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Department of Waste and Resource Management
Faculty of Agriculture, Civil and Environmental Engineering

DEVELOPING AN ECONOMICALLY VIABLE BUSINESS CASE FOR HYBRID WASTE TO ENERGY PROJECTS IN GHANA

Cumulative Dissertation

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DEDICATION

Thanks to God almighty, who grants me all the resources and strength to pursue my dreams and aspirations. With God all things are possible to him that believes. Philippians 4:13

This thesis is dedicated to my parents, my husband and kids. Your unflinching support and dedication made this possible. Thank you for your unending love, sacrifices and contributions.

To my kids: Adom, Nyamekye and Aseda – this is specially dedicated to you. The baton of hard work, fortitude and determination is handed to you. Always remember that nothing is impossible for him who believes, takes the first step and is dedicated to see the end.

“Although the bud may have a bitter taste, sweet will be the flower”.

William Cowper, 1731 – 1800

(Methodist Hymn 503 verse 5)

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DECLARATION OF INDEPENDENCY

I hereby declare that this dissertation is prepared and submitted by me independently without any assistance other than from those cited and acknowledged in the thesis and the contents have not been submitted to any other institution for the attainment of any academic qualification.

Rostock, 17.04.2025

ABSTRACT

Developing countries such as Ghana require sustainable solutions to the numerous waste management challenges. Waste to energy (WtE) is a potential technological solution within the framework of a circular economy. Ghana has a current population of over 33 million. There is only one commercial large-scale WtE plant which produces mainly energy and compost. Further investment is required to implement sustainable WtE models. However, decision making for such an investment requires detailed business cases. The current study therefore aims to develop a business case to promote the implementation of a hybrid WtE (HWtE) model. The proposed model incorporates Solar PV, Anaerobic Digestion and Pyrolysis technologies. A hybrid WtE plant located in Ghana is used as a case study to evaluate the current potential and to design strategies for future replication.

This dissertation is structured as a cumulative of five publications in book chapters and peer review journals. The study begins with a bibliometric study of the trends of WtE development in Africa. It provides an overview of the subject area using 378 publications from the SCOPUS database. The recent themes, nature of publications and countries are presented. The results show that most publications are reviews in nature, and they involve theoretical or proposed systems rather than primary data or case studies. The trend also shows a growing interest in circular and sustainable development themes. This is published in a book chapter and presented as PAPER 1.

The Objectives I and II are linked to the case study plant. A detailed technoeconomic assessment (TEA) was carried out involving three parameters and eight scenarios. The parameters are: project financing, products and city-scale models. Each of these parameters have been thoroughly examined in three publications. Eight products have been examined according to two broad categories: Energy (electricity) and Alternative Fuels and Materials (AF&M). The RETSCREEN software version 9.1.0.9 and MS EXCEL were used for the TEA. In addition to onsite data, a market assessment was carried out to assess the market value, potential competitors and offtakers for the identified products. The outcomes indicate that the scale of the pilot plant is too small to reach economic feasibility for an energy generation plant. A financing model incorporating grants and subsidies improves feasibility. The capital cost and energy exported to grid are the major influencing factors. Source segregated waste reduces both the capital and operational costs and enhances feasibility. For the products model, a combination of both AF&M and energy is the most feasible scenario as compared to AF&M only or energy only scenarios. For the large city scale model, all scenarios are feasible. This confirms the relevance of scale in achieving feasibility. These have been published in a book chapter (PAPER II) and two journal articles (PAPER III and PAPER IV).

The environmental impact assessment is important for such projects because it enhances onsite processes and access to project financing. An environmental assessment is carried out comparing the onsite WtE processes and conventional landfilling. The modelling is carried out using the OpenLCA software (version 3.03) together with the Ecoinvent Database. The outcome indicates that the pyrolysis and RDF have the lowest potential environmental impact as compared to anaerobic digestion and segregation. As compared to the landfilling, carbon savings of 3.5tCO_2eq/ ton of waste treated can be achieved through WtE. This has been published in PAPER V.

Objectives III and IV focus on the future replication and are presented in PAPER IV and Chapters 4 and 5 of this dissertation. Chapter 4 synthesizes the outcomes of the TEA into three business models (Scenarios): (1) on-grid prosumer, (2) on-grid supplier and (3) off-grid prosumer. Feasibility follows the order: on-grid prosumer> off-grid prosumer> on-grid supplier. In chapter 5, a multicriteria decision-making analysis (MCDA) methodology is used to select geographical hotspots for siting HWtE projects in Ghana. The case study plant is sited in a rural area. PAPER IV examines the replication of the HWtE model in an urban area whiles simultaneously assessing the parameter of economies of scale. The results indicate that districts in the Greater Accra Region, Kumasi Metropolis and Sekondi-Takoradi Metropolis have the highest potential for siting a future plant. The impact of urbanization and the concentration of manufacturing industries in these same locations make them an attractive location for the marketing of AF&M products.

Within the context of a circular economy, an integrated concept is presented. The concept integrates recycling, energy and plant nutrient recovery with the integration of solar PV, alternative fuels and emissions reductions. The HWtE model is a viable solution for Ghana's waste management solutions. It is however recommended that project developers and decision makers for future projects carefully consider the quality of the sourced waste, financing model, products model and adequate scale. Also, policies on source segregation and subsidies have a potential impact on feasibility and attracting investments.

Keywords: waste to energy, alternative fuels, Solar PV, anaerobic digestion, pyrolysis, business case, MCDA, technoeocnomic feasibility, circular economy, Ghana

ZUSAMMENFASSUNG

Entwicklungsländer wie Ghana stehen vor erheblichen Herausforderungen in der Abfallwirtschaft, für die nachhaltige Lösungsansätze dringend erforderlich sind. Die energetische Verwertung von Abfällen (Abfall-zu-Energie, WtE) stellt eine vielversprechende technologische Option im Kontext einer Kreislaufwirtschaft dar. Bei einer Bevölkerung von über 33 Millionen Einwohnern verfügt Ghana derzeit lediglich über eine kommerzielle Großanlage zur energetischen Abfallverwertung, die vorwiegend Energie und Kompost produziert. Die Implementierung nachhaltiger WtE-Modelle erfordert jedoch substanzielle Investitionen, deren Realisierung auf fundierten Business Cases basieren muss.

Die vorliegende Studie zielt darauf ab, einen solchen Business Case zu entwickeln, um die Umsetzung eines hybriden WtE-Modells (Hybrid Waste to Energy, HWtE) zu fördern. Das vorgeschlagene Modell integriert Solar-Photovoltaik-, anaerobe Vergärungs- und Pyrolysetechnologien. Eine hybride WtE-Anlage in Ghana dient dabei als Fallstudie zur Bewertung des aktuellen Potenzials sowie zur Entwicklung von Strategien für eine zukünftige Replikation.

Die Dissertation umfasst fünf Veröffentlichungen in Form von Buchkapiteln und peer-reviewten Fachzeitschriftenartikeln. Die Untersuchung beginnt mit einer bibliometrischen Analyse der Entwicklungstrends von WtE in Afrika, die einen systematischen Überblick über das Themengebiet anhand von 378 Publikationen aus der SCOPUS-Datenbank bietet. Dabei werden aktuelle Forschungsschwerpunkte, Publikationsarten und geografische Verteilungen dargestellt. Die Ergebnisse zeigen, dass es sich bei den meisten Veröffentlichungen um Übersichtsarbeiten handelt, die sich vorwiegend mit theoretischen oder konzeptionellen Systemen befassen, während Primärdaten und Fallstudien unterrepräsentiert sind. Der erkennbare Trend deutet auf ein wachsendes wissenschaftliches Interesse an Themen der Kreislaufwirtschaft und nachhaltigen Entwicklung hin. Diese Analyse wurde als Buchkapitel publiziert und bildet ARTIKEL I der Dissertation.

Die Zielsetzungen I und II fokussieren auf die Fallstudienanlage und umfassen eine detaillierte technoökonomische Bewertung (TEA) unter Berücksichtigung von drei Parametern und acht Szenarien. Die untersuchten Parameter sind Projektfinanzierung, Produktportfolio und stadtweite Skalierungsmodelle, die in drei separaten Veröffentlichungen eingehend analysiert wurden. Acht Produkte wurden anhand zweier Hauptkategorien untersucht: Energie (Strom) sowie alternative Kraftstoffe und Materialien (AF&M). Für die TEA kamen die Software RETSCREEN Version 9.1.0.9 und MS EXCEL zum Einsatz. Ergänzend zu den vor Ort erhobenen Daten wurde eine Marktbewertung durchgeführt, um Marktwert, potenzielle Wettbewerber und Abnehmer für die identifizierten Produkte zu evaluieren.

Die Ergebnisse zeigen, dass die Pilotanlage zu klein dimensioniert ist, um ausschließlich durch Einnahmen aus der Energieerzeugung wirtschaftlich rentabel zu operieren. Ein Finanzierungsmodell, das Zuschüsse und Subventionen integriert, verbessert die Rentabilität signifikant. Als zentrale Einflussfaktoren wurden die Kapitalkosten und die ins Netz eingespeiste Energiemenge identifiziert. Durch die Implementierung einer Trennung an der Quelle kann eine aufwendige Vortrennung vor Ort vermieden werden, wodurch sowohl Kapital- als auch Betriebskosten reduziert und die wirtschaftliche Machbarkeit erhöht wird. Bezüglich des Produktmodells erweist sich eine Kombination aus AF&M und Energie als das wirtschaftlich tragfähigste Szenario im Vergleich zu Szenarien, die ausschließlich AF&M oder nur Energie umfassen. Für das Modell im Maßstab einer Großstadt zeigen alle Szenarien wirtschaftliche Realisierbarkeit, was die fundamentale Bedeutung der Skalierung für die Erreichung von Wirtschaftlichkeit bestätigt. Diese Erkenntnisse wurden in einem Buchkapitel (ARTIKEL II) sowie zwei Zeitschriftenartikeln (ARTIKEL III und IV) publiziert.

Die Umweltverträglichkeitsprüfung ist für derartige Projekte von essentieller Bedeutung, da sie die Prozesse vor Ort optimiert und den Zugang zu Projektfinanzierungen erleichtert. Die Umweltbewertung erfolgte durch einen Vergleich der WtE-Prozesse vor Ort mit der konventionellen Deponierung. Die

Modellierung wurde mittels der Software OpenLCA (Version 3.03) in Verbindung mit der Ecoinvent-Datenbank durchgeführt. Die Ergebnisse belegen, dass Pyrolyse und RDF (Refuse Derived Fuel) im Vergleich zu anaerober Vergärung und Abfalltrennung die geringsten potenziellen Umweltauswirkungen aufweisen. Im Vergleich zur konventionellen Deponierung können durch WtE-Technologien CO_2-Einsparungen von 3,5 t CO_2eq pro Tonne behandelten Abfalls erzielt werden. Diese Erkenntnisse wurden in ARTIKEL V veröffentlicht.

Die Zielsetzungen III und IV konzentrieren sich auf die zukünftige Replikation des Modells und werden in Artikel IV sowie in den Kapiteln 4 und 5 der Dissertation präsentiert. Kapitel 4 synthetisiert die Ergebnisse der TEA in drei Geschäftsmodelle (Szenarien): erstens netzgebundener Prosumer, zweitens netzgebundener Versorger und drittens netzunabhängiger Prosumer. Die wirtschaftliche Machbarkeit folgt der Rangfolge: netzgebundener Prosumer, gefolgt von netzunabhängigem Prosumer und netzgebundenem Versorger. In Kapitel 5 wird eine multikriterielle Entscheidungsanalyse (MCDA) angewendet, um geografische Hotspots für die Ansiedlung zukünftiger HWtE-Projekte in Ghana zu identifizieren. Während sich die Fallstudienanlage in einer ländlichen Region befindet, untersucht Artikel IV die Replikation des HWtE-Modells in urbanen Gebieten unter gleichzeitiger Bewertung des Parameters der Skaleneffekte. Die Ergebnisse zeigen, dass die Bezirke in der Region Greater Accra, die Kumasi Metropolis sowie die Sekondi-Takoradi Metropolis das höchste Potenzial für die Ansiedlung zukünftiger Anlagen aufweisen. Die Auswirkungen der Urbanisierung und die Konzentration der verarbeitenden Industrie an denselben Standorten machen diese zu besonders attraktiven Absatzmärkten für AF&M-Produkte.

Im Rahmen einer Kreislaufwirtschaft wird ein integriertes Gesamtkonzept vorgestellt, das Recycling, Energiegewinnung, Materialrückgewinnung und die Rückführung von Pflanzennährstoffen durch die Integration von Solar-Photovoltaik, alternativen Kraftstoffen und Emissionsreduktionen miteinander verbindet. Das HWtE-Modell stellt eine praktikable Lösung für die Abfallwirtschaft in Ghana dar. Projektentwicklern und Entscheidungsträgern für zukünftige Projekte wird empfohlen, die Qualität der zu beschaffende Abfälle, das Finanzierungsmodell, das Produktportfolio sowie den angemessenen Projektumfang sorgfältig zu evaluieren. Darüber hinaus können politische Maßnahmen zur Förderung der Mülltrennung an der Quelle sowie Subventionsprogramme die wirtschaftliche Machbarkeit und die Attraktivität für potenzielle Investoren maßgeblich beeinflussen.

Schlüsselwörter: abfall-zu-energie, alternative kraftstoffe, solar photovoltaik, anaerobe vergärungs, pyrolyse, business case, MCDA, technoökonomische bewertung, kreislaufwirtschaft, Ghana

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Anaerobic Digestion	-	AD
Alternative Fuels and Materials	-	AF&M
Break-even point	-	BEP
Bulk Generation Charge	-	BGC
Cost-benefit analysis	-	CBA
End User Tariff	-	EUT
Geographic Information System	-	GIS
Hybrid Waste to Energy		HWtE
Independent Power Producer	-	IPP
Internal Rate of Return	-	IRR
Landfill Gas to Energy	-	LFGTE
Levelised Cost of Energy	-	LCOE
Net Present Value	-	NPV
Pay Back Period	-	PBP
Power Purchasing Agreement	-	PPA
Refuse Derived Fuels	-	RDF
Return on Investment	-	ROI
Multicriteria Decision Making Analysis	-	MCDA
Simple Additive Weight	-	SAW
Technoeconomic assessment	-	TEA
Waste to Energy	-	WtE
Waste to Resource Optimization and Scenario Evaluation Model	-	WROSE

LIST OF PUBLICATIONS

This doctoral thesis is based on the following publications:

I. Armoo, E.A., Boahemaa, B., Narra, S., Beguedou, E. (2024). Bibliometric Study of Trends in Waste to Energy Research in Africa. In: Narra, MM., Narra, S. (eds) Innovations in Circular Economy and Renewable Energy in Africa. World Sustainability Series. Springer, Cham. https://doi.org/10.1007/978-3-031-68330-5_1

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V. Armoo, E. A., Baidoo, T., Mohammed, M., Agyenim, F. B., Kemausuor, F., & Narra, S. (2025). Environmental Assessment of Hybrid Waste-to-Energy System in Ghana. Energies, 18(3), 595. https://doi.org/10.3390/en18030595

1 INTRODUCTION

1.1 Background

To humans, consumption and waste generation cannot be avoided. Every year, over two million tons of waste is generated globally (UNEP, 2024). However, global population continues to plummet. It is expected to exceed 9 billion by 2040 and will continue in this upward trend for the next 50 to 60 years with some countries in Sub Saharan Africa (SSA) experiencing more rapid growth (United Nations, 2024b). The management of increasing quantities of waste with varied characteristics is challenging and has potential crosscutting impacts on human societies and the global environment.

Due to the crucial role of waste management in resource efficiency and environmental protection, it is directly linked to the following Sustainable Development Goals (SDG) proposed by the United Nations: (3) Good Health and Well-being; (6) Clean Water and Sanitation; (7) Affordable and Clean Energy; (9) Industry, Innovation, and Infrastructure; (11) Sustainable Cities and Communities; (12) Responsible Consumption and Production; (13) Climate Action; (14) Life Below Water and (15) Life on Land (United Nations, 2024a). The waste management hierarchy has been proposed as a guide for sustainable waste management and has been adopted as the foundation of major international waste management policies such as the EU Waste Framework Directive (Directive 2008/98/EC)(European Parliament, 2008). The hierarchy begins at the base with consumer responsibility. The consumer takes active steps to prevent or reduce consumption and takes decisions on disposal pathways such as segregation and recycling. Next, local authorities or governmental agencies have the responsibility to decide on the next fate of the waste. This mainly involves collection, transport and treatment (Ferrari et al., 2016).

Circular economy (CE) has also been used as an underpinning principle for sustainable waste management. CE effectively links the aspects of the waste hierarchy into a sustained cycle of materials and energy conversions (Paiho et al., 2020). One of the most effective techniques to achieve a CE is the conversion of waste to energy (WtE)(Brunner & Morf, 2024). WtE has been widely researched and implemented all over the world and has the advantage of solving the double needs of waste management and energy generation (Tomić & Schneider, 2022). Energy produced from waste is considered a renewable energy (RE) resource which in turn drives the CE (Negrete-Cardoso et al., 2022). With a target to triple current global renewable power capacity by 2030, WtE within the context of RE and CE has the potential to supplement global energy demand and contribute to climate protection (IRENA, 2024b).

The average global waste generation of 0.74 kg per day has been closely linked to income levels and Gross Domestic Product (GDP) of countries. Wealthier economies generally generate in excess of 2 kg/person/day as compared to lower and middle income economies in regions such as SSA and South Asia, which generate 0.46 and 0.56 kg/person/day respectively (Silpa et al., 2018). With high investments and strong policies, countries such as Norway, have waste generation rates of 1.1 kg/person/day; below the European average (1.33 kg/person/day) although it has a relatively high GDP (Malinauskaite et al., 2017).

The developing world, including SSA, is particularly lagging in sustainable waste management and viable CE solutions. Generally, investment into waste management is stimulated by national laws, policies and regulations as well as governmental priorities. In developing countries, waste management is often plagued with low investments into infrastructure and poor law enforcement leading to numerous impacts which extend to the global environment. These impacts include pollution of air, water and land from open burning and marine litter, vector diseases on human health and ecosystem destruction (Ferronato & Torretta, 2019). One of the challenges in developing countries is the low waste collection rates. While waste collection in advanced economies is almost 100%, developing countries attain average collection rates of 40% (UNEP, 2024). Also, the general lack of source segregation leads to greater difficulty in attracting sustainable solutions and investments (Malav et al., 2020). Waste collection rates are particularly low with only 43% coverage in urban areas and 9% in rural areas. This has resulted in the high open dumping rates of 69% and 52.7% in SSA and Middle East and North Africa (MENA) regions respectively. Other developing regions such as East Asia & Pacific regions also recorded 46% for landfilling rates (Silpa et al., 2018). With such low waste collection rates, waste planning and subsequent treatment options such as WtE remain unfeasible. However, with high population growth rates, developing countries such as those in SSA show great potential for WtE projects and the incorporation of innovative models for sustainable development (Hasan et al., 2024).

1.2 Justification

Africa is the second most populous continent, with a population of 1.5 billion in 2024 (Galal, 2025). The population growth rate continues to increase as other regions experience a downward trend. It has been estimated that, by 2050, Africa's urban population alone will increase to 1.4 billion. This requires a critical expansion of the already poor infrastructure (OECD, 2025). One of such critical infrastructural needs is waste management. Although the per capita waste generation in Africa is generally low, the cumulative generation from a high population and increasing urbanization requires increased attention. Conventional waste management approaches such as landfilling have high indirect economic and environmental cost which are unsustainable (Rajoo et al., 2020).

