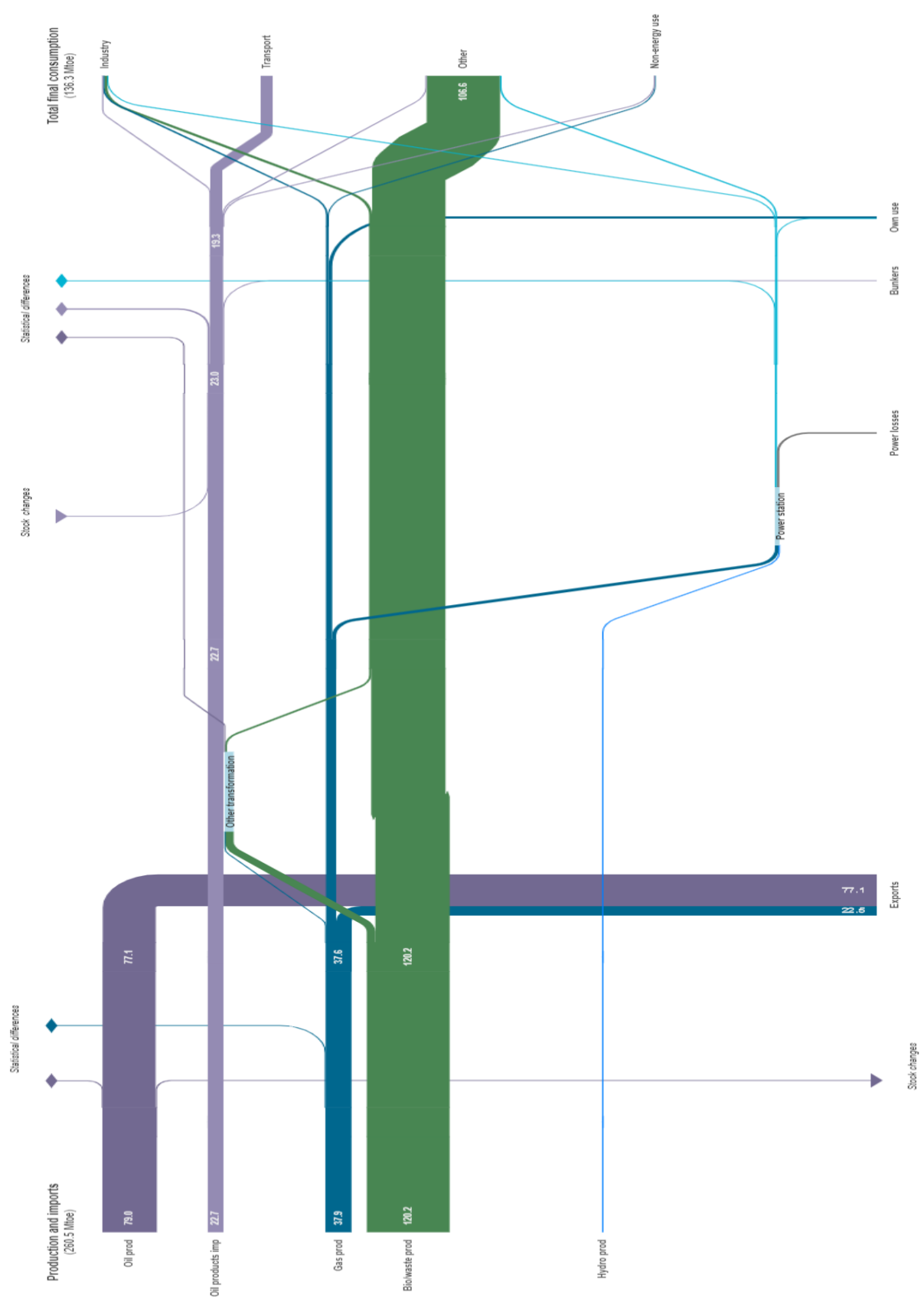


Figure 0-4: Energy distribution in Nigeria