The IEA estimates that Africa will lead the next phase of the global energy demand due to increasing population, urbanization and industralisation (IEA, 2019). Across Africa, waste is becoming an attractive option for energy generation. However, considering the population, WtE development is very low. Out of the 498 WtE plants in Europe, Germany alone has 91, serving a population of over 80 million (CEWEP, 2022). On the other hand, Nigeria, which has a population of over 230 million, has recently launched its first WtE project in Lagos. The project is planned to convert 2500 - 3000 tons of Municipal Solid Waste (MSW) to electricity per day (Odeyemi, 2024). In Kampala (Uganda), a feasibility assessment is ongoing for an incineration plant to treat MSW for electricity and heat (Smart City Sweden, 2024). Ethiopia has also recently launched an incineration plant which processes 1,400 tonnes of MSW per day into electricity to cover 30% of the city's energy needs (UNEP, 2017). In Tunisia, the UN-Habitat has supported the implementation of a 60 kWh/day Landfill gas to energy (LFGTE) project. It is the first in the country and supplies electricity to 500 homes (UN-Habitat, 2025). In Egypt, the construction of two plants for the city of Abu Khreita has been completed. Together, they have a capacity of 123 MW to treat 2,800 tonnes of MSW per day (The Electricity Hub, 2022). The Abu Rawash plant in Giza (Egypt), is also under construction and expected to have an installed capacity of 30 MW and treat 1,200 tonnes of waste daily (MEED, 2025). In South Africa, the 4.6 MW Bronkhorstspruit Biogas Plant has been in operation since 2015. It also presents a business-to-business model where power is directly supplied to a BMW vehicle manufacturing factory in an offtaker model. The plant is located directly in a feedlot with access to animal waste and organic waste from surrounding community (Norfund & Bio2Watt, 2012). In Ghana, the 100 kW hybrid solar-biogas Safisana plant produces grid connected electricity and compost (Agyenim et al., 2020; Kessman, 2019).

There may be several contributory factors to the low implementation of WtE systems in Africa. In many developing countries across the globe, major issues relate to waste quality, financing and policies. Due to the low waste quality and segregation rates, technologies such Anaerobic Digestion (AD) attract little interest. Thermochemical technologies such as incineration, gasification and LFGTE have been successfully implemented with mixed waste. However, the high moisture content reduces the technical efficiency of such systems. Also, the high capital investment as compared to low tariffs, ability-to-pay and government subsidies poses threats to the financial feasibility of such projects in developing countries (Mutz et al., 2017). With so many potential challenges, pilot studies are necessary to clearly assess the context specific issues and develop appropriate strategies for implementation. A 400-kW pilot WTE plant is currently under development in Ghana with a grant financing from the German government. The plant is technically equipped to treat 50 tonnes/day of mixed MSW through a hybrid of AD, pyrolysis and Solar PV technologies to produce electricity, compost and other recovered materials (Tena, 2022). Such systems provide an opportunity for detailed research to support the development of such critical projects.

1.3 Research goal and objectives of the study

The overarching goal of this research work is to develop a business case to support a hybrid WtE model implementation in Ghana. The work is positioned within the framework of circular economy and sustainable development. It is envisaged that the outcome of the study will stimulate further investment and provide a clear policy direction for decision makers. With similar challenges, the outputs extend as a knowledge base to other developing countries, especially in Africa.

The newly constructed hybrid waste to energy plant located at Atwima Nwabiagya Municipality in the Ashanti region of Ghana is used a case study plant. The plant is under the project: "Hybrid Waste-to-Energy as a sustainable solution for Ghana", funded by the German Federal Ministry of Research, Technology and Space. Beyond the pilot plant, the long-term objective is to refine the model and replicate it to other locations.

The following specific objectives have been outlined:

Objective I : Develop business cases for identified products based on the case study plant

Objective II : Incorporate the business cases into integrated cases (scenarios)

Objective III : Develop a decision-making framework to support the development of the WtE under various scenarios within Ghana

Objective IV : Create a spatial representation of hotspots to support decisions on development of future WtE projects in Ghana

1.4 Structure of this dissertation

This dissertation is structured as a cumulative of five publications which align with the goal and objectives stated above. It presents a synthesis of the overall results, its applications and the innovative aspects. The publications are referred to as PAPERS I to V throughout the work and the full versions are attached in Annexes I to V.

Chapters 1 to 3 present the introduction, the state of knowledge and methodologies. Chapter 4 presents a synthesis of Objectives I and III whiles Chapter 5 delves into Objectives III and IV. Objectives I and II are based on the case study plant which is referred to as the Hybrid Waste to Energy plant (HWtE).

Chapter 1 presents the underlining concepts of the study, the justification, the goal and objectives of the entire study. Chapter 2 presents the status of knowledge within the field of WtE including main terminologies. In this chapter, the local context is also described in detail.

Chapter 3 presents the methodology. The chapter summarises the business case development process for the current plant which is important for future studies seeking to build upon the outcomes of this study. Other documents have been used as a guide (Gogela et al., 2017; Government of Australia: Department of Finance, 2025). The linkages between the objectives and the publications are also presented.

Chapter 4 presents the business cases for two major product categories based on the HWtE plant. Chapter 5 focuses on the geographical assessment to identify hotspots. To conclude, an overall assessment is provided with recommendations for implementation and further research. Details of the interlinkages between publications and objectives are presented in Figure 3.2.

2 Literature review

2.1 Waste to energy (WtE)

Waste-to-Energy (WtE) refers to the process of converting waste into usable forms of energy, such as electricity, heat, or fuel. The objectives of WtE are mainly to decrease the mass and volume of waste to save land disposal space and its potential environmental impact. The major product categories are: energy and recovered materials (Hoang et al., 2022). The waste may originate from various sources including MSW, industrial waste, biomass and commercial waste (Alao et al., 2022). In the context of sustainable waste management and CE, WtE becomes relevant to treat residual waste after material recovery and recycling options have been exhausted (ESWET, 2020).

Global energy security is an important area of interest. The global energy mix is dominated by about 80% fossil fuels including natural gas, coal and oil (International Energy Agency, 2022). Regions such as Europe have invested heavily in WtE projects. It is estimated that, in 2021 alone, 103 million tonnes of waste generated 35 and 87 billion kWh of electricity and heat respectively; which met the energy needs of 21 million European residents (CEWEP, 2021).

In the implementation of WtE projects, the main aspects are the technical, economic and environmental. However, sociocultural, political, policy and regulatory aspects also play a crucial role in the success of projects (Malav et al., 2020). The following sections details the main aspects of WtE implementation.

2.1.1 Technical aspects of WtE

The technical aspect is the underlying component of WtE. This includes feedstocks, technologies, residue treatment and process optimisation such as emission control (Khan et al., 2022). Feedstocks may originate from varied sources with various characteristics which influences the technology. They may be categorized as mixed or source segregated. They include MSW, animal waste, sewerage sludge, biomass, food waste, plastic, e-waste, and wood residues, fats, oils or grease (FOG), textiles etc. (Arancon et al., 2013; Moula et al., 2017; Skaggs et al., 2018).

MSW may originate from households, commercial, residential, construction, institutions and special wastes sources emphasizes the importance of source segregation. The characteristics of MSW is influenced by factors such as income levels, consumption patterns and geographical location (Roy et al., 2022). Material Recovery Facilities (MRF) or transfer stations are usually integrated into the broad CE design of municipalities to separate mixed waste to various treatment flows (Jalalipour et al., 2019; Sambiani et al., 2023). Without this, WtE plants must integrate onsite segregation systems to ensure waste of required characteristics are obtained. Within the CE framework, source segregation allows for greater resource recovery and provides greater flexibility for WtE planning and treatment technologies. At treatment facilities, the type of feedstock generally determine the technology and the products (Alao et al., 2022).

Different WTE technologies are available depending on the type, quantity and characteristics of feedstock, available investments, environmental standards and other specific factors. WtE technologies are generally categorized as thermal/ thermochemical, biochemical and chemical (Khan et al., 2022). The outputs of these processes are mainly categorized into energy and fuels. Electricity and heat are the major energy products whiles fuels are varied and include bio-oil, hydrogen, biomethane (Roy et al., 2022; Yusuf & Almomani, 2023). However, in cases where there are available markets, other byproducts such as fertilizer from digestate and biochar can be explored as commercially viable products (Rezania et al., 2023).

Technical combination of two or more WtE technologies operating as a single unit are referred to as Hybrid WtE (HWtE) systems. The objective is to obtain resource and cost optimization through the treatment of multiple waste streams. However, this may increase the capital investment as compared to choosing one technology (Manwell, 2004; Xiong et al., 2016). In some designs, Hybrid Renewable Energy

Systems (HRES) have been designed with the integration of WtE with other RE systems such as Solar PV (Afonaa-Mensah et al., 2024; Hasan et al., 2024).

Thermal technologies

Thermal technologies operate with conversion processes at extremely high temperatures (300 -12,000°C) leading to the modification of the chemical structure of the material/ feedstock. There are three major types: combustion, pyrolysis and gasification. Combustion technologies; generally referred to as incineration; employs the complete oxidation of suitable components of the feedstock at temperatures in excess of 1000°C (Khan et al., 2022). They are the commonest thermal technologies due to their high energy recovery, suitability for mixed waste with high calorific value and has the capacity to reduce material mass by 70 - 80% and in volume by 80 - 90%. This translates into lower investment costs in terms of segregation as compared to higher revenues from energy products (Lombardi et al., 2015). However, they are least preferred due to their perceived environmental impacts which is significantly improved in modern systems by emission control systems (Tsui & Wong, 2019).

Pyrolysis is a thermal decomposition process taking place at temperatures between 300 - 800°C in the absence of oxygen, leading to the production of biochar (solid), bio-oil (liquid), and syngas (gas) (Gupta et al., 2018). Pyrolysis is suitable for various feedstocks; mainly dry segregated waste including green waste, biomass and plastics (Bassey et al., 2023; Jahirul et al., 2012; Salman et al., 2017; Syamsiro et al., 2014). Some studies have also assessed wet waste such as sludge (Mohammadi et al., 2019). Gasification on the other hand involves the partial decomposition at temperatures in excess of 800°C under controlled oxygen conditions to produce mainly syngas and low volumes of tar and char. The syngas is in turn converted into energy (Gupta et al., 2018; Yang et al., 2018).

Pyrolysis and gasification differ in the priority products with pyrolysis producing more bio-oil as compared to higher volumes of gas in gasification. In some cases, WtE plants depend on the combustion or gasification of pre-processed fuels such as Refuse Derived Fuel (RDF) and Tire Derived Fuels (TDF), Solid Refuse Fuels (Infiesta et al., 2019; Yang et al., 2021). These technologies have high potential environmental impacts due to potential pollution from flue gases. The carbon footprint (in tCO_2eq /tMSW) is relatively higher in incineration (1.67) and gasification (1.3 - 1.5) as compared to pyrolysis (0.7 - 1.2). Their sustainable implementation must therefore be coupled with high emission control and ash disposal measures. More modern technologies such as hydrothermal carbonization are also becoming increasingly popular although it is mostly suitable for materials of biogenic origin (Mayer et al., 2019). The above studies collectively suggest that while traditional incineration remains prevalent, alternative thermal WtE technologies like gasification and pyrolysis offer potential benefits in terms of energy efficiency and environmental impacts (Nosherwani & Nausherwani, 2018).

Biochemical technologies

Biochemical technologies employ biochemical processes on organic wastes. The common technologies include anaerobic digestion (AD), aerobic composting, landfill gas to energy (LFGTE). AD occurs without oxygen, producing biogas and digestate through microbial activity. The process occurs in a controlled environment (digestor) with temperatures ranging from 20 - 45°C (mesophilic) and 45 - 60°C (thermophilic) (Alao et al., 2022). The end-product is a complex mixture of gases (biogas) which averagely contains 50 - 70% methane, 25 - 50% carbon dioxide and 1 - 15% trace gases. LFGTE process begins with a short aerobic process and continues with similar anaerobic processes as AD. The major advantages of AD over LFGTE is its compact design which requires less land space, more efficient biogas capture and its low emission profile (Nosherwani & Nausherwani, 2018). On the other hand, LFGTE projects have a longer lifespan with lower investment and maintenance costs. Landfills can continue to release biogas for over 100-year whiles AD projects typically terminate after 20 years. Operation and maintenance is also more sophisticated in AD (Dada & Mbohwa, 2016; Karlsson, 2019). AD has lower environmental impact as it prevents open methane release with methane emissions estimated to be below 5% (Ayodele et al., 2017).

Composting is an aerobic process which typically requires oxygen and produces CO_2, water, and compost, under mesophilic and thermophilic conditions to form a stabilized organic substance with reduced pathogenic content as compared to the input substance. The process involves two main stages: decomposition and stabilization followed by humification and maturation (Azim et al., 2018). Composting can be applied to a vast variety of organic feedstocks including solid digestates from AD process (Zeng et al., 2016). This presents an effective process for recycling the nutrients still present in digestate once released from the bio-digestor. The stabilization process of composting ensures that the final product has lower odour, moisture, pathogens and volatile compounds. However, due to the lower organic matter content, bulking agents such as farm residues can be mixed to improve the fertilising properties of the final compost (Bustamante et al., 2012; Fernández-González et al., 2020).

2.1.2 Economics aspects of WtE

The economic aspects of technological advancement are key to stimulate actual implementation. The factors affecting feasibility are context specific and include factors such as feedstock availability, governmental subsidies and markets (Van Den Berg & Duong, 2018). Sources of revenue for WtE plants include gate fees, revenues from the sale of recycled materials and recovered energy. Local authorities can raise revenue through direct waste fees from waste generators; cross-financing of MSW services, other local fees or taxes, local or national grants, income from domestic or international carbon programs such as the Climate Development Mechanism. In spite of this, WTE systems may not be financially sustainable from revenues alone and without subsidies and external support (Couth & Trois, 2012; Mutz et al., 2017).

Technoeconomic assessment (TEA) of WtE systems have been extensively used for feasibility assessments and several tools are available to support this. The RETSCREEN Clean Energy Management Software and Hybrid Optimization of Multiple Energy Resources (HOMER®) are some of the commonly used tools for such assessments (Ramli et al., 2017). These softwares also integrate some aspects of environmental impacts assessment such as avoided Greenhouse Gas (GHG) emissions (Sharma et al., 2019). Several parameters must be incorporated into a TEA. The major ones are the Capital investment cost (CAPEX) and the Operating expenses (OPEX) (Cudjoe et al., 2021; Rahmatzafran et al., 2020). Others include discount rate, debt to equity ratio, cost of debt which include debt value, debt term and interest rate (Brückmann et al., 2021). Also, taxes and incentives including grants and subsidies may be incorporated (Afonaa-Mensah et al., 2024; Bölük & Kaplan, 2022; Yakah et al., 2024). The outcome of a TEA is comparatively evaluated using metrics such as the Internal Rate of Return (IRR) (Aui et al., 2019), Return on Investment (ROI) (Zhao et al., 2016), Levelised Cost of Energy (LCOE) (Hadidi & Omer, 2017) and benefit to cost ratio (Obeng et al., 2020). It is recommended to carry out a sensitivity assessment to determine the influence of key parameters on the outcome (Odoi-Yorke, et al., 2022). In terms of energy projects, LCOE is the most commonly used parameter for evaluating feasibility (Weinand et al., 2023).

For instance, a hybrid solar- biogas plant was evaluated in three North African countries (Tunisia, Algeria and Morocco). Co-digesting agro-industrial waste with organic fraction of MSW(OFMSW) was found to be feasible with IRR between 10 and 20% based on seasonal availability of feedstock (El Ibrahimi et al., 2022). On the other hand, for a LFGTE project in South Africa it was concluded that, although the project had the potential to produce 6.6 GWh of electricity to 2,952 households, the plant was not economically feasible (Njoku et al., 2020).

Models for WtE plants may also produce alternative fuels (AF) and recovered material. AF is important for meeting industrial energy demand. They are generally described as by-products of waste processing with recoverable calorific value that can be used as fuel (WBCSD, 2005). Materials such as scrap metals and plastics can be recovered from the WtE process within the circular economy framework. An evaluation of five case studies in South Africa revealed that flexibility in terms of multiple revenue sources/ products and feedstock type increases the financial feasibility of a biogas project (Gogela et al., 2017).

2.1.3 Environmental aspects of WtE

The environmental aspects of WtE projects are important to evaluate the impacts on both the local and extended global environment. The most well-structured methodological framework for conducting an environmental assessment is the Life Cycle Assessment (LCA). LCA has been utilized with various waste treatment options and strategies (Dastjerdi et al., 2021). The methodology for LCA has been standardized in the ISO 14040 series, which ensures a consistent and rigorous approach (Guinée et al., 2001; International Organization for Standardization (ISO), 2006a, 2006b).

LCA evaluates impacts across multiple impact categories, such as climate change, resource depletion, and human health, to provide a holistic understanding of the environmental implications of waste management systems. Common metrics for LCA include climate impact; evaluated as Global Warming Potential (GWP). Also, common softwares such as SimaPro, GaBi, Umberto or openLCA are used with common databases such as Ecoinvent (Bakkaloglu et al., 2022; Hemmati et al., 2024; Mayer et al., 2019).

In Table 2.1 an overview of selected studies is presented. LCA studies linked to WtE cover varying scope, objectives, countries, methodology and outcomes. GWP is the most studied metric for impact assessment due to direct and indirect impacts on the global health and environment. Waste, especially organic waste releases methane and other potent GHG when disposed of in uncontrolled spaces such as landfills. It has been estimated that avoiding 180 milion tonnes of methane emissions per year at the global scale can potentially eliminate 26 million tonnes of crop losses and 73 billion hours of lost labour from extreme heat (UNEP & GCAC, 2021). LCA is particularly important in supporting countries in developing waste management strategies based on the least emission scenarios. These scenarios incorporate several technologies as well as uses for the products. For instance, an LCA was carried to compare scenarios for biowaste treatment in the UK with the objective to select the least emission scenario. This is in response to the increasing quantities of segregated biowaste within the waste stream which directly impacts global methane emission and subsequently climate change. Similar studies are also presented in Singapore, Sweden, Brazil and China to identify the least impact scenario for organics such as food waste and paper mill waste. AD is one of the most preferred treatment options with lower impact and energy outcomes. Other thermal options such as pyrolysis and Combustion also provide significant gains with the incorporation of adequate internal mitigation measures.

Table 2.1: Sample studies conducting LCA assessment with varying scope and objectives

Objective/ scope	**Country**	**Technology**	**LCA methodology**	**Software**	**Impact category**	**Main findings**	**Reference**
Selection of least emission scenario from biowaste treatment technologies	UK	AD, COMP, INC, LF	IPCC AR5/ AR6; ReCiPe midpoint	GaBi	FPMDF, FD, F WC, F ET, FE, HT, ID, LU, MET, ME, MD, SOD, TA, TET, PED	Lowest potential impact from scenario - AD to heat and electricity generation	Bakkaloglu et al., 2022
Impacts profile of RDF production and co-combustion in cement plants as compared to coal	Canada	COMB	IPCC	GaBi	RC, GWP, AP, NP, HT, SS	Avoided GWP per ton RDF used (2020): 19.3 ton$CO2_{eq}$	Reza et al., 2013
Comparison of four food waste conversion scenarios	Singapore	INC, AD, COMP (raw waste), COMP (digestate)	Environmental Devel-opment of Industrial Products (EDIP 2007)	Ecoinvent Database[1]	GWP, AP, ET, PCOP, PED	Lowest potential impact from AD + COMP (digestate)	Khoo et al., 2010
Four raw biogas digestate treatment scenarios for producing high-quality biofertilizers.	China	Composting and pelletising	CML	OpenLCA	GWP, ADP, AP, EP, ODP, PCOP, HTP, TETP, FAETP, MAETP	Lower environmental impact as compared to the application of raw digestate; pretreatment must be incorporated to reduce pollutant levels	Alengebawy et al., 2022
Scenario assessment for different end uses of biogas from pulp and paper mill sludge – transportation, electricity, cooking	Sweden, Brazil, China	AD and Pyrolysis	CML-IA midpoint	SimaPro	ADP, CC, ODP, HTP, FAETP, MAETP, TETP, PCOP, AP, EP	Biogas use as transportation fuel has the highest environmental performance	Mohammadi et al., 2019

Comparative assessment of internal plant processes treating organic waste to biogas	Ghana	AD	baseline	Open LCA	GWP, ADP, AP, EP, ODP, PCOP, HTP, TETP, FAETP, MAETP	Significant environmental benefits: Transportation of waste to plant site is the major contributor to environmental impact	Baidoo et al., 2024

Technologies: Anaerobic Digestion (AD), composting (COMP), incineration (INC), landfill (LF), Combustion (COMB)

Impact categories: Abiotic depletion potential (ADP), Acidification potential (AP), Climate Change (CC), Eutrophication potential (EP), Fine particle matter formation (FPMDF), Fossil depletion (FD), Freshwater aquatic ecotoxicity potential (FAETP), Freshwater consumption (FWC), Freshwater ecotoxicity (FET), Freshwater eutrophication (FE), Global warming potential (GWP), Human toxicity potential (HTP), Ionising radiation (ID), Land use (LU), Marine aquatic ecotoxicity potential (MAETP), Marine ecotoxicity (MET), Marine eutrophication (ME), Metal depletion (MD), Nutrification Potential (NP), Ozone depletion potential (ODP); Photochemical oxidation potential (PCOP), Primary energy demand (PED), Resource consumption (RC), Terrestrial acidification potential (TA), Terrestrial ecotoxicity potential (TETP), Stratospheric ozone depletion (SOD), Summer Smog (SS).

[1] Software has not been specified. Only the database has been stated.

2.2 Decision-making for WtE projects implementation

The decision-making process for WtE projects is crucial to its implementation and is usually expected to culminate into an investment. Key stakeholders in the decision-making process include consumers/ residents, local authorities, governments and investors/ project financiers. Tradeoffs of multiple priorities must be made, and the priorities of stakeholders must converge into the final investment decision and during project implementation. Projects are typically initiated and owned in full or in part by the local authorities and held in trust for residents, although investments may be sourced from external private financiers. On the one side, local authorities and residents prioritise the environmental aspects while investors may be more interested in the technical and economic aspects (Qazi et al., 2018).

The decision-making process must follow a structured process within a specified framework. Within the framework of CE, several waste management decision support tools are available: including WARM, WRATE and EASETECH (Vea et al., 2018) . Also, the Solid Waste Emissions Estimation Tool (SWEET) has been developed by the U.S. Environmental Protection Agency for city scale emissions estimation using four technologies: combustion, composting, recycling and AD (Stege et al., 2022; U.S. EPA, 2024). One of the downsides of these softwares is that they are applicable in advanced counties without incorporating the practical challenges of developing countries (El Bari & Trois, 2023).

The Waste to Resource Optimization and Scenario Evaluation Model (WROSE) has been developed by University of KwaZulu-Natal in South Africa. It has been proposed as a decision support tool targeting local authorities in developing countries to develop robust waste management frameworks which also promote zero waste and climate change mitigation components. The tool has been used extensively to analyse and design more sustainable solutions for South Africa and can be easily implemented in other developing countries due to similar nature of challenges. Its flexibility allows innovation whiles using country specific data. The model involves a two-phase process: (1) Scenario analysis based on environmental and economic indicators and (2) socioeconomic and institutional aspects (Trois et al., 2023)

In general, decision-making process for WtE projects follow the following frameworks: Multistage evaluation and Multicriteria analysis. The evaluation phases/ stages used in the Multistage evaluation are synonymous to the criteria in the Multicriteria assessment. The major difference is that the Multicritera analysis provides scientific methodologies for integrating the selected criteria for a single decision (Alao et al., 2022; Hadidi & Omer, 2017; Vlachokostas et al., 2021; Xiong et al., 2016).

2.2.1 Multistage evaluation

The multistage evaluation breaks down the entire process into phases based on selected evaluation criteria such as economic, technical or social criterion. The general guidelines for project developers based on expert experience within the European Region have been developed (Vaitkus & Stankiewicz, 2013).

The Multistage evaluation begins with a planning stage where the general methodological framework/ process is established. The multistage evaluation required data input to produce a final decision. Data is categorized into two main types: quantitative and qualitative data. Quantitative data provides a specified result which can easily be replicated. The three major criteria; technical, economic and environmental; are dependent on the input of quantitative data. Qualitative data on the other hand are usually subjective and are linked to aspects such as social, political and policy, context-driven and intangible (Babalola, 2015).

Table 2.2 presents examples of studies which focus on various stages or criteria. The selected method for each study is based on its objectives. Various software may be used to achieve the expected results. The combination of softwares and methodologies allows extensive applications covering a wide range of objectives. The technical aspects include specific waste resources, applicable technologies and their capacities (Vaitkus & Stankiewicz, 2013). Resource assessment is conducted within the preferred geographical location using data and techniques such as material flow analysis (Mohammed et al., 2024; Oduro-Appiah, 2020). The STAN software for instance provides an effective tool for such material flow assessments (TU Wien, 2022). ASPEN Plus and RETSCREEN softwares are used extensively in energy modelling. Waste characteristics are required in terms of heating values, moisture, material fractions etc. (Addae et al., 2021). Other softwares such as MATLAB, Python, Gurobi, CPLEX and EXCEL are also used (Hrabec et al., 2020; Pluskal et al., 2022).

Economic and environmental decisions are always preceded by the technical stage. This stage factors in specifications on plant design, planned capacity and technologies. The Cost Benefit Analysis (CBA) and the Technoeconomic Assessment (TEA) are the commonest methodologies. For instance, a preliminary technoeconomic modeling of a 100 kg/h pyrolysis system with the objective of producing heavy fuel (bio-oil) product was found not to be economically feasible compared to the current market prices. The AspenHYSYS software was used to remodel an appropriate plant capacity (>1000kg/h) to make production feasible and to recover investment cost. This confirms the positive impact of economies of scale on feasibility (Fivga & Dimitriou, 2018). Several tools and scopes have been used by several studies to evaluate various aspects of WtE (Table 2.2). The social, operational and policy aspects are also important in decision-making to ensure that stakeholder and governmental interests converge to achieve successful project implementation. The details of these stages have also been thoroughly described in Section 2.1.

Table 2.2: Multistage evaluation aspects incorporating quantitative criteria

Criteria/ stage	Methods	Objective	Metrics	Common Tools/ softwares	Application	Sample references
1. Technical	Material Flow Analysis	Analysis of material flows within a system	• Input/ output computation	STAN	Determine the direction and quantities of materials within a system boundary	Oduro-Appiah et al., 2020; TU Wien, 2022
	Energy and Exergy Analysis	Evaluates the energy efficiency in WtE systems	• Energy Efficiency • Exergy Efficiency	• Aspen Plus • MATLAB • TRNSYS • RETSCREEN	Energy balance and system simulation	Dincer & Acar, 2014; Lagorse et al., 2008; Salman et al., 2017
	Mathematical Optimization Models (Linear/ Integer/ Non-linear Programming)	Optimizes the design and operation of WtE facilities	• Optimisation of operational aspects	• MATLAB • Python • Gurobi • CPLEX • EXCEL	• Costs minimisation • Energy efficiency • Handles discrete decisions	Pluskal et al., 2022; Sandoval-Reyes et al., 2024
2. Economic	CBA	Compare the economic benefits to the input investment	• Value of benefits	Spreadsheet	• Cash flow analysis Breakeven analysis	Chen et al., 2017; Mohammed et al., 2017
	TEA	Assesses the economic feasibility of a WtE project	• NPV • IRR • PBP • ROI • LCOE etc.	• Homer • RETSCREEN	• Feasibility • Risks and sensitive factors • Cash flow profile	Odoi-Yorke, Abaase, et al., 2022; Ramli et al., 2017

Table 2.2 continued: Multistage evaluation aspects incorporating quantitative criteria

Criteria	Methods	Objective	Metrics	Common Tools	Application	Sample references
3. Environmental	LCA	Environmental impact of different WtE technologies over their entire lifecycle	• GWP • AP • HETP • etc	• openLCA • SimaPro • GaBi	Selection of most environmentally friendly technology	Ayodele et al., 2017; Hemmati et al., 2024; Longo et al., 2020
	First order mathematical models	Emissions estimation	• methane, carbon dioxide and other pollutants	• SWEET • LandGEM	city- level/ site-level estimates of annual/ lifetime emissions from various sources in the waste sector	Daura et al., 2014; Njoku et al., 2020; Stege et al., 2022
4. Social & political	Qualitative data collection methods	Determine key sociopolitical aspects	Social acceptance and participation	• Interviews • focus group discussions • questionnaires	• Public participation • Land allocation for project	Afful et al., 2024; Khan et al., 2022; Paiho et al., 2020
5. Policy and regulatory assessment	Policy document reviews, stakeholder engagements	To identify key policies and regulations in the context of project	All relevant policies and regulations identified	Context specific policies and regulatory documents	Identification of key policies to support implementation	European Commission, 2020; Williams et al., 2023
6. Operational and strategic assessment	Expert development of implementation plans	To develop an operation and implementation strategy	Development of an operational and strategic document	SWOT analysis	Determination strategies and risk mitigation actions	Agyekum, 2020

2.2.2 Multi-criteria Analysis

The integrated methods involve Multi-criteria Decision Analysis (MCDA) and geo-spatial assessment methodologies which combine various tools and methodologies as described in Table 2.2. MCDA is a robust methodology for integrating both qualitative and quantitative data. It involves the characterization of alternatives through scoring, weighting and ranking multiple criteria. The objective is usually to support technology or site selection. Broader applications involve the data driven support of policy development with respect to new projects (Vlachokostas et al., 2021).

Table 2.3 compares the methodologies with respect to their pros and cons and their broad applications with relation to WtE research. The various methodologies have various advantages and disadvantages over each other. The selection of the appropriate methodology is dependent on the scope and intended application of the results. The Analytical Hierarchy Process (AHP) is the most popular methodology due to its straightforward approach using pairwise comparison (Vlachokostas et al., 2020). Generally, the SAW is a simplified step by step methodology for scoring and weighting whiles the AHP, TOPSIS and other MCDA methods involve more complex steps (Khoiry & Amelia, 2023). Most studies incorporate various methodologies to achieve decision-making objectives.

Table 2.3 also presents the decision-making based on location analysis. Most studies aim to select the best location for siting WtE plants using various geographical criteria such as access to transportation networks and topography. Geographical Information System softwares such as ARCGIS and QGIS are mostly employed for geospatial assessments with the main purpose of selecting appropriate project sites. Several studies have integrated MCDA and GIS to provide a holistic approach to final decisions. For instance, Sambiani et al., 2023, determined the optimal location for siting a WtE plant within the complex urban setting of Lome' in Togo using a combination of MCDA and GIS. Data on waste resources, geography, socio-cultural and technoeconomic criteria are used to identify potential areas of least 3.47 km^2 where WtE plants and transfer stations may be sited. Dima et al., 2022 also conducted a similar study in the Central African Republic within an urban setting (the capital city of Bangui) using MCDA and GIS methods. The study identified an appropriate site with of 3.5 km^2 for a proposed biogas plant with a capacity of 2.3 GW to treat 20% of the city's biowaste to cover 60% of its electricity demand. Such studies in developing countries have the potential to support local authorities and key agencies to make vital waste management decisions.

Table 2.3: Multi-criteria Decision frameworks incorporating various criteria

Category	Method	Objective	Metrics	Strengths	Downsides	Application	Sample references
MCDA	Simple additive weighting (SAW)	Evaluate and rank alternatives based on their respective attribute values and assigned weights.	Ranking of alternatives according to order of magnitude	• Simple and straight forward process	• Subjective due to expert judgement	• Site selection	Khoiry & Amelia, 2023; Mokhtari et al., 2016; Ofosu-Peasah et al., 2024
	Analytical Hierarchy Process (AHP)	Uses pairwise comparisons to rank alternatives and prioritize criteria.	Hierarchical structure of criteria.	• Structured & easy to use • Can handle qualitative & quantitative criteria • Consistency check ensures logical comparison	• Subjective bias in pairwise comparisons	• Technology selection	Afrane et al., 2022; Agbejule et al., 2021; Babalola, 2015
	Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	Selects the best alternative based on proximity to an ideal solution	The best alternative is the closest to the ideal and farthest from the worst.	• Simple & computationally efficient • Accounts for both best and worst scenarios • Can be useful for large number of alternatives	• Requires subjective input • Assumes linear relationships between criteria	Technology/ site selection	Afrane et al., 2021; Arıkan et al., 2017

Table 2.4 continued: Multi-criteria Decision frameworks incorporating various criteria

Category	Method	Objective	Metrics	Strengths	Weaknesses	Application	Sample references
MCDA	ELimination Et Choix Traduisant la REalité (ELECTRE)	Uses pairwise comparisons to filter out non-optimal solutions.	Identifies the best alternative by considering trade-offs among criteria.	• Good for handling conflicting criteria • Can handle incomplete or uncertain data	Complex mathematical formulation	Site selection in a complex urban environment	Dima et al., 2022; Vlachokostas et al., 2020
	Preference ranking organization method for enrichment evaluation (PROMETHEE)	Pairwise comparisons using predefined preference functions	The best alternative to the predefined preference	• Handles complex decision problems • Works well with qualitative & quantitative data	Complex mathematical formulation	Technology selection	Arıkan et al., 2017; Sadhya et al., 2022
Geographical assessment	Location allocation based on criteria data	Identifies optimal locations for WtE plants	Visualization based on allocated values	Can handle large data sets for both qualitative and quantitative criteria	Requires large data input	Site selection, route optimization for waste facilities	Sambiani et al., 2023; Yalcinkaya, 2020

2.3 Waste management in Ghana

Ghana is one of the countries in SSA plagued with severe waste management challenges. In spite of its stable socio-political situation, similar challenges associated with developing countries continue to prevail (Kessman, 2019). It is therefore an attractive destination for projects that intend to provide solutions to developing countries. The following sections delve into aspects of waste management in Ghana.

The national solid waste management strategy published in 2020 acknowledges the challenges with the waste management system in Ghana including indiscriminate dumping and burning, relatively high service delivery charges, poor infrastructure and management of disposal sites (Ministry of Sanitation and Water Resources, 2020). Waste management in Ghana is the responsibility of local authorities. This includes collection, transportations and decisions on final treatment and disposal. On the other hand, the resident is expected to pay for such services whiles ensuring the waste is made available for proper onward disposal by local authorities. This has proven to be a largely ineffectively managed system resulting in improper waste management with its incident health implications (Mudu et al., 2021). One cause of this is the lack of independence of the waste management departments to enforce waste management by-laws (Agyabeng et al., 2024). It has therefore been proposed for more public participation to support the efforts of the local authorities (Afful et al., 2024). However, in the absence of such enforcement activities, researcher studies continue to propose innovative.

2.3.1 Current waste management model in Ghana

According to the recent census data in 2021, only 33.4% of Ghanaian households have formal waste collection services. The remaining is either burned in open areas or disposed of in open spaces or dumps. Waste collection is also characterized by large differences between rural and urban areas: 5.8% and 51.4% respectively. Also, 57.3% of rural households dispose of waste in open spaces/dumps as compared to 24.6% of urban dwellers (Ghana Statistical Service, 2022a).

Figure 2.1 shows the framework of the current waste management system in Ghana indicating the flows. The conventional waste approach is disposal in landfill/ public dumps (Flow A). This is also the general practice for formally collected waste. For instance, it is estimated that the Kpone landfill, located in the Greater Accra Region alone received an average of 931.22 tons/day between 2013 and 2017 (Abledu & Amfo-Otu, 2019). Also, the Oti landfill in the Kumasi Metropolis receives 891,000 tons of MSW per year (Asante et al., 2023). Informal sector workers are actively involved in waste recovery activities by returning potential recyclables into the waste stream from landfill/dumping sites (Flow B). There were 157 registered scavengers at the Kpone landfill who recovered 1,034 tons/year (Abledu & Amfo-Otu, 2019).. The work of the scavengers is enhanced by the siting of some plastic recycling in close proximity to landfills to their operational costs (Fiati, 2021).

Flow B, F and G show the different sources feeding the recycling industry. There are about 25 well established plastic recycling companies in Ghana with a capacity to process 320 ton/day into carrier bags, bin bags, buckets and other household materials (Kessman, 2019). This may represent only 2-5% of plastic waste with the remaining burnt or locked up in landfills or open dumps (Okai, 2020). E-waste and metal scraps value chain is also active and employs over 40,000 workers who dismantle and recover essential components from both local and imported e-waste/ scraps for recycling (Kessman, 2019). Recycling industry is a very active value chain across the country involving collectors, scavengers, middle men/ aggregators, local recycling companies as well as exporters (Andrews et al., 2015; Asabea et al., 2020; Offeh Gyimah et al., 2021).

Flow C represents the flow of mixed waste to Material Recovery Facilities (MRF) or transfer stations. These include the Integrated Recycling and Composting Plants (IRECOP), Accra Compost and Recycling Plant (ACARP) (Sarquah et al., 2023) and Kumasi Compost and Recycling Plant (KCARP) (Bassey et al., 2024). These facilities are involved in the production of compost (Flow E), recovery of recyclables (Flow F).

Evidence has also shown that transfer stations have also been beneficial to reducing the volumes of waste ending up in the landfills although many challenges have not resulted in its full potential (Agyei et al., 2023; Manteaw & Boachie, 2019).

Source segregated waste from organic fraction of MSW sourced directly from markets and has only been recorded for the Safisana plant in Accra (Flow H). The plant converts the waste into electricity for the national grid, compost and organic products for the local market (Agyenim et al., 2020; Kessman, 2019; Safisana Ghana, 2024).

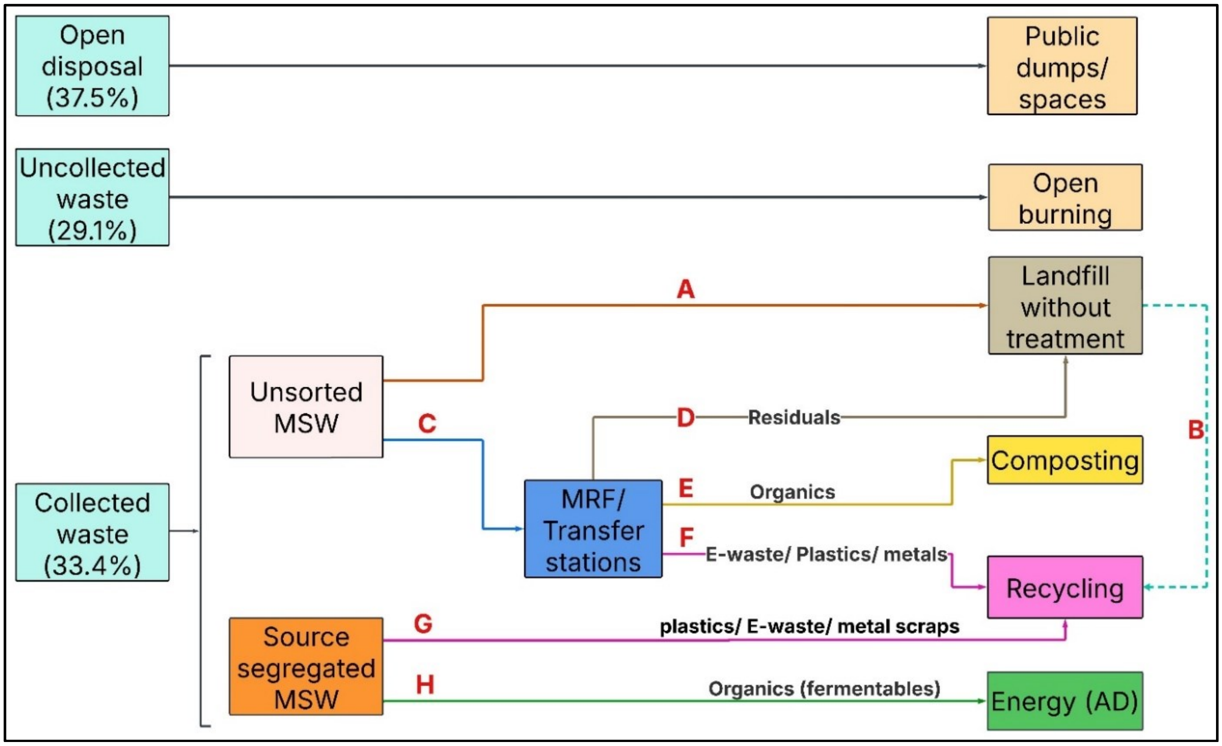

Figure 2.1: Framework of current waste management system in Ghana showing flows and management options

2.3.2 Waste generation and composition

Ghana's average waste generation rate of 0.47kg per capita per day is far below the global average of 0.74kg (Miezah et al., 2015; Silpa et al., 2018). Figure 2.2 presents a comparison between the regional population and the waste generation rates (Miezah et al., 2015). Also, there is a wide variation between large cities/metropolitan areas (0.72 kg/capita/day) as compared to municipalities (0.4 kg/capita/day) and districts (0.28 kg/capita/day).

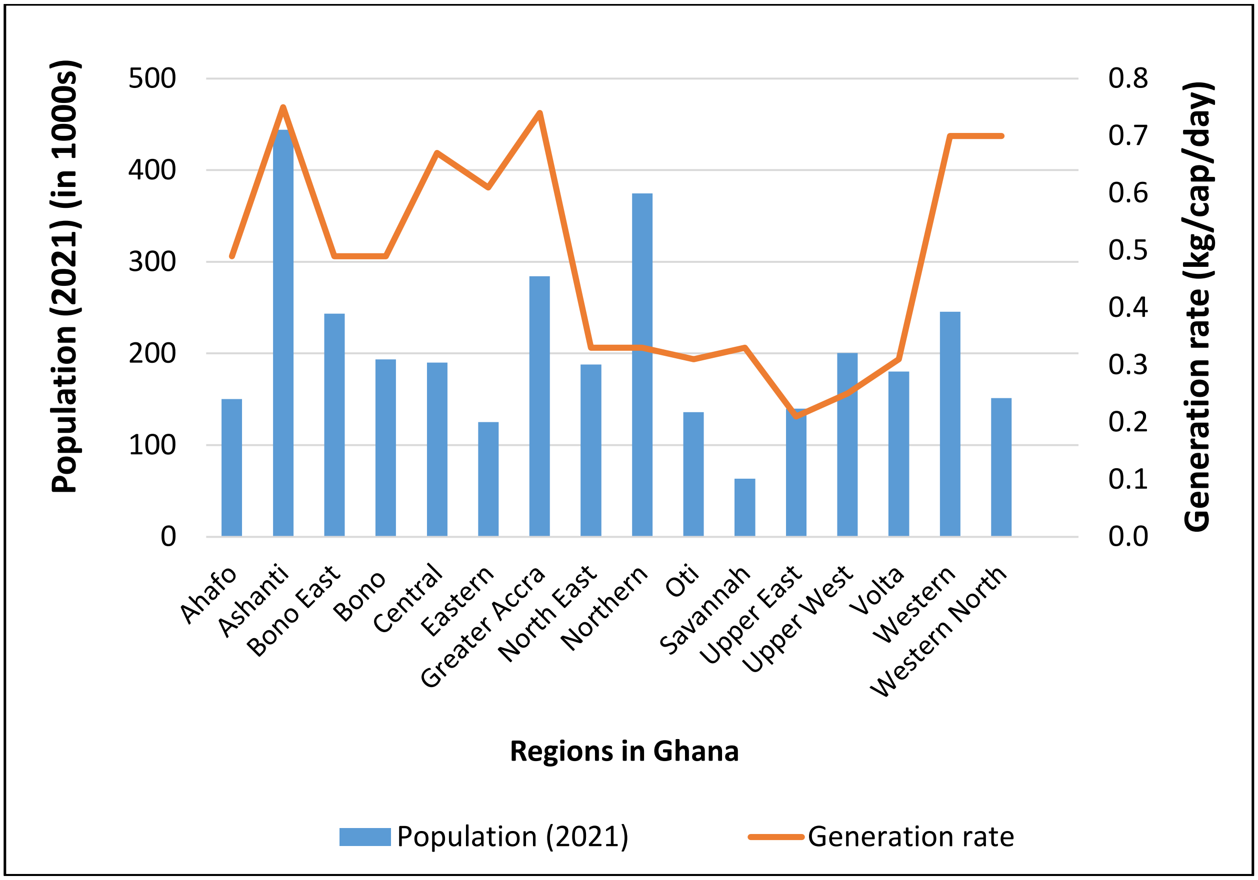

Figure 2.2: Regional population in Ghana in 2021 as compared to the waste generation rates according to Miezah et al., 2015

Although other studies have also been carried out, the varied sources of waste make comparison difficult. Table 2.5 presents some studies showing waste generation and characteristics in different parts of Ghana. These include households, commercial centers such as markets, institutions such as educational facilities. Some studies have also been carried out at waste recovery facilities which show some difference in composition due to the mixed sources. The composition of organic waste is highest followed by plastics with less than 1% metals. The high inert fraction of mixed waste in Ghana has been attributed to the sociocultural practice of sweeping untarred /unpaved surfaces such as road (Amponsem et al., 2023).

Table 2.5: Various waste generation and characterization studies across Ghana

Region/ location	Source	Generation rate	Organics	Feacal matter	Plastics	Paper	Wood	Textiles	Leather/rubber	Cardboards	Metals	Glass	Special wastes	E-waste	Inert	others	Reference
National average	Household	0.47	61	-	14	5	-	-	1	-	3	3	-		6	6	Miezah et al., 2015
Accra & Kumasi	MRF	-	48.6	-	20	7.1	0.3	4.2	1.5	-	1.2	1.0	4.8	0.6	5.6	5.3	Sarquah et al., 2023
Ashanti																	
Kumasi	Household	0.60	64	-	4	3	3	3	-	-	-	-	-	-	22	-	Asase et al., 2009
	Household	0.75	48.4	-	17.6	6.5	-	0.1	1.6	-	4.5	2.9	-	-	10.7	7.8	Miezah et al., 2015
	Market (wet season)	-	59.6	-	11.4	8.3	-	5.3	2.8	-	2.1	1.8	-	-	4.7	4.1	Addae et al., 2021
	Market (dry season)	-	45.8	-	14.6	12.7	-	7.3	3.9	-	2.3	2.6	-	-	6.4	4.3	
Asokwa Submetro[1]	Household	0.49	54.4	-	6.8	2.8	-	1.8	-	*	1.7	1.1	-	-	*	31.4	Asase, 2011
KNUST campus[1]	Household	0.30	69.2	-	7.3	4.4	-	1.8	-	*	2.6	1.3	-	-	*	13.4	
Atwima Nwabiagya[2]	Community containers	-	37.8	2	17.1	1.2	1.5	4.4	-	3.2	1.2	1.3	4.2	-	16.8	9.3	Mohammed et al., 2024
Oforikrom	Wood market	-	34.3	-	19.1	1.83	5.85	3.33	-	2.2	1.55	1.98	2.03	-	17.1	9.6	Amponsem et al., 2023

[1]Paper & cardboard are combined; others & inert are combined

[2]The data collected include areas within a 30km radius of the municipality which included 20 other districts

Table 2.4 Continued: Various waste generation and characterization studies across Ghana

Region/ location	Source	Generation rate	Organics	Feacal matter	Plastics	Paper	Wood	Textiles	Leather/rubber	Cardboards	Metals	Glass	Special	E-waste	Inert	others	Reference
Greater Accra																	
Accra	Household	0.74	65.8	-	10.4	5.3	-	2.0	2.1	-	3.1	2.8	-	-	5.2	4.1	Miezah et al., 2015
Central																	
Cape coast	Household	0.67	63.2	-	10.6	4.1	-	1.1	1.2	-	2.1	1.9	-	-	10.2	5.6	Miezah et al., 2015
	Household	0.46	64	-	11	5	-	4	-	-	3	2	-	-	-	3	Agbemabiese, 2020
Western																	
Takoradi	Household	0.7	60.0	-	11.5	7.3	-	1.2	2.9	-	2.4	1.5	-	-	8.0	5.0	Miezah et al., 2015
Takoradi[*3]	Household		78.6	-	9.2	11	-	3.7	-	*	3.4	3.6	-	-	4.7	6.5	Seshie et al., 2020
Northern																	
Tamale	Household	0.33	58.6	-	10.9	3.2	-	0.9	1.0	-	2.8	4.9	-	-	4.5	3.4	Miezah et al., 2015
Tamale [*4]	Household		55.08	-	16.99	*	*	0.87		*	5.79	4.16	-	-	*	17.11	Anim Addo & Wahabu, 2019
Upper West																	
Wa[*5]	Market	-	46.6	-	4.9	13	-	3.4	-	-	2.6	-	-	-	-	29	Bowan & Tierobaar, 2014

[3]Paper & cardboard are combined

[4]Large composition of other waste were combined as Paper/book/printed materials, Cardboard, fruits, leaves/grass/wood, animal excreta, straw and crop residue

[5]Large composition of other waste - was not specified

2.4 Waste to energy related studies in Ghana

Ghana's potential for integration of WtE into its current waste management system is high and largely untapped (Figure 2.1). Generally, due to projected increasing population growth rates, WtE potential is expected to increase. The prospects of generating electricity from AD and LFGTE technologies and the projected waste generation rates over a 20-year lifespan in the Kumasi Metropolis has been assessed. The TEA revealed that, technically, the plants have the potential to supply between 60 and 209 GWh/year for AD and 6.9 -185 GWh/yr from LFGTE. The two proposed projects show a potentially good economic feasibility with an LCOE of 0.089 and 0.1 $/kWh and payback periods of 7.9 and 14 years respectively for AD and LFGTE at discount rates of 10%. Although LFGTE has lower investment costs, the lower energy potential results in better financial metrics as compared to AD (Obuobi et al., 2022). Similarly, there is a higher WtE potential for Accra as compared to Kumasi due to the higher projected population growth rates although both cities have equal waste generation rates (Cudjoe et al., 2021).

WtE also has potential roles in the energy sector. Ghana is the second most electrified country in SSA (84%) (Ministry of Energy, 2019). Over the past two decades, Ghana's energy system has been dominated by fossils and biomass. Out of the total 21,466.26 GWh electricity generated in 2021, the sources were composed of 35% hydro, 64.52% thermal (fossil fuels), 0.25% renewables (solar and waste) (Ghana Grid Company Limited, 2022). Between 2000 and 2019, the share of petroleum in the energy mix increased from about 25% to 47.6% whiles biomass dwindled by about 24% (Energy Commission of Ghana, 2020). Consequently, overdependence on fossil-based energy is subject to high insecurities in terms of supply and price fluctuations in the global market resulting in high system disturbances. A SWOT (Strength, Weaknesses, Opportunities and Threat) analysis indicates slow growth within the renewable energy sector is affected by factors such as high cost of capital, interest rate fluctuations, uncompetitive tariff regime, fragile economic growth patterns, and inadequate interest and government funding into research and development. On the other hand, strengths and opportunities include stable political situation, regional integration for project expansion and increasing energy demand (Agyekum, 2020; Agyekum et al., 2021).

AD technology is the most researched WtE technology in Ghana. This may be due to the high proportion of organics within the waste stream as shown in Table 2.5. At a national scale, AD has been estimated to have an energy potential of 8.4 PJ/year from MSW based on the waste generation rates of 10 major cities (Kemausuor et al., 2014). Also, it is estimated that 0.33 tonnes of CO_2eq GHG emissions are avoided per kWh of electricity produced through for AD technology (Amponsem et al., 2023). This compares to 0.34 t/kWh recorded for (Port Harcourt) in Nigeria (Ayodele et al., 2017). The private sector has been more aggressive in promoting AD technology on small scales for sanitation purposes rather than energy generation. The Government has been criticized for its low interest in investing in large scale plants and the implementation of progressive polices (Kipkoech et al., 2024).

However, thermal conversion methods have a higher energy recovery rate as compared to biochemical technologies. The energy recovery potential for AD and gasification has been estimated 41.7 and 106 kWh/t MSW respectively (Osei-Appiah & Dioha, 2019). Pyrolysis is also a useful technological solution for the high volumes of single use and multi-layered plastics in Ghana (Bassey et al., 2023). Plastic types such as PP and LDPE independently produce greater yields of 89% and 94% as compared to mixed plastics (78%) (Bassey et al., 2024). Specifically, catalytic pyrolysis produces higher outputs than thermal pyrolysis inferring that the presence of catalysts improves gas (69.2%) and oil (15.16%) yields as compared to thermal pyrolysis: 59% gas and 13% oil (Ndiaye et al., 2023). The potential for fuel (AF) production using plastic pyrolysis is also feasible within the Ghanaian context. The properties of the fuel (condensate oils) produced from plastic waste has been found to have similar properties as commercial fossil fuel products such as diesel, kerosene and gasoline. This has the potential to supplement both industrial fuels and for transportation as well as conversion to electricity via combined heat and power systems. This therefore requires greater policy direction into source segregation (Tulashie et al., 2022).

Decisions on technology selection have been studied. To select the most viable WtE technology, MCDA (fuzzy TOPSIS) approach was used with technical and economic criteria. The results ranked four selected technologies according to preferences in the following order: gasification > AD > pyrolysis > plasma arc gasification. This is because gasification is seen to have a higher conversion efficiency, mass and volume reduction efficiency (70-80%), NPV and LCOE as compared to AD. Also, source sorting is largely inexistent with high inert composition which makes the practical implementation of AD technically complex. However, AD was ranked slightly higher in terms of economic viability as compared to gasification (Afrane et al., 2021). In effect, it is recommended for future studies to explore the viability of hybrid of the two technologies (Afrane et al., 2022).

Assessments of hybrid technologies have also been explored in the Ghanaian context. Although hybrid solar-biogas systems for rural communities is technically attractive; especially for solving the energy needs of off-grid communities, the high LCOE as compared to the current End User Tariffs (EUT) make the technology practically unfeasible (Odoi-Yorke et al., 2022). A comparative technical decision-making evaluation was carried out to determine the best alternative among Solar PV, WtE (combustion) and a hybrid of the two. The economic feasibility assessment indicates that the hybrid system is the least feasible with Solar PV alone having the best performance. This was attributed to higher capital and operational costs (Asante et al., 2023).

Several barriers confront the initiation of new WtE projects. For instance, due to challenges with financing the energy sector in Ghana, the government has placed a moratorium on the signing of further PPAs. Most WtE plants depend on revenues from long term power supply agreements. This policy therefore has the potential to stifle investment into WtE projects and setback Ghana's efforts to attain the 10% RE within the energy mix by 2030 within the framework of the Intended Nationally Determined Contribution (INDC) (Ministry of Energy, 2019). Also, experts within the waste management industry in Ghana attribute the low adoption rate of WtE to the high capital investment as well as a lack of waste segregation (Osei-Appiah & Dioha, 2019). Other factors include challenging investment climate, low technical skills and a general lack of public knowledge as a potential solution (Kipkoech et al., 2024). To remove such barriers, practical pilot projects such as the hybrid WtE plant provides a platform for researchers to develop innovative strategies and approaches. The status of research in Ghana in relation to the field of WtE has been summarized in Table 2.6. The various aspects of WtE research as described in Section 2.1 have been linked to the local context. The technical aspects have mainly focused on the assessment of AD. This is due to the high organic fraction of MSW as well as the availability of biomass and agricultural residues (Table 2.4; Kemausuor et al., 2014). The economic and environmental aspects are closely expected to support decision makers in the selection of appropriate waste management options. The research methodology follows in Chapter 3.

Table 2.6: Selected of WtE related studies linked to Ghana and key aspects

Type of study	Objective	Feedstock	Location/ study area	Methodology	Key findings	Reference
Technical prospects	AD	OFMSW, Liquid waste, forestry and crop residues, animal manure	National	Theoretical estimations	• 2.9 million m^3 potential methane yield from AD systems • Electricity supply - 8.7 million urban or 12 million rural households	Ofori, 2016; Darmey et al., 2023; Kemausuor et al., 2014
Experimental/ technical assessment	Pyrolysis for high yield conditions and favourable properties; comparing plastic types	PP, PET, HDPE, LDPE and a mix of all plastics	University of Cape Coast and the surrounding communities	• Fixed-bed batch reactor	• High potential of oil as alternative fuel • Order of oil yield LDPE>PP> HDPE>mixed plastic> PET	Tulashie et al., 2022
	Impact of Pyrolysis process on product yield and properties	Mixed plastic waste: PET, HDPE, LDPE, PP, PS	KNUST campus (Oforikrom Municipality)	• Thermal and catalytic pyrolysis -Batch reactor (450°C) • Chemical properties - FT-IR & GC–MS	• Catalyst facilitates higher gas, liquid yield and calorific value – 43.175MJ/kg • High potential as industrial and transport fuel • Thermal: 13% oil, 59% gas, 27% solid • Catalytic: 15.16% oil, 69.16% gas, 14.8% solid	Ndiaye et al., 2023

Table 2.5 Continued: Selected of WtE related studies linked to Ghana and key aspects

Type of study	Objective	Feedstock	Location/ study area	Methodology	Key findings	Reference
Experimental/ technical assessment	• Impact of Pyrolysis temperature (450, 500, 550 °C) and different plastics (SUP, LDPE, PP) on yield	Mixed Plastics - rejects from MRF (KCARP)	Kumasi	• Gas and oil properties - GCTCD, GCMS	• Optimal oil yield for mixed SUP at 550°C: 65.9%; lower heating value: 44.7 MJ/kg • Oil energy content - LDPE>SUP>PP> LDEP+PP	Bassey et al., 2024
	Gasification for electricity for rural communities	Crop residues (maize, millet, groundnut and cassava)	Sawla-Tuna-Kalba District (Savannah Region)	Laboratory analysis – LHV; theoretical estimations	• Electricity generation potential - 312.23 MWh/day • >200 times energy demand	Awafo et al., 2024
Technoeconomic assessments	AD (Technical and economic aspects)	Food waste	Accra and Kumasi	Theoretical estimations based on waste generation from population data	• Accra - long term WtE generation potential • LCOE: 0.0891 $/kWh (Accra); 0.0906 $/kWh (Kumasi)	Cudjoe et al., 2021; Other similar studies (Amo-Asamoah et al., 2020)
	AD (Technical, economic and environmental aspects)	OFMSW	Oforikrom Municipality	Theoretical estimations based on waste generation from population data	• Electricity generation potential – 601.87 MWh/yr; PBP – 2 yrs • Avoided emissions – 200.78 kt/yr	Amponsem et al., 2023

Table 2.5 Continued: Selected of WtE related studies linked to Ghana and key aspects

Type of study	**Objective**	**Feedstock**	**Location/ study area**	**Methodology**	**Key findings**	**Reference**
Technoeconomic assessments	AD (Technical, economic and environmental aspects)	Cassava waste	Ghana	Aspen Plus - Potential for bioelectricity for production and starch drying; SimaPro	• Low grid Tariff results in low economic feasibility • GWP reduction compared to fossil fuel use (97.7%)	Padi et al., 2022
	AD, gasification	MSW	Accra	LandGEM, theoretical estimations	• High economic feasibility • High CAPEX • PBP: 8 yrs (thermochemical processes); 4 yrs (biochemical processes)	Osei-Appiah & Dioha, 2019
MCDA	AHP for technology selection (LFGTE, INC, AD, COMP)	-	Accra	Technical, Environmental, socio-economic criteria; 9 sub criteria. 10 expert inputs	Ranking - INC>AD>COMP>LFGTE	Agbejule et al., 2021
	Fuzzy TOPSIS for technology selection	-	National	10 criteria. 5 experts	Ranking- gasification > AD > pyrolysis > plasma arc gasification	Afrane et al., 2022

GC-TCD: Gas Chromatography Thermal Conductivity Detection FT-IR: Fourier Transform Infrared spectroscopy; GC-MS: Gas Chromatography-Mass Spectrometry; TLCC: total life cycle cost; NPV: Net Present Value; (I)PBP: (Investment) Payback Period; LCOE: Levelised Cost of Energy; IRR: Internal Rate of Return.

3 METHODOLOGY

This chapter aims to consolidate the research methods followed to meet the goal and objectives. The business case is presented as the broad outcome of several steps. Generally, the methodology follows six steps which are grouped into three major stages. Stage 1 is a preparatory stage which involves data gathering. Stage 2 focuses on a business case for the HWtE plant and is linked to Objectives I and II whiles Step 3 seeks to develop a future strategy and is linked to Objectives III and IV.

At Stage 1, data from the HWtE plant was collected between 2021 and 2023. The technical model was thoroughly assessed from technical specifications and onsite facilities. Based on the technical model, potential products were selected for assessment. In the next step, a market study was conducted to collect data from other sources including industries and competitors. The methodology for the selection of products and data collection has been detailed in Section 3.2.

In Stage 2, the data collected is used for the development of a business case for the HWtE plant. Several tools and methods are used depending on the specific objective. Feasibility assessment constituted a major aspect of the entire study which required the development of a financial model in MS EXCEL. This provided a flexible platform for an iterative process at each stage. An environmental assessment was also conducted to identify the potential impacts and to compare with the conventional waste management process within the local context.

The future strategy is presented in Stage 3. Scenario analysis is used extensively. This is thoroughly described in Sections 4.2 and 4.3. In Section 5.1, an MCDA methodology is described to select hotspots for the siting of future plants. The stages and steps are represented in Figure 3.1.

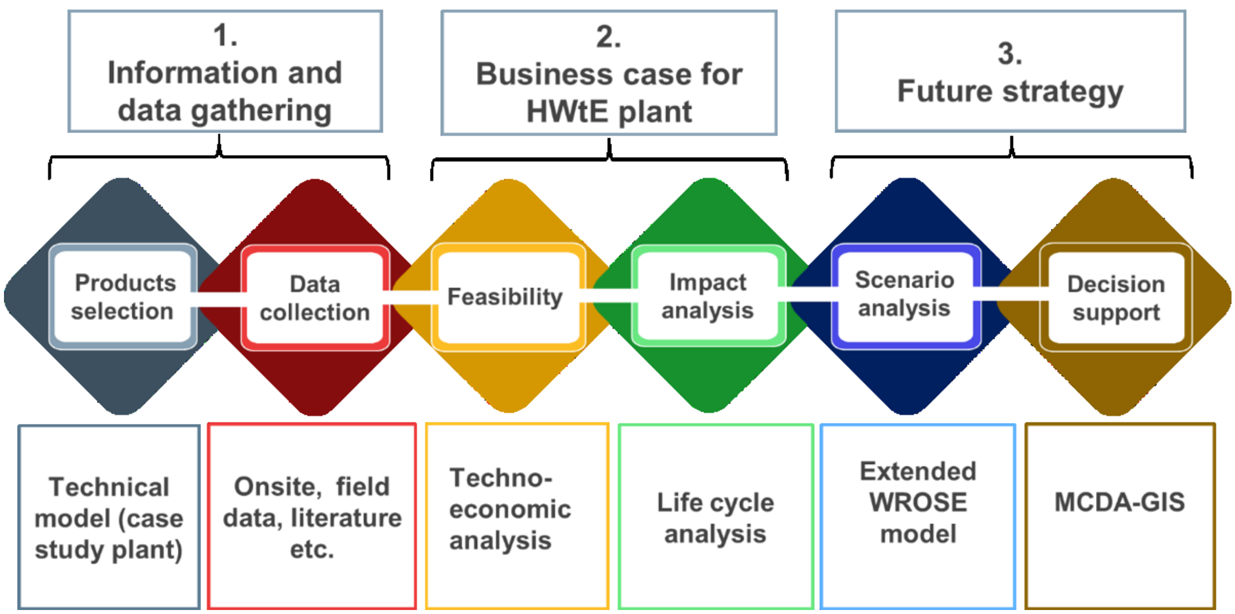

Figure 3.1: Broad methodology and key aspects of the research

3.1 Detailed methodological framework

According to the objectives of the study, there are two major blocks: the feasibility assessment of the HWtE plant and the linkage of as a baseline for designing future projects. All related publications are presented ANNEXES I - V. To commence, a bibliometric literature review is carried out on WtE research in Africa and published in PAPER I. The next four publications as well as the outputs contained in this thesis links up to the objectives of the research.

For the feasibility assessment in Stage 2 (Figure 3.1), the dependent variables are two major resources: waste and solar radiation. Waste is assessed in terms of quantity and characteristics. This in turn determines the outputs (products) from each system. The environmental and economic assessments depend on the technical specification of the installed systems and their technical outputs.

Feasibility assessment is conducted for both the HWtE plant and future cases. Three parameters are evaluated. The project financing and product models are linked the HWtE plant whiles the city scale model is linked to a proposed future model. The feasibility assessments are published in three papers (PAPERS II, III & IV). PAPER II focuses on only one product (energy) whiles evaluating project financing models in two scenarios. PAPERS III and IV compares the feasibility of various product combinations in six scenarios based on the categorization of products.

PAPER IV also provides an outlook into the future by exploring the feasibility of a future plant sited in an urban area. This comparison is important as the HWtE plant is in a rural setting with nearby farms and depends on waste from several metropolitan and municipal areas to meet its demand. On the other hand, the research outcomes can be transferred to urban areas with high generation and collection rates.

The environmental assessment is an important aspect of WtE businesses due to potential impact on project approvals, international regulations as well as acquisition of project financing. The environmental impacts are published in PAPER V.

This dissertation focuses on linking the outputs of the assessment conducted in the HWtE plant to a potential future project. The output of the product categorization and market assessment provides a basis for the development of business model. A feasibility assessment is carried out on the business models using the data from the case study plant. This may be done with project specific input data for future projects. It is important for future project developers to design viable business models and market linkages. Finally, national geographical hotspots are developed based on based on multi-criteria, products and technologies. It incorporates the key influencing parameters from the pilot plant into the identification of potential areas for siting future plant. It has been recommended from previous market study for new WtE projects in Ghana to invest in pilot plants due to high uncertainty and underdeveloped aspects (Kessman, 2019) . The methodology used in this study therefore presents how a pilot plant can provide a link to future investment. In the next sections of this chapter, the methodology for each stage is detailed. Figure 3.2 presents a detailed flow chart showing the linkages, publications and major outputs of the study and its link to the major objectives.

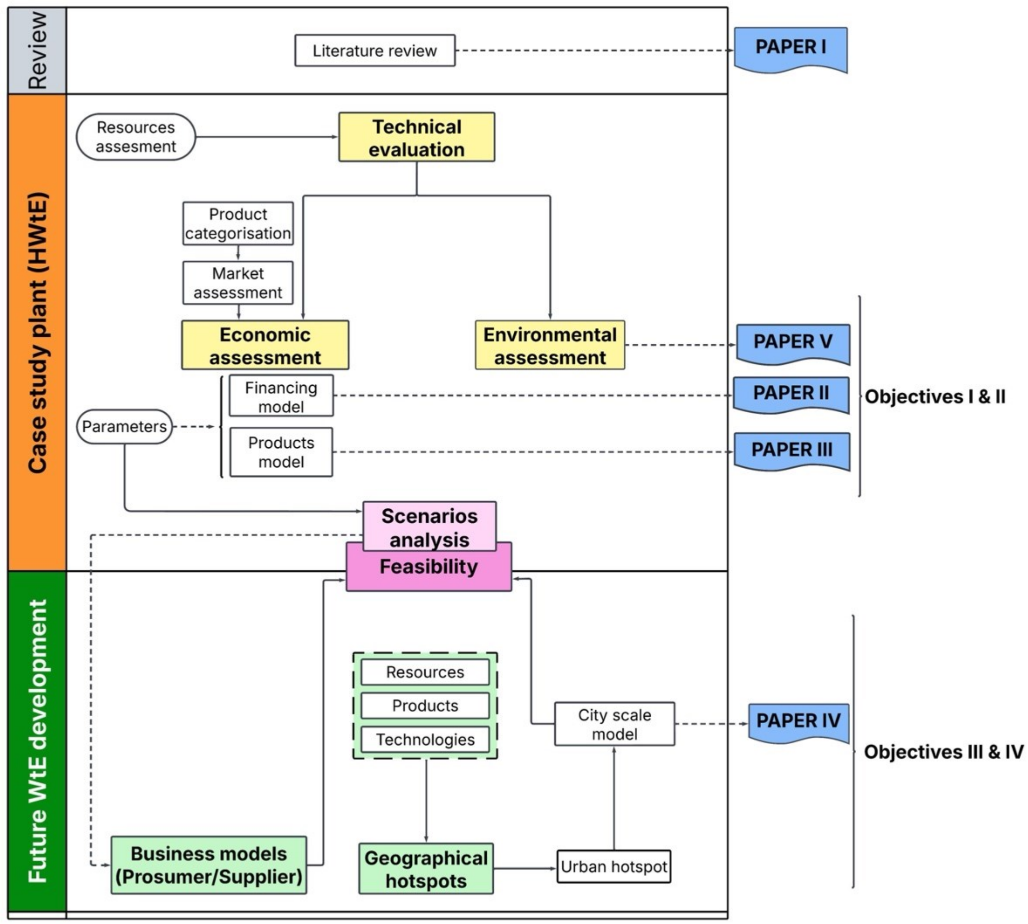

Figure 3.2: Detailed methodological framework and linkages to research objectives and publications

3.2 Information and data gathering

3.2.1 Products identification

The technical model of the case study plant was used as a basis for the research. The technical framework has been detailed in the related publications (PAPERS II to V). The following systems are installed onsite: a segregation system, two WtE systems (AD and pyrolysis), RDF pelletiser, plastic processing, composting, Solar PV and a laboratory. As a first step, all technically viable outcomes of the processes were mapped out for practical viability.

3.2.2 Data collection and market assessment

Data is required on three main aspects: the supply, demand and markets (Figure 3.3). The supply involves the main resources including feedstock characteristics and quantity, solar output, the sources and potential suppliers, the cost of supply as well as requirements for supply contracts. The technical specifications and operational processes for production are considered. Finally, the potential market was investigated. The market includes potential offtakers, the buying price, the cost of supply, location and distance.

A market study was carried out on compost production in Ghana. The objective was to ascertain the market demand for compost products of similar characteristics as the anticipated compost product form the plant and to identify the average market price of compost. The methodology and results are detailed in PAPER III. Compost samples were purchased from suppliers rather than the producers to understand the supply chain and price of the product. Physical characteristics of the product were then taken. Apart from the open market survey, Safisana Ghana Limited and Jekora Ventures Limited sites were visited to observe the production process for compost. Plastic recycling hubs were visited in Accra. Plastic granules production and sales were piloted at the plant. This was done to ascertain demand and characteristics of both the local and international market.

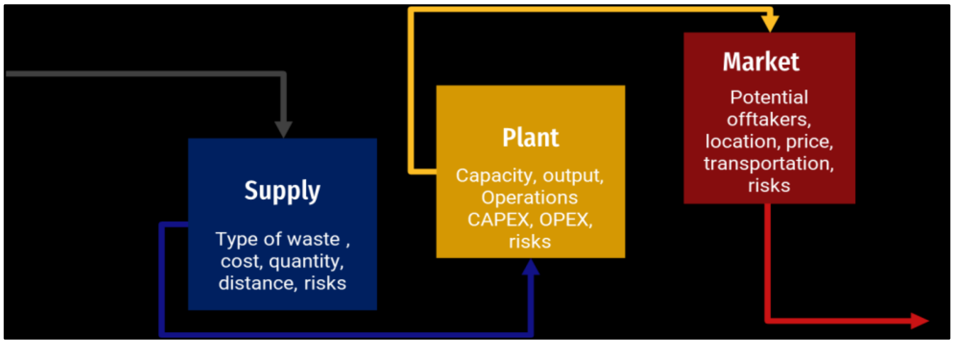

Figure 3.3: Input data required throughout the study

Other research publications and project reports related to the HWtE project provided additional inputs and have been summarized in (Table 3.1). In some cases, interviews were carried out to obtain further information. In addition to this, identified data gaps were filled with locally available data in similar setting as the current plant.

Table 3.1: Data sources and additional supporting sources

Category of data	Type of data	Source/ Reference
Supply	Waste quantity and estimated composition, stakeholders and risks	Mohammed et al., 2024; Sarquah et al., 2023
Plant	Operation of segregation system	Onsite assessment and Sarquah et al., 2023
	Solar system specifications and capacity	Onsite assessment
	Biogas system specifications and capacity	Onsite assessment and project documents
	Pyrolysis system specifications and capacity	Project documents and Bassey et al., 2023
	Compost process	Onsite assessment
	Plastic recycling	Onsite assessment
	Laboratory	Onsite assessment and project documents
Market/demand	Plastics recycling in recycling hubs	Field investigation: Identification of key suppliers, buyers and buying price
	Potential suppliers, demand of RDF	Field investigation: Identification buyers and buying price
	Electricity tariffs	Public Utilities Regulatory Commission - Ghana, 2024
	Compost market	Market and price investigation
Others	Environmental assessment	Baidoo et al., 2024
	Risks and barriers	Stakeholder investigations and Williams et al., 2023

3.3 Business case for HWtE plant

3.3.1 Technoeconomic assessment (TEA)

The waste (material) flow analysis was conducted to compute the fraction of materials to be received by each treatment stream at the plant site. Prior to the commencement of this research, project related resource mapping data had been conducted within the Atwima Nwabiagya Municipality where the plant is located (Mohammed et al., 2024). In addition to this, waste characteristics from two other plants in Ghana with a similar segregation process as at the plant site were used (Sarquah et al., 2023). The STAN software version 2.7.101 was used to model the material flows (TU Wien, 2022).

In PAPER II, the feasibility of the electricity generation as the sole product for supply to the national grid was carried out using the RETSCREEN® Expert software v9.1.0.98 (Natural Resources Canada, 2005). The RETSCREEN software only allows the evaluation of energy.

To assess other products and using various scenarios, a detailed financial model was developed in MS EXCEL. Feasibility assessment is carried out at four stages: comparing two products and scenarios (PAPER II and III), proposed plant in an urban area (PAPER IV) and well as business model scenarios presented in this thesis. This provided great flexibility in the feasibility assessment and allowed an iterative process. The following financial metrics were used because they are the most commonly used metrics for such TEA: Internal Rate of Return (IRR), Net Present Value (NPV), Return on Investment (ROI), Benefit to cost ratio (BC), Levelised Cost of Energy (LCOE) and Breakeven analysis (Hasan et al., 2024; Winquist et al., 2019; Zhao et al., 2016).

3.3.2 Environmental impact assessment

Environmental assessment was carried out as a comparative study of the energy recovery systems as compared to the disposal of waste in the landfill site (PAPER V). Sometimes, WtE plants receive public backlash due to perceived environmental impacts. The objective is to assess the potential environmental impact of the plant as compared to the Business as Usual (landfilling). Also, the avoided impacts could be explored as a support for obtaining grant financing or carbon credits. The Life Cycle Analysis (LCA) methodology was used. The OpenLCA software v2.3 was utilized in accordance with the ISO 14040/14044:2006 guidelines (International Organization for Standardization (ISO), 2006a). The ReCiPe 2016 Midpoint (H) impact assessment method was applied using 10 selected midpoint characterization factors due to their relevance to the study's scope and consistent with similar research in the field (Ayodele et al., 2017; Huijbregts et al., 2017). The LandGem software v3.03 was used to model the landfill emissions for the same quantity of waste over a 100-year period (lifetime emissions). The identified potential impact areas for project developers to incorporate mitigation measures.

3.4 The strategy for future replication

This thesis focuses on providing a strategy for future project developers focusing on two major outputs: Business models and geographical hotspots. These are detailed in Chapters 4 and 5. The hybrid technical model allows for multiple waste streams to be treated resulting in the potential for multiple products concurrently. Business scenarios and hotspots were developed to guide future strategies. A Multicriteria Decision-making Approach (MCDA) is used together with the Geographic Information System (GIS) software (ArcGIS Pro) to generate a geospatial representation to support decision-making. These are detailed in the next two chapters (Chapters 4 and 5).

4 THE CURRENT PLANT LINKED TO BUSINESS MODELS

This chapter presents a bridge between the business case for the case study plant and a business strategy for future plants. It is envisaged that, the outcomes provide a guide for investment decisions for both investors and local authorities.

The chapter synthesizes the technoeconomic assessment according to product categories. Subsequently, product categories are combined into scenarios, remodeled and their feasibility is compared. Since the scenarios represent product combinations, the results of the scenario analyses provide an indication of the most viable approach to establishing future plants.

4.1 Potential products and markets of the HWtE model

The HWtE model is expected to be replicated in other areas across the country in the future. Therefore, this section provides an overview of potential products to be explored. The AD process is directly linked to the production of biomethane. Biomethane is considered a major intermediate product with several technical possibilities for producing marketable products: bio-CNG (upgraded biomethane), hydrogen, heat energy and electricity. For future plant, it may be preferable to select the most financially feasible of the other three products. Heat is a by-product of electricity production form biomethane. This can supplement an internal demand for biodigester rather than as a product.

The digestate from the digestion process is upgraded to compost. Raw liquid and solid digestate are not explored as separate products. Previous studies have indicated that upgrading digestate to compost improves the amendment properties and stabilizes the digestate (Bustamante et al., 2012). Also, adding a bulking agent such as farm waste improves the composting process, reduces NH_3 emissions by 70% and results in a high quality fertilizer product (Zeng et al., 2016).

Beyond this, the pyrolysis system produces electricity from bio-oil. Residual Fuel Oil (RFO) also referred to as bio-oil or biodiesel is a potential product with local viability in the transportation and industrial sectors. TEA is conducted based on the prevailing market price and the expected quantity of bio-oil produced.

Plastic waste has two competing alternatives: upcycling into recycling pellets and pyrolysis. However, within the context of a circular economy, recycling must first be exhausted before energy conversion. Thus, during segregation, the plant protocols must preferably direct recyclable plastics, and for instance, end-of-life plastics to the pyrolysis system. The increasing local recycling market is increasingly creating a value chain for waste plastic and source segregation especially in urban areas (Fiati, 2021). Thus, segregated waste plastics may be purchased directly from aggregators to supplement internally segregated fractions.

Other products include pelletised RDF from residuals and scrap materials. Scrap metals, glass, e-waste may have to be aggregated and sold out to large aggregators. This requires a significant storage of space depending on the collection frequency. The plant also has the potential to commercialise its laboratory which is specifically equipped to support the generation of quality scientific data for the waste management sector. Finally, the environmental impact due to avoided greenhouse gas emissions is a potentially viable revenue stream which could support the business model of the plant. The process and product linkages have been shown in Figure 4.1.

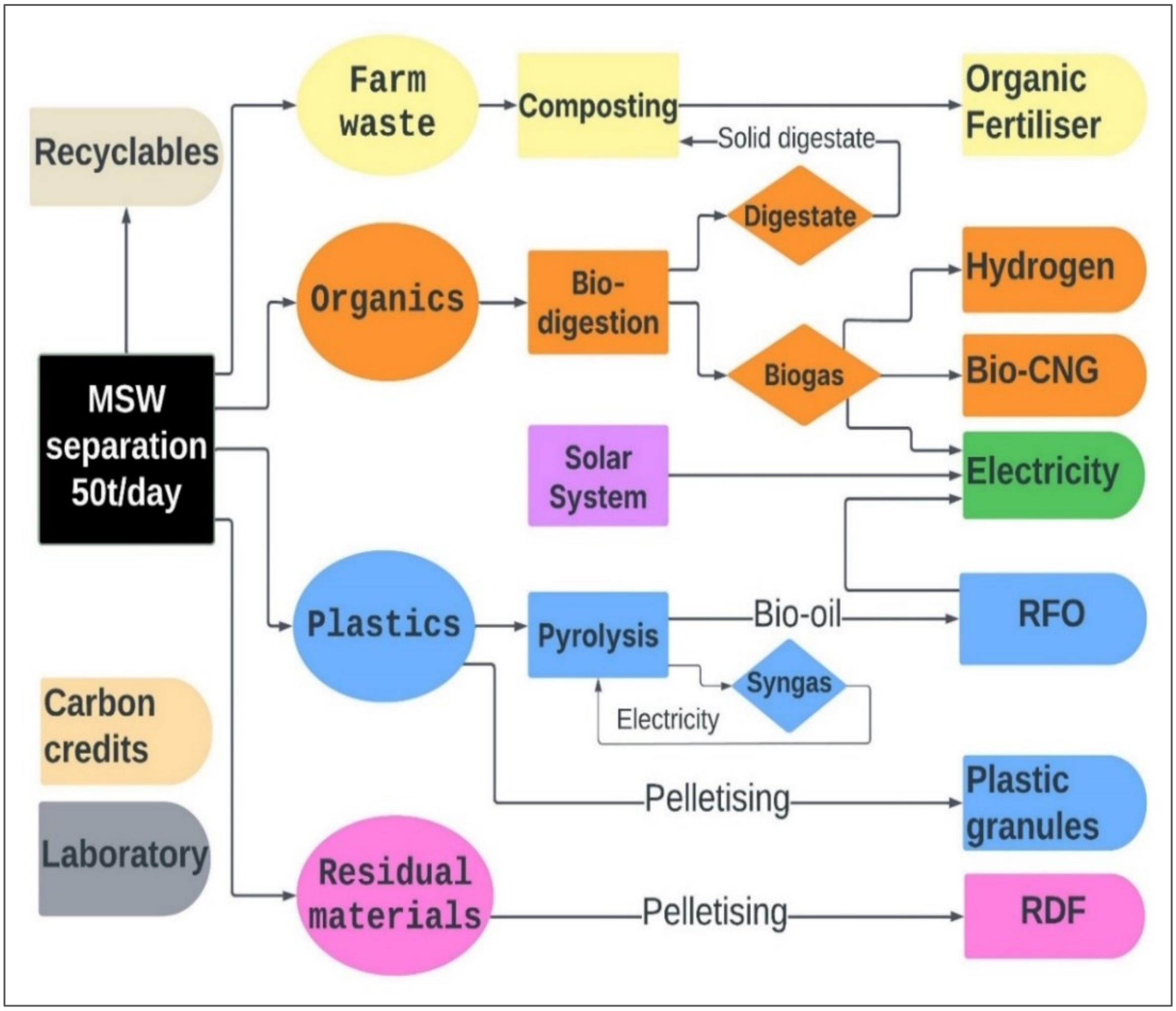

Figure 4.1: The technical model of the HWtE plant showing the potential products

4.1.1 Stakeholders and Target markets

From production, the market is an important consideration. The main offtaker for produced energy is the national power regulators. On the other hand, other products require a market study to identify the existing or potential industries, location and commodity prices for the products. Both desk and field data were used. Future studies may explore interviews with these industries to assess their willingness to enter into procurement agreements. Trade flows may also be explored to identify networks, relationships and distribution channels. The products proposed are not exhaustive. It may rather compose a framework to guide developers rather than a strict replication.

On a city scale, it has been referred to as "circular cities". In this context, the following common characteristics are to be considered: conservation and efficiency, closing of loops and reuse and resource sharing (Paiho et al., 2020). For instance, in Indonesia, WtE plant has incorporated the CE concept to establish an incineration plant with electricity as the major product and other products: fly ash to pavement blocks, carbon credit and recyclable materials (Purwanta et al., 2022). Also, in Hanoi - Vietnam, four CE based scenarios were tested for the city scale waste management. It incorporated different combinations of Mechanical biological treatment, composting, RDF and incineration.

Hydrogen is identified as an entirely new product and a plant focusing on the production of hydrogen may have to invest in market entry assessment and in securing local demand. the Inorganic fertilizer production is identified as the most readily available market. Hydrogen can be converted into ammonia through the Haber Bosch process, which can in turn become a component of inorganic fertilizer or ammonia nitrate fuels used in the mining industries. It has been estimated that African agricultural demand for ammonia will increase to 181 kg nitrogen/ha/yr by 2050 (Mukelabai et al., 2022). Ghana is a hotspot for both industries. The mining and inorganic fertilizer producing industries are the key potential offtakers for the local hydrogen product. There is no primary production of inorganic fertilisers in Ghana. All companies compose mixtures from imported ingredients (urea, mono-ammonium phosphate (MAP) and di-ammonium phosphate (DAP), etc) which originally contain hydrogen. It has been estimated that 618,638 tonnes of fertiliser were imported into Ghana in 2020 alone which was an increase of 46% on the previous year's import. Large potential companies for the local hydrogen market include the six major importing companies: Yara Ghana, Chemico Limited, Louis Dreyfus Company Ghana (LDC), OmniFert, GloFert and Agricultural Manufacturing Group (AMG). All blending plants are located at the southern part of the country, closer to the Tema Port. (IFDC, 2021).

The compost to be produced at the plant depends on the input of digestate and farm waste as bulking material. Therefore, nearby farmers are important stakeholders. In terms of the market, Ghana has an active nationwide network of fertilizer distributors and suppliers which is well documented in a stakeholder engagement report by OM4D (OM4D, 2018). A future plant must therefore invest in farmer education and marketing activities on the acceptance of organic fertilizers.

Plastic pellets production is dependent on the input supply of plastic waste. In Ghana, the plastic waste targeting recycling originates from waste pickers, mixed waste from waste trucks or tricycles, as well as waste aggregators such as NGOs. To meet the demand, more plastic waste may have to be sourced from aggregators since mixed waste may not satisfy required demand. After production of the pellets, the plastics are traded to the local recycling companies located mainly in Accra or Kumasi to exporting companies (Fiati, 2021).

RDF, bio-CNG and RFO from plastics are also relatively new products on the Ghanaian market. Globally, RDF is demanded by heavy industries such as cement industries (Sakri et al., 2021). However, in most Ghanaian cities such as Accra, Kumasi and Takoradi, industrial zones/clusters are geographically demarcated which provides an opportunity for reducing transportation costs when multiple offtakers are identified. The Ghana Free Zones enclave in Tema presents a particularly interesting location for this purpose. The industrial census identifies the regions with the largest manufacturing industrial clusters in Ghana constituting 68% of the national total: Greater Accra (28%), Ashanti (27%) and Western (13%) (GSS, 2006).

Lastly, the potential for laboratory services is dependent on the academic and research institutions or industries requiring data which is scattered across the country. The closest proximity to the Kwame Nkrumah University of Science and Technology, and the University of Energy and Natural Resources presents the plant site as an important location for the middle belt of the country. Also, the Council for Scientific and Industrial Research has a strategic location within the Ashanti Region (Fumesua) which may be a strategic partner for the laboratory. Table 4.1 summarises the information below.

Table 4.1: A summary of suppliers and markets for the products

Product	**Suppliers**	**Target market/ potential offtakers**	**Identified end-products**
Pellets	Waste pickers, agents, wholesalers or aggregators, NGOS	Plastic recycling industries	Recycled products
Compost	Farm waste	Fertilizer distributors, farmer cooperatives	Organic fertilizer

Bio-CNG	Waste management companies, waste tricycles	Fuel stations e.g LPG, Medium to heavy industries	Transportation/ industrial fuel
Hydrogen	Waste management companies, waste tricycles	Inorganic fertilizer producers, chemical producers, export	Inorganic fertilizer, chemicals
RDF	Waste management companies, waste tricycles	Medium to heavy industries	Industrial fuel
RFO	Waste management companies, waste tricycles	Medium to heavy industries	Industrial fuel
Lab	Academia, industries	Academia, industries	Data

4.1.2 Product categories and groups

The products presented above are linked to potential markets or offtakers. Energy (electricity) demands a large utility/ offtakers for a Power Purchasing Agreement (PPA) on the other hand, the other products require multiple industrial/ commercial offtakers. As such, the products are categorized based on the target markets. These are further grouped mainly as energy and Alternative Fuels and Materials (AF&M). The categories and products are linked below:

i. Energy : electricity, heat
ii. Alternative Fuels : RDF, hydrogen, bio-CNG, RFO
iii. Materials : compost, recyclables (plastic, scrap metals, glass, e-waste etc)
iv. Others (potential) : emissions, laboratory

4.1.3 Alternative Fuels and Materials (AF&M)

Energy as a product has been extensively discussed in PAPER II. Also, the feasibility for individual products have been presented in PAPER III. However, the role of AF&M as an integral component of the business model of HWtE plants has not been discussed. AF&M are relevant in the energy economy due to their versatility and their capacity to be stored and transported as compared to a final energy product (electricity). Electricity to grid is subject to the availability of potential long term contract agreements. AF&M on the other hand is beneficial as industrial fuels when adequate logistical and infrastructure are available to support this (Rahman et al., 2013). Most industrial production depends on the onsite gasification of fuels rather than electricity (Infiesta et al., 2019; Lombardi et al., 2015). The cement industries are classic examples of this. Fuels such as RDF are extensively used. Studies in neighbouring Togo establishes the potential for other forms AF from agricultural residues to drive WtE in the cement industry (Beguedou et al., 2023a; Beguedou et al., 2023b).

In Ghana, agriculture is a major economic activity, especially in rural areas. In cocoa, oil palm and coconut growing areas for instance, cocoa and oil palm is preprocessed before transfer to large off-takers leaving behind large amounts of biomass. Research indicates that coconut for instance can produce 62 – 65% waste biomass which may be harnessed for energy purposes. Gasification may be technically feasible to convert this to energy (Obeng et al., 2020). In effect, the market may be created for companies which are interested in improving the climate impact of production to source locally available options.

Figure 4.2 demonstrates how AF&M fits into the energy supply framework, especially for commercial and industrial purposes. Feasibility assessment for AF&M may differs from energy to grid due to the dependence on open market sale of products. Some of the products such as hydrogen and RDF are relatively new on the Ghanaian market and requires a careful identification of offtakers (Seglah et al., 2023). Also, long term offtaker agreements may more difficult as compared to PPA for energy to grid projects.

However, AF&M present the advantage to store and transport the products as compared to electricity which depends on direct grid transfer. Also, from the perspective of the industries, investment must be made into subsequent fuel conversion technology such as gasification systems for onsite energy generation (Madlool et al., 2011; Osibote et al., 2018). An assessment of the use of AF in the cement sector in Senegal indicates significant potential. However, sourcing barriers were seen as a major hurdle for potential plants (IFC, 2017). The following section details the proposed process for conducting financial feasibility.

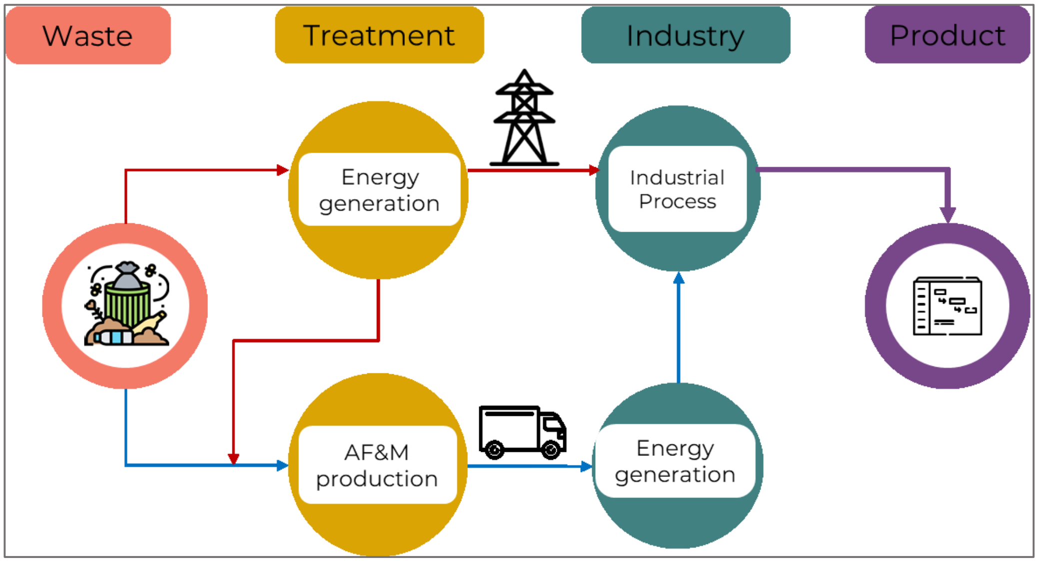

Figure 4.2: The linkage between the product driven WtE concepts and the final uses

4.2 Scenarios for future plants

The hybrid nature of the plant allows for multiple waste streams to be treated resulting in the production of multiple products concurrently. This provides an opportunity for exploring CE designs. The purpose of scenario analysis is to identify the most financially feasible product combination to support investment decision-making for future plants. Scenarios as used in this study refers to various products linked to a waste streams and technologies.

In terms of the outlook for replication, the Waste to Resource Optimization and Scenario Evaluation Model (WROSE) was used as a guide for the study. It provides a structured framework for developing countries to design specific waste management systems, integrating several integrated scenarios to support final decision-making. It also incorporates the technical, economic, environmental and institutional aspects. Models such as the WROSE model have been used in the developing country perspective to integrate various waste management solutions (Trois et al., 2023).

Potential WtE businesses may have to decide on the final use of the generated energy and the relationship to the grid. There a two broad groups: the energy supplier or the energy prosumer. The prosumer is described as an energy producer who also consumes the generated energy. The prosumers can be further categorized into two as proposed in a previous study: off-grid and on-grid prosumers. The off-grid prosumers use all the energy generated for its internal production and operations whiles the on-grid prosumer transfers excess energy to the grid after all internal operation and production demand has been met (Kotilainen, 2020). The third category is the conventional energy supplier. This is represented in Figure 4.3 below.

4.2.1 Scenario 1- On grid prosumer (Energy and AF&M)

This WtE business focuses on the commercialization of all identified products as shown in Figure 4.1. In the practical application, biomethane may preferably be further processed into one of the following products: hydrogen, bio-CNG or electricity. However, due to the pilot studies, the potential and economic comparison of producing all products were explored. This is also due to the lack of availability of hydrogen and bio-CNG on the Ghanaian market which requires some assessment on market uptake studies. This scenario is the medium risk scenario in terms of revenues. It requires both a long term PPA as well as open market sale of AF&M. The revenue model will depend on secure income from a tariff.

4.2.2 Scenario 2 – Energy supplier

is the most common model for WtE plants where energy is the single marketable produce. It is assumed that digestate and residuals are disposed of at no value. The digestate is assumed to be given out to local farmers to be composted at no cost to the plant. This may be a form of corporate social responsibility for the local community. This is the lowest risk scenario due to the requirement to sign a long term PPA which removes direct engagement in sales and marketing activities. This may reduce the O&M costs of the plant and potentially improve feasibility.

4.2.3 Scenario 3 – Off-grid prosumer (AF&M only)

In this scenario, only AF&M products while electricity generated is only used for internal purposes. Based on the comparative revenue model, this is the highest risk scenario. It represents open market sales and marketing activities which may be subject to local or regional markets. Long term supply contracts may be secured to reduce this risk.

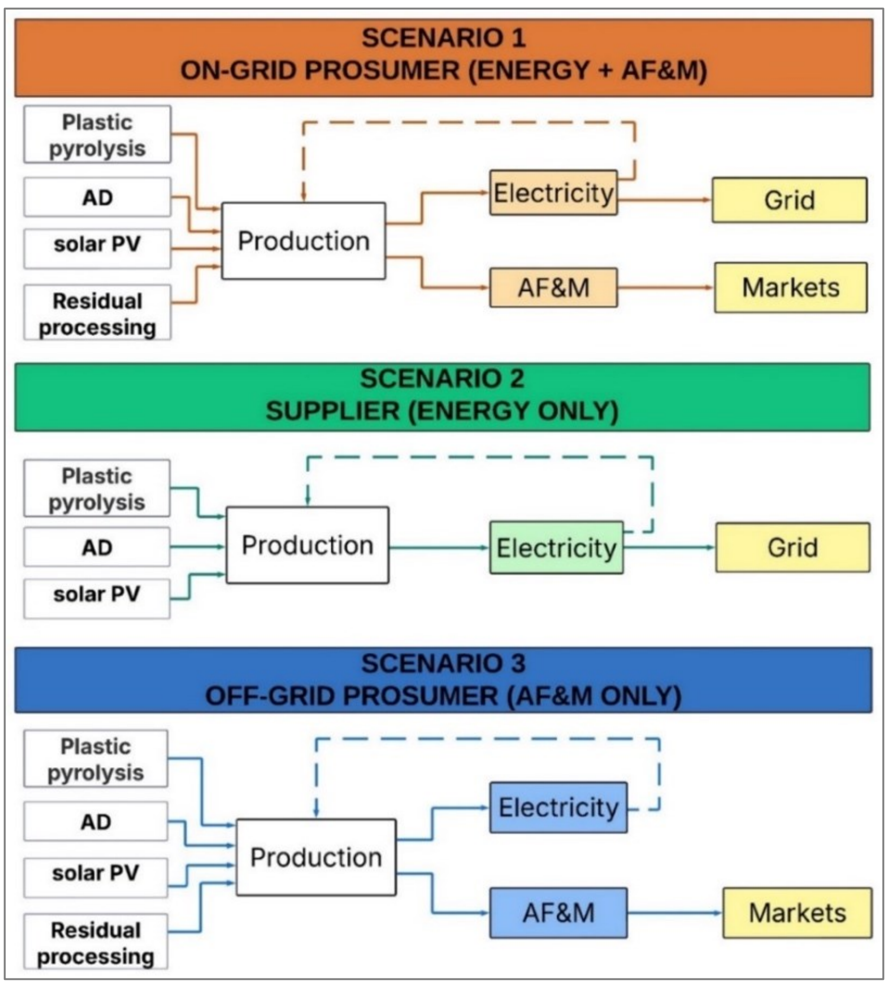

Figure 4.3: Schematic representation of the scenarios and product categories

4.2.4 *Comparative economic feasibility of business model scenarios*

The scenarios are comparatively analysed by combining the various products and services as shown in Figure 4.3. For scenarios 1& 2, the electricity exported to grid is firstly influenced by the quantity of the electricity freed after internal demand has been exhausted. This is mainly linked to the multiple outputs of the AD system. For scenario 1, the energy output is the baseline, where the capacity for electricity generation from AD is 100 kW as currently installed at the plant. However, for Scenario 2, it is assumed that all the biomethane produced from the AD is directed into electricity production without any fuels. Thus, the capacity of the CHP increases to 300 kW. Finally, for scenario 3, all biomethane is assumed to be directed for AF with electricity of total electricity capacity of 300 kW from Solar PV and pyrolysis.

Revenue streams for Scenarios 1 & 3 is dominated by plastic pellets, compost and hydrogen (Figure 4.4). In Scenario 2, electricity is the only product. In practical application, the bio-CNG and hydrogen outputs may not be produced at the same plant site. The competing products from biogas have been evaluated in PAPER IV. Table S.1 shows the linked product quantities and prices used in estimating revenues.

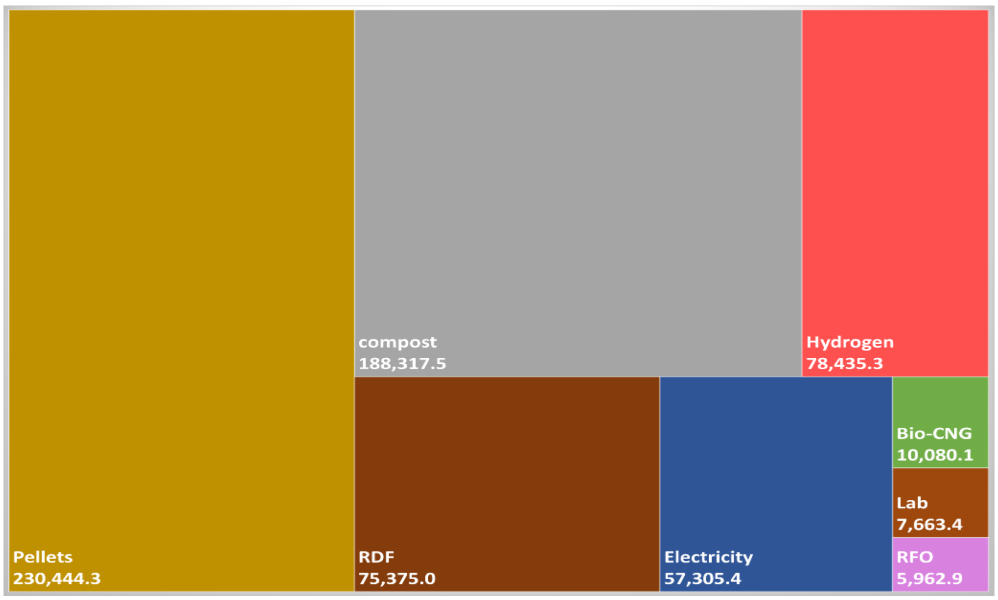

Figure 4.4: The estimated annual revenues products (€/yr)

The scenarios were modelled in MS Excel, and the details are presented in Table 4.2 below. As compared to the published results, plastic pyrolysis and the laboratory have been included into the revenue model. A breakeven analysis is important for determining the minimum selling price and the production quantity to be able to make profit. In Table 4.2, the minimum number of production units with a corresponding target price is presented. The price is particularly important during negotiations with offtakers and customers to determine the most feasible selling price. It is also important to assess the capacity of the plant to continue to maintain production even when demand reduces. Generally, the units for bio-CNG and hydrogen are very low because these are split products from biomethane. The percentage allowable reduction refers to the percentage reduction from the breakeven point to the production units.

Table 4.2: The results of the breakeven analysis

Break even basis	RFO	Plastic pellets	Bio-CNG	Hydrogen	Compost	RDF
Unit	litres	tonnes	tonnes	m^3	tonnes	tonnes
Minimum number of units	5,542.12	16.11	5.14	2.3	81.65	777.78
Minimum price per unit (€)	0.53	36.66	523.79	610.91	6.50	2.32
% allowable reduction	30.1	94.9	48.3	86.7	94.7	84.5

Results from Table 4.3 shows that Scenario 1 (On-grid Prosumer) performed relatively better than scenario 3 and lastly scenario 2. This is because Scenario 1 presents more products which bring in more revenue as compared to the CAPEX and OPEX. On the other hand, the production of Scenario 2 produces lower economic returns with negative NPV. This is because the economic returns of the production process are not maximized. On the other hand, the production of AF&M alone also reduces the long-term income security of the model and exposes the plant to multiple solvency risks.

The LCOE is largely influenced by economies of scale. Scenario 3 generates the lowest quantities of electricity due to the use of the biomethane for fuel. Also, due to the production of AF&M, the internal demand increases and reduces the electricity revenues. However, it is relatively more feasible than scenario 2. Economies of scale is a basic concept for energy projects. In conclusion, it is recommended to diversify the products by incorporating key products such as pellets and compost. However, from the perspective of LCOE, all scenarios are above the BGC price at 100% debt financing. However, for Scenarios 1 & 3 since the NPV for the overall investment is positive, it is a more feasible and debts can be serviced. This is an indication of an investment that can be explored although LCOE is too high.

Table 4.3: Comparative results from technoeconomic assessment of the scenarios

Parameter	Scenario 1	Scenario 2	Scenario 3
NPV (€)	10,431,253.20	(299,843)	9,697,296.93
IRR (%)	24.6	8	23.5
LCOE (€/kWh)	0.57	0.310	0.691
PBP	13	18	14

4.3 Chapter discussion

4.3.1 An integrated circular economy concept for HWtE development

The categorization of products from the HWtE plant is an important output of this research study. This is because WtE studies in Ghana has been conventionally linked to electricity production or in some studies valorization of digestate (Table 2.6). However, incorporating the CE principles into the framework of WtE is largely an unexplored concept within the context of Ghana. From the detailed bibliometric study carried out on WtE research in Africa, it was concluded that trends are shifting towards CE solutions rather than single systems and projects (PAPER I). This also aligns with the waste hierarchy as proposed within the EU Framework directive. Material recovery must be explored before energy conversion.

Thus, an integrated concept is proposed which integrates resource efficiency and economic value (Figure 4.5). The first step involves active citizen participation in source segregation. Policy direction is required for law enforcement. Economic Instruments such as incentives, Pay-as-you-throw (PAYT) and landfill taxes. Also, Extended Producer Responsibility are required in Ghana for both local producers and importers of goods to actively involved in waste recovery and source segregation (El Bari & Trois, 2023). In Ghana, it has been proven through the plastic value chain that, placing an economic value on a waste product is enough incentive for source segregation. For instance, the Communal buy-back system has been successfully implemented by a private recycling company in Accra (Coliba) (Okai, 2020). However, challenges exist with the collection and transportation of waste. For instance, the local collection and brokerage of plastic is actively underway by the private sector and with the involvement of informal workers (Oduro-Appiah et al., 2019). The transportation cost associated with door-to-door collection of specific waste fraction is high. As such, innovative approaches are required to reduce the cost of waste collection. Overall, other components such as transfer and sorting stations may be vital in the value chain (Manteaw & Boachie, 2020).

The second component is the expansion of the already active recycling industry. The current recycling industry depends on post disposal separation from mixed waste. Lessons from the HWtE plant indicates that the recovered materials contain high impurities, which increases the operational cost and reduces the quality and economic value of the final product.

Once the materials cannot be directly recycled, fractions such as organics may be converted to energy or compost. Non-recyclable combustible materials such as plastics and paper also processed into AF such as RDF or used in pyrolysis plants for energy generation Linking this component with Figure 4.2, recovery of energy and fuel products must be explored. A cycle is created for the conversion of waste into new products. The integration of Solar PV and emissions reduction is vital in securing the long-term economic feasibility of such system.

In summary, proposed concept therefore consists of the following stages

- Recyclables are recovered
- Non recyclables are treated in a HWtE system (organics, combustible plastics, residuals)
- Solar PV supports energy generation capacity and economic feasibility
- Plant nutrients are recovered from organics through AD and composting
- AF are transferred to industries for onsite energy generation

Similar concepts have been proposed in developing countries. For instance, recovery of recyclable materials, conversion of fly ash to pavement blocks and carbon credits have been proposed for improving the CE concept for a waste incineration plant in Bantargebang (India) (Purwanta et al., 2022). The African Circular Economy Network for instances has supported over 500 CE case studies across the continent. Only countries have an active CE roadmap with a well-developed concept (Muzamwese, 2025). This demonstrates the relevance of such a concept which integrates several actors into a broad outcome.

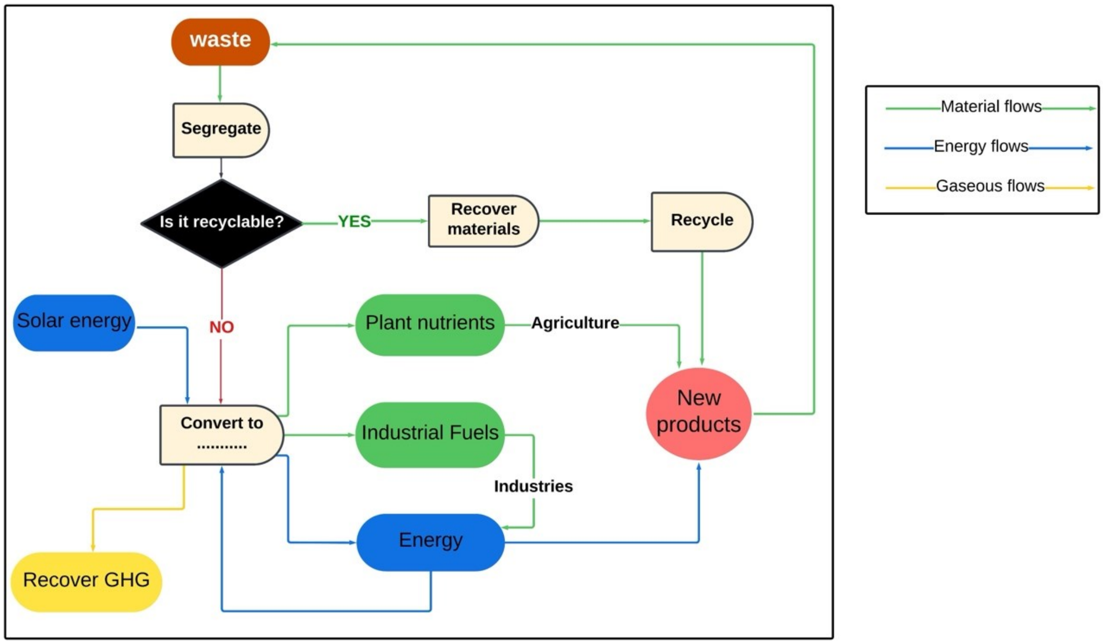

Figure 4.5: Integrated concept for strategic development of WtE in Ghana

4.3.2 Scenarios and achieving economic feasibility

As compared to the WROSE model, the scenarios extend to the business perspective beyond technologies or processes. The WROSE model prioritises achieving environmental sustainability and resource efficiency (Dell'Orto & Trois, 2022). Whiles this is important; in developing countries, governments and local authorities often do not have the financial capacity to implement CE concepts. Often the private sector or international financing is required. To the investor, the technology/ process must be financially sustainable (Williams et al., 2023).

This is confirmed by similar assessment comparing renewable energy projects in Ghana and Kenya. In Ghana, the high cost of finance is identified as the major factor affecting financial feasibility. Investors depend on international commercial finance or concessional loans due to the cheaper cost of finance as compared to the local lending rates of 21-37% as indicated in the study. On the contrary, public private partnership in Kenya has supported geothermal projects with concessional loans with debt rate of 3% and long maturity periods. This resulted in LCOE of 0.051 €/kWh as compared to the fossil generation at 0.107 €/kWh. In Ghana, LCOE for Solar PV projects showed a large difference based on the source of financing: commercial debt (0.254 €/kWh) and concessional (0.1 €/ kWh) (European Commission, 2024; Pueyo et al., 2016).

The results of the sensitivity analysis for the case study indicates that the amount of electricity exported and project financing are key to the financial feasibility of WtE plants in Ghana. In PAPER II, it is shown that grants/ subsidies are required to achieve feasibility. A similar argument is made in a study investigating the financial readiness and investment preparedness of 524 waste management companies in Ghana for green/CE financing. Specifically, the results reveal that the capacity of businesses to attract CE financing depends on internal financing policies and country-level investment environment including the country's economic performance (inflation, interest rates etc) and policies on taxes and subsidies. It is therefore recommended that businesses in the waste management sector get involved in strong alliances to influence country level policies (Agyapong & Tweneboah, 2023).

A detailed comparison of the technoeconomic feasibility of the scenarios indicates that incorporation of electricity exported to grid and the sale of AF&M is a more feasible model to ensure sustainable revenue streams and to maintain a realistic payback period to service loans. In Singapore, an investment decision was required on the most cost-effective and environmentally friendly city scale waste management strategy. A decentralized WtE project integrating AD, composting, gasification and incineration outperformed the total incineration of all waste fractions which was the business-as-usual (BAU) case. This is because multiple products are produced within the CE framework (Xiong et al., 2016).

Also, the decentralized model presented in that study could be explored by local authorities of city scale planning. Therefore, establishing a network of several large plants may improve the feasibility. For the city of Izmir in Turkey, a study considering the economic feasibility of large scale biogas plants showed that the installation of eight plants with a capacity of 92 MW is required to produce power at a feasible LCOE (Yalcinkaya, 2020). It has already been established that increasing the plant capacity to 1.6 MWh/yr will improve the LCOE to 0.0886 €/kWh (PAPER II). Larger scale plants reduces LCOE, by bringing in more revenue compared to capital and operational costs (Mukelabai et al., 2022).

If a capacity expansion is envisaged, the Solar PV system poses as a more preferred RE technology as compared to the WtE systems due to lower CAPEX and O&M costs. Based on 2023 global power generation costs published by IRENA, LCOE (€/kWh) of Solar PV is 0.041 as compared to 0.068 for bioenergy. Solar PV has been particularly pinned to continue in a downward cost trend due to high investment in research for higher efficiency products and lower production processes (European Commission, 2024; IRENA, 2024a). Also, in relation to the case study plant, the technology cost (CAPEX) in €/kW is lowest for Solar PV (1,050) as compared to AD (5,000) and pyrolysis (5,000) (PAPER III). Although Solar PV is not a WtE system, it also plays a role in reducing capital costs.

Examples of such hybrid renewable energy systems are already available in Ghana and require a business case to stimulate further investments. The HPW limited as an offgrid prosumer generates all its energy without grid connection through gasification, AD and Solar PV (HPW AG, 2025). On the other hand, the Safisana Plant can be described as an energy supplier since its main business is energy generation. It integrates AD and Solar PV (Agyenim et al., 2020). The offgrid energy prosumer model is common on a small scale for commercial business especially for Solar PV. However, as a larger WtE system, the off-grid prosumer may become an interesting model in Ghana when a reliable market for AF&M is well established. In South Africa, a study involving 21 biogas projects also identifies economies of scale as an influencing parameter for economic viability. However, the most recommended business model is the incorporation of generated energy and heat into onsite (or proximity) uses such incorporation into milling and dairy industries. It was also discovered in the study that multiple revenue streams provide greater financial stability for WtE systems (Gogela et al., 2017). All these are consistent with the results of this study on the case study plant, and it is therefore recommended for businesses in Ghana with significant organic waste generation to consider establishment of WtE systems.

4.3.3 The role of the state in developing WtE

The active involvement of the state in implementing policies to boost WtE development is required. WtE initiatives in Africa aim to develop sustainable solutions to address the unique challenges of developing economies. For instance; the German biogas industry is heavily subsidized by the state through policies such as the German Renewable Energy Act (2000) which makes provision for feed-in-tariffs and premiums to improve feasibility of investments (Thrän et al., 2020). On the contrary, low feed-in tariffs and a lack of incentives have been found to make implementation of industrial AD plants for local cassava starch processing economically unfeasible. This could have the potential to reduce the GWP of industries by 97% in seven African countries (Angola, Cameroon, DR Congo, Ghana, Malawi, Nigeria and Tanzania) compared to the use of fossils (Padi et al., 2022). Incentives are also required at the local level to promote social change towards waste management. For instance, in Tamale (Ghana) it was found that the reluctance of residents to waste segregation is linked to a lack of incentives such as appropriate bins and waste storage infrastructure as well as frequency of waste collection (Asare et al., 2021). It is therefore recommended that WtE business incorporate advocacy to influence policies that support their businesses.

5 NATIONAL HOTSPOTS FOR REPLICATION

This study is closely linked to the technical model of the pilot HWTE plant located in Atwima Nwabiagya Municipality of the Ashanti Region of Ghana. However, the overall purpose is to provide a basis for further expansion of the WtE sector in Ghana and particularly HWtE model. This chapter focuses on a national perspective beyond the pilot plant. The goal is to support decision-making by identifying priority areas within the country (hotspots) where the HWtE model can be potentially replicated. The technoeconomic and environmental assessment carried out previously is used as a basis for the assessment carried out in this chapter.

5.1 Multicriteria Decision Making Analysis (MCDA) for HWtE model in Ghana

The Multicriteria Decision Making Analysis (MCDA) is a structured process of making key project decisions through multiple criteria which are a priority to project developers. MCDA has been used extensively in WtE research and supports decision makers in selecting the most viable option when several criteria are involved (Vlachokostas et al., 2021). Several MCDA methods have been used for various studies in relation to WtE projects. These include ELimination Et Choix Traduisant la REalit´e translated as Elimination and Choice Expressing Reality (ELECTRE) (Dima et al., 2022), Analytical Hierarchy Process (AHP) (Hoang & Fogarassy, 2020), Simple Additive Model (SAM) (Vlachokostas et al., 2021) and Technique of Order Preference Similarity to the Ideal Solution (TOPSIS). Most of these MCDA approaches have also incorporated Geographical Information System (GIS) (Sambiani et al., 2023).

WtE related MCDA studies in Ghana have mainly been linked to selection of WtE technologies and sites for waste treatment facilities including landfills. For instance, AHP and GIS have been used to select a suitable landfill site for Tamale Municipality using criteria such as roads, rivers, settlements, slope and soil type (Ampofo et al., 2023). On the other hand, AHP has also been used to select the most appropriate technology from landfilling, incineration, AD and composting (Agbejule et al., 2021). Also, AHP-TOPSIS was used to select WtE technologies in Ghana; where AD and gasification was identified as the best applicable technologies using technical, social, economic and environmental criteria (Afrane et al., 2021, 2022). In another study, several hybrid technology combinations were compared to support adoption of renewable energy technologies by Small and Medium Enterprises in Ghana (Odoi-Yorke, Abofra, et al., 2022). The selection of biomass resources for the production of bioenergy production can also be assessed using Fuzzy TOPSIS approach (Ossei-Bremang & Kemausuor, 2021).

5.1.1 The AHP SAW- MCDA methodology

The Analytic Hierarchy Process (AHP) is one of the most used MCDA methods. It was first developed by Saaty, 1980 and has been used extensively as a standard methodology for complex decision-making within the MCDA context (Table 2.3). AHP generally follows six major MCDA stages: (1) identification of alternatives, (2) selection of criteria, (3) criteria weighting, (4) data normalization, (5) alternatives evaluation and (6) result validation. However, its uniqueness as compared to other MCDA methods is the pairwise comparison of criteria and weighted linear combination of selected criteria to rank the alternatives (Shao et al., 2020).

For this study the methodology is as follows. As a first step, the alternatives and criteria were selected. The data for these components were input into MS Excel. The decision matrix is developed for the criteria for pairwise comparison after which the matrix is normalized to arrive at the weights for each criterion. Next, the Simple Additive Weighting (SAW) is used for the ranking of alternatives based on the weights. SAW is also a widely used MCDA method which is applied after the selection of weights to rank alternatives.

The SAW methodology follows the process presented in Khoiry & Amelia, which evaluates and ranks alternatives based on multiple criteria by calculating a weighted sum of the performance of each alternative (Khoiry & Amelia, 2023). SAW method has been applied in various academic studies within the waste management and energy sectors. These include site selection for the waste management facilities such as landfills. SAW has also been used in combination with other methods such as Geographic Information System (GIS). Examples include the identification of a suitable landfill sites in Lorestan Province, Iran using SAW method and artificial neural networks (Mokhtari et al., 2016). A recent study proposed and Energy Security Index for West Africa using SAW. The following eight criteria and 24 sub-criteria were used: electricity access, affordability, investment, governance, suitability, reliability, security, availability and demand-side management. These studies show the versatility with the use of the SAW. SAW is relatively simple, straight forward and adaptive process and provides a valuable DST within the context of this study (Ofosu-Peasah et al., 2024). Table 5.1 below summarises the AHP-SAW process as applied in this study. The following sections detail the process.

Table 5.1: The AHP-SAW model used for the identification of HWtE hotspots in Ghana

Input	Process	Output
	Identification of alternatives, criteria and weights	• 115 alternatives (MMAs) • 4 criteria
Alternatives and criteria Data	Data entry (MS Excel)	• Data values
	Computation of weights (AHP)	• Pairwise comparision
	Normalisation	• weights
	Computation of weighted sum (SAW)	• Scores for MMAs
	Ranking of Alternatives and results validation	• Identification of the highest potential MMA
	Geospatial analysis (GIS)	• Geospatial map
	Decision making	• Hotspots based on project priorities

5.1.2 Alternatives for MCDA

Geospatial assessment of WtE potential and identification of hotspots was done using data linked to Ghana's administrative governance areas. Ghana is administratively sectioned into 16 regions at the top tier which is further partitioned into 261 Metropolitan, Municipal and District Assemblies (MMDA). The MMDAs are categorized according to population and level of development. Since waste management in Ghana is localized, the MMDAs are the local authorities in charge of waste management (Ministry of

Sanitation and Water Resources, 2020). The 16 regional capitals are located within either metropolitan or municipal assemblies due to their higher populations. The results of the 2021 Population and Housing Census provide details of the population demographics as well as waste management statistics. For the purposes of this study, identification of hotspots will concentrate on metropolitan and municipal areas which are termed MMAs; districts are excluded. Out of the 261 MMDAs, 114 of them have been demarcated as MMAs. This is because these areas have higher population, better infrastructure for waste collection systems which make them are more organized. (Ghana Statistical Service, 2022c). Alternatives as used in the MCDA analysis refers to each of the MMAs which are being compared to obtain the highest ranked MMAs (hotspots). The result are the ranked scores which indicate the MMA with the highest potential.

5.1.3 Criteria and linked sub-criteria

Four decision-making criteria for WtE decision-making have been selected based on similar studies as: technical, economic, environmental or social (Afrane et al., 2022; Agbejule et al., 2021). Afrane et al., 2021 used three technical criteria and ten economic criteria but did not consider environmental and social aspects. However, the expert judgements data revealed that within the technical criteria energy generation per annum was the top ranked whiles within the economic criteria, initial investment was top ranked (Afrane et al., 2021). This is consistent with another study which found the capital investment to be the major barrier to WtE implementation in Ghana (Osei-Appiah & Dioha, 2019). On the other hand, Agbejule et al. used the technical, environmental and socioeconomic criteria with weights determined by 10 experts. The technical combination of resources to the energy capacity is largely dependent on the priority of project developers.

Linking the studies above with the outcome of technoeconomic and environmental assessment previously carried out in this study, the following sub-criteria were selected for the analysis. The technical aspects of the project are highly influenced by feedstock composition leading to energy generation. Therefore, waste generation was chosen as the data input for the technical criteria. The economic feasibility on the other hand is primarily controlled by the project financing parameters, mainly the capital cost. The results indicate that the integration of Solar PV influences overall CAPEX and feasibility. Thus, the solar potential was chosen for the economic criteria. The environmental assessment indicates that the greatest potential environmental impact apart from global warming potential is on human and ecosystem toxicity. Thus, the population density is chosen as the input data for the environmental criteria. This is because densely populated areas are potentially more vulnerable to such environmental impacts as compared to sparsely populated areas. Finally, the social criteria are linked to the level of unemployment. Circular economies provide employment opportunities especially in the low-income category and in the informal sector. Establishing one WtE plant within a city creates value for disposed waste and creates a demand for both direct and indirect employment (Oduro-Appiah et al., 2019).

1. **Technical criteria:**

Although most MCDA studies relating to WtE consider technology selection as a major aspect of the technical criteria, in this study, the technical aspects are linked to the technical model of the HWtE plant and the proposed outcomes. However, the feedstock for an MMA (waste quantity) is subject to geospatial differences which constitute an important component of technical considerations as demonstrated in Figure 2.2. Thus, the waste generation per municipality is used as the technical sub-criteria.

For the broad national WtE hotspots, the population is the main factor influencing the quantity of waste generated within a geographical location. Since the last population and housing census (PHC) was conducted in 2021, the historical growth rate was used to estimate the population as of 2024. The population in each MMA is computed as indicated in PAPER IV.

$$P_n = P_b \times ((1 + g)^{(n-b)}) \qquad (1)$$

Where:

- P_n = population in the n^{th} year after the base year (b); in this case the $b = 2021$
- g = regional population growth rate (Ghana Statistical Service, 2022b).

Following the regional average waste generation presented by (Miezah et al., 2015), waste generation per capita is used to estimate the annual waste generation within each MMA. The quantity of waste is computed as follows:

$$Q_{p,n} = P_n \times Q_{gen/cap} \tag{2}$$

Where:

- $Q_{p,n}$ = quantity of waste in the n^{th} year by the population
- $Q_{MSW,n}$ = estimated quantity of waste generated by the population within the MMA in the n^{th} year
- $Q_{gen/cap}$ = waste generated per person per day (kg/cap/day)

In the detailed assessment of specific MMAs, detailed Material Flow Analysis (MFA) must be considered. Already existing waste management projects must be considered to avoid over estimation of truly available waste for future WtE projects. For instance, in PAPER IV, the waste available for future WtE projects by 2030 targeting the Greater Accra Metropolitan Area was conducted using MFA. Factors such as uncollected waste, demand of current large waste management plants and current waste recovery activities such as plastic recycling were considered. In this case, waste generation for the study areas is estimated as follows in

$$Q_{MSW,n} = \left(P_n \times Q{gen}_{/cap} \times \%W_{coll}\right) - \%W_{rec} \tag{3}$$

Where:

- $\%W_{coll}$ = percentage of collected waste within the MMA; The remaining is lost in open spaces, drains and burning
- $\%W_{rec}$ = proportion of collected waste recovered for recycling, composting or RDF by the existing composting plants and private recycling companies.

2. Economic criteria:

As shown in Chapter 3 the major parameters influencing feasibility is the CAPEX. The CAPEX is also influenced by the Solar PV system which is five times less than the AD and pyrolysis systems (PAPER III). The solar intensities gives an indication of the potential solar energy received at a particular location (Shao et al., 2020). The potential for solar energy was assessed using the Global Horizontal Irradiation Index (GHI). GHI represents the total solar radiation intensity incident on a horizontal surface such as solar panel. In Ghana, the five Upper and Northern Regions receive the highest solar radiation intensities (GHI) ranging from 2,018 to 2,082 kWh/m^2/annum. On the other hand, the southern areas experience ranges between 1,592 and 1,839 kWh/m^2/annum. The GHI data for each location was obtained from the Energy Commission's publication on the energy profile of districts in Ghana (Energy Commission of Ghana, 2019). Figure 5.1 provides a geospatial representation of this data. In effect, the solar potential of the MMA is used as the economic sub-criteria for the MCDA analysis.

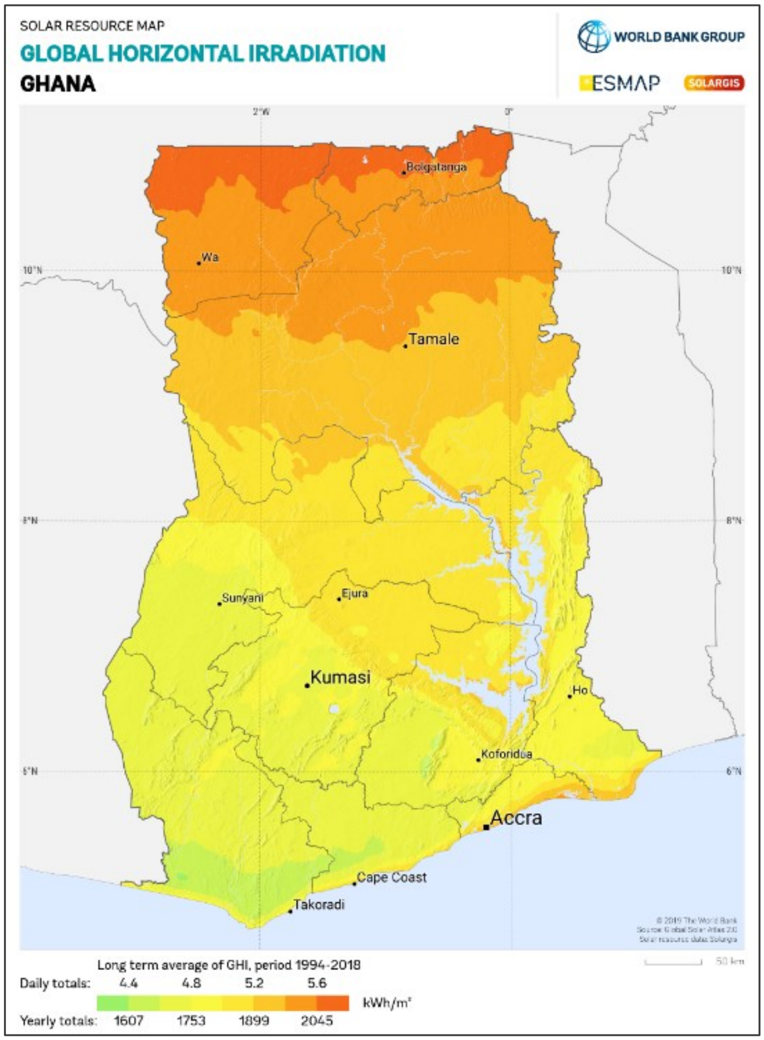

Figure 5.1: The solar resource map of Ghana according to Global Horizontal Irradiation (GHI) Index.

*Source: (Solargis, 2021)

3. **Environmental criteria:** The environmental impact of WtE projects cannot be overlooked. In PAPER V, the HWtE plant may have potential impacts in terms of human toxicity and ecotoxicity. The release of wastewater and heavy materials in digestate may potentially impact humans and the broader environment. On the other hand, considering the current dominant landfilling and open dumping option, a HWtE project can potentially have a more positive environmental impact. This can avert potential public health concerns associated with poor waste management. In a similar study in Ghana, public health protection was ranked highest by experts as an environmental criteria since WtE is perceived as a more sustainable waste management option (Agbejule et al., 2021). The sub-criteria considered is the public health risk which is measured by the population density. Population per square area determines the critical need for waste management infrastructure. As is the case in most developing countries, highly populated areas with higher densities are associated with more critical need for waste management infrastructure (Vinti & Vaccari, 2022). The environmental assessment of the HWtE plant as compared to the conventional landfilling indicates that the WtE plant reduces GHG by 3.52 tCO_2eq/ton of waste (PAPER V). Thus, this sub-criterion is linked to the positive impact WtE projects are likely to have in areas of critical need. The data input was obtained from the 2021 Census published by the Ghana Statistical Service (Ghana Statistical Service, 2022c).

4. **Social Criteria:** Job creation is one of the major social impacts of new projects. Thus, the unemployment data for each MMA is the sub-criteria for assessing the social aspects. Unemployment as used refers to a lack of consistent employment for the active population above 15 years of age. In effect, high unemployment rates within a MMA signals the high need for job opportunities and the high potential positive social impact such a plant may have. The data was obtained from the 2021 Census published by the Ghana Statistical Service (Ghana Statistical Service, 2022c).

5.1.4 Weights for the criteria

AHP requires the determination of weights through pairwise comparison of criteria. The process specified by Saaty 1990 and thoroughly detailed by Shao 2020 is followed (Saaty, 1990; Shao et al., 2020). The weights assigned to each criteria are adopted from two previous study results (Afrane et al., 2021, 2022). These studies used the same four criteria with weight determination from 10 experts through questionnaires. This was found to be satisfy the same objective of this study. The following weights were derived from the survey results: Technical (0.3947); Economic (0.2556); Environmental (0.1982) and Social (0.1536) (Afrane et al., 2022). The matrix for this study is therefore represented in Table 5.2. The consistency check shows a consistency ratio of 0.09 which is less than 0.10 showing the judgments are consistent.

Table 5.2: Criteria matrix showing assigned weights

Criteria	**Technical**	**Economic**	**Environmental**	**Social**	**Overall weights**
Technical	1	2	2	3	0.3998
Economic	1/2	1	3	2	0.2927
Environmental	1/2	1/3	1	3	0.1981
Social	1/3	1/2	1/3	1	0.1093

5.1.5 Computation scores for ranking of alternatives

Consequently, all data linked to the 114 MMAs, four criteria and weights were imported into MS Excel. The ranking for each of the alternatives (MMAs) was computed using the process as detailed in equations 4 and 5 below:

$$S_i = \sum_{j=1}^{n} w_j \times x_{ij} \quad (4)$$

Where,

- S_i = Total score for alternative *i*
- w_j= Weight of criterion *j*
- x_{ij} = Performance value of alternative *i* for criterion *j*
- n = Number of criteria

The input data was normalized for each criterion, and the scores were computed using the following Equation 5:

$$S_i = \sum_{j=1}^{n} W_j \times Z_{ij} \quad (5)$$

Where,

- S_i – Overall score for alternative
- W_j = Weight of criterion j
- Z_{ij} - Normalized value of criterion j for alternative i
- n – Number of criteria

The MCDA results are assessed based on the ranking of scores. The top highest ranking (20 MMAs) is presented in Figure 5.2 The Greater Accra and the Ashanti Region dominate with high potential. This is due to higher population which is linked to waste generation. Although the Northern regions seem to have higher GHI, overall scores are low due to lower waste generation and population density (Figure 5.1). Although the Greater Accra region is located in the south of the country, the largely urban settlement with low vegetation cover results in a higher solar potential as compared to the middle zone of the country where the Ashanti Region is located (Energy Commission (Ghana), 2023). The Ashanti region has a high population with high densities in the Kumasi Metropolitan Area and Old Tafo Municipality. Sekondi-Takoradi Metropolitan Area is also an important hotspot due to its relatively high population. This confirms that metropolitan areas are an important hotspot for siting future plant considering the four criteria used.

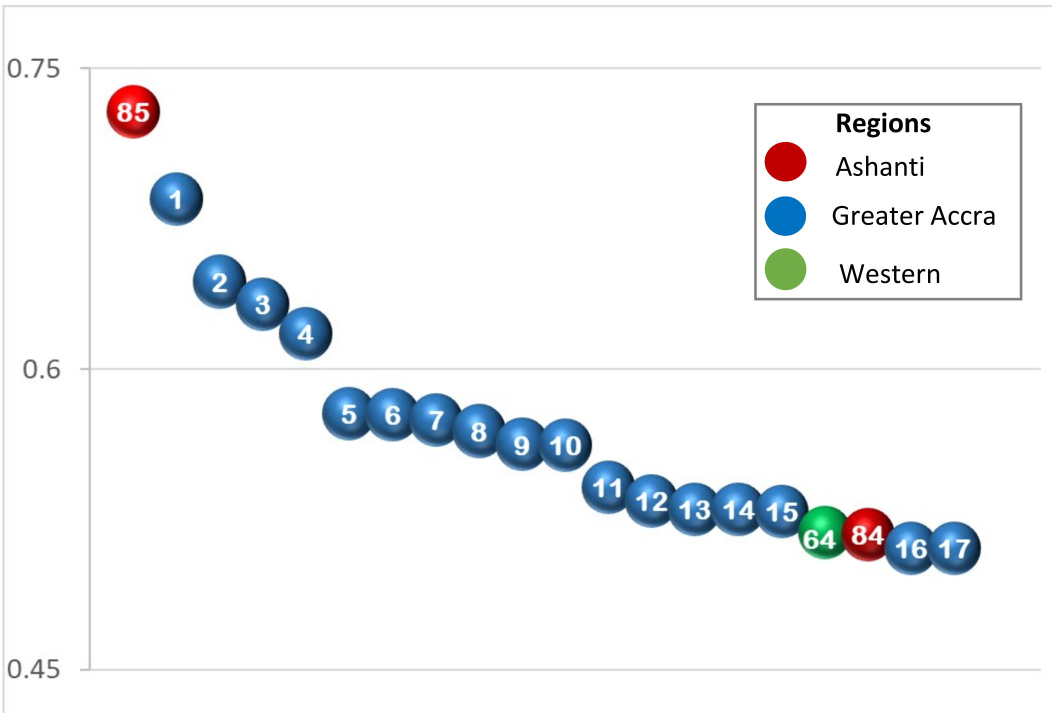

Figure 5.2: Regional location of the highest ranking 20 MMAs according to the relative scores.

* Detailed label numbers represent MMAs which are shown in

Table S.2.

5.1.6 Geospatial visualisation

The scoring data was exported into ArcGIS Pro software to visualize the geospatial representation of the ranked scores for the selected alternatives (MMAs). All MMAs were assigned the respective weights in the attribute table. The districts were assigned a null value because they were not considered in the study. Figure 5.3 shows the output map. Each of the MMAs were given a numbering code (Field ID) to enhance visualization which is detailed in

Table S.2.

Considering the population dynamics and the GHI index of the country, the Greater Accra Region is strategically positioned for HWtE plants with strong integration of Solar PV. Following that, Sagnerigu Municipal and the Tamale Metropolis are attractive locations in northern Ghana. Following this result, a detailed modelling of a future WtE plant was carried out for Greater Accra region (PAPER IV).

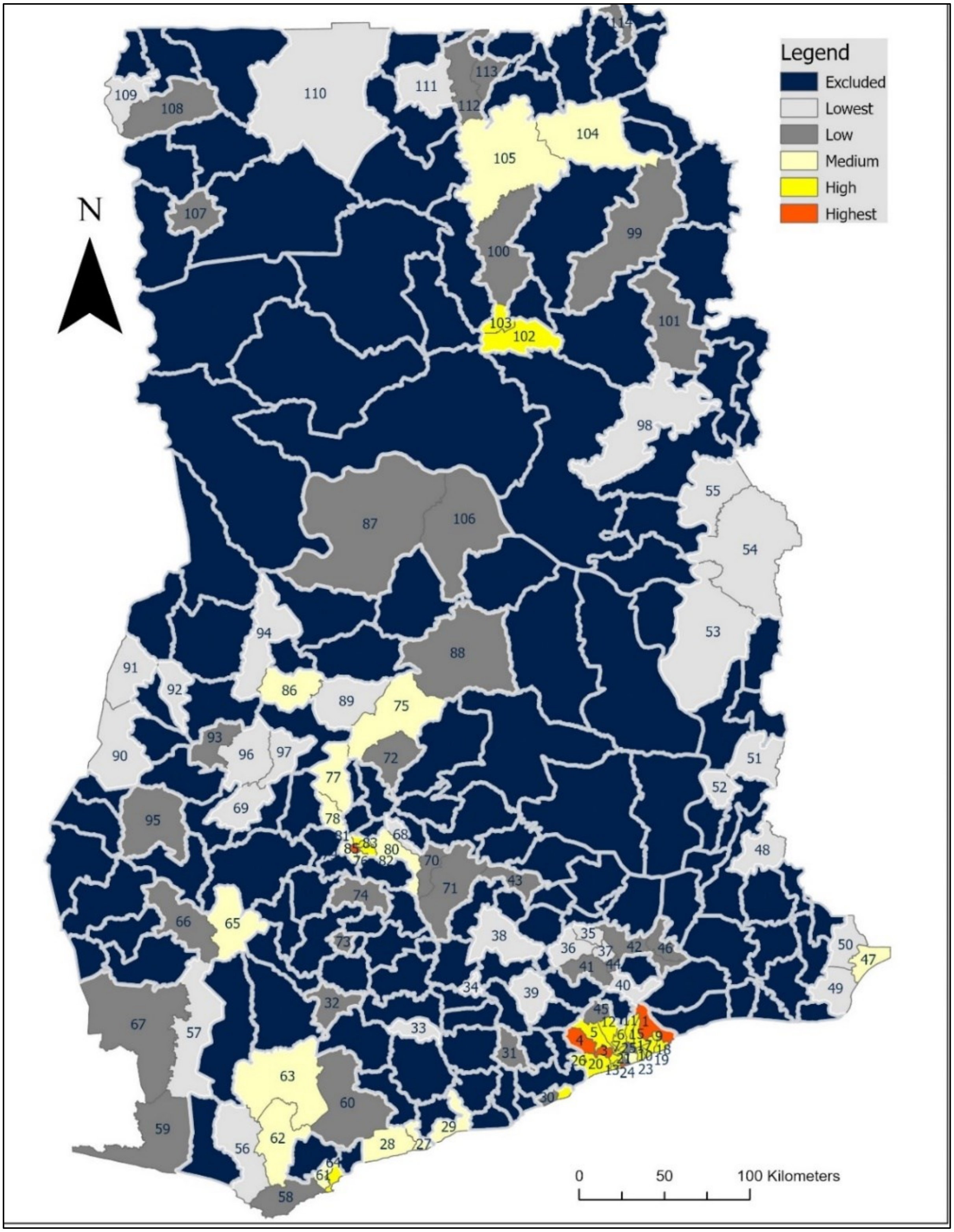

Figure 5.3: HWTE hotspots for Ghana based on MCDA decision-making process

* Detailed label numbers represent MMAs which are shown in

Table S.2.

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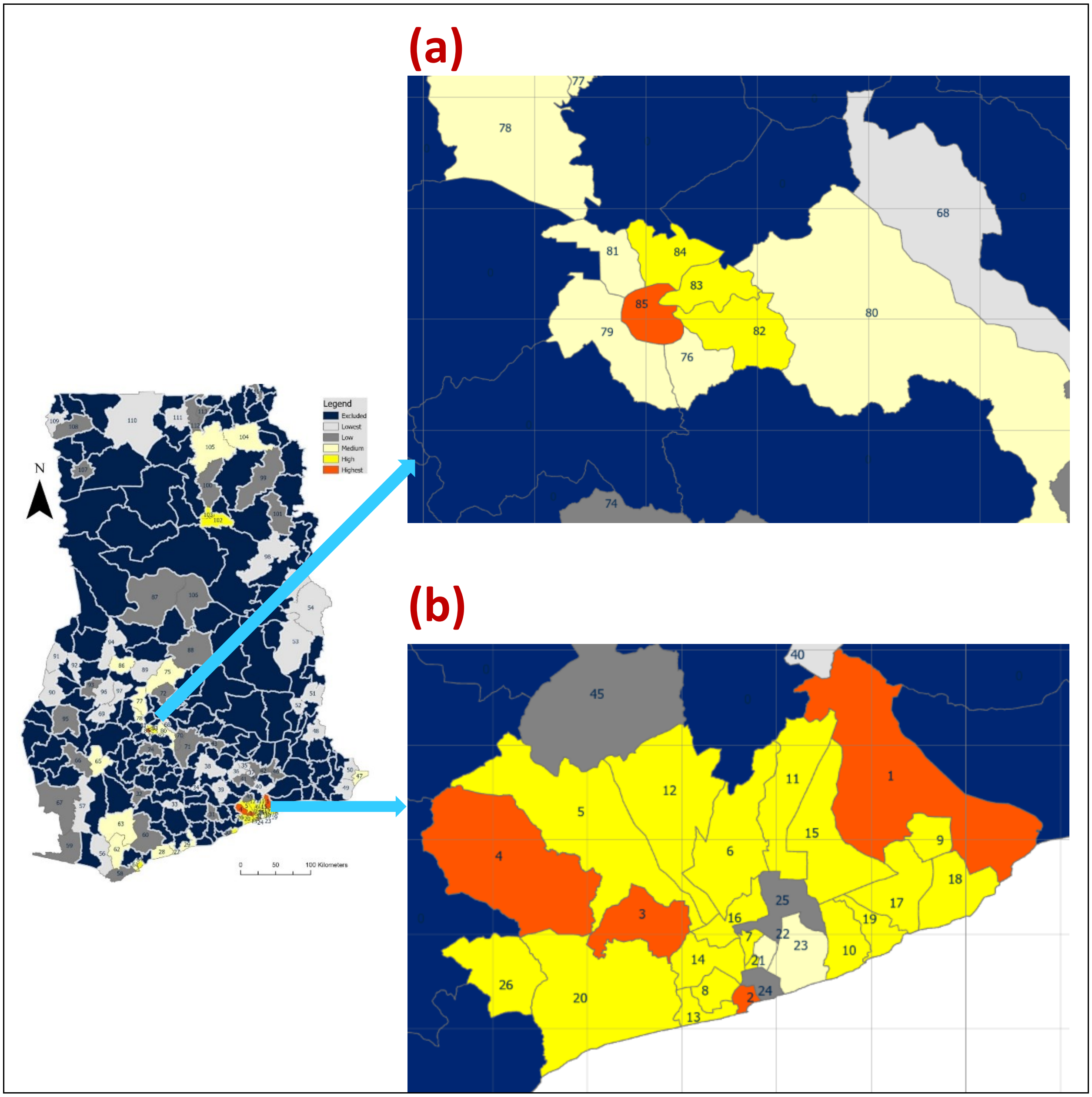

Figure 5.4: Detailed maps for (a) portions of Ashanti region and (b) Greater Accra region

* Detailed label numbers represent MMAs which are shown in

Table S.2.

5.2 Regional analysis of hotspots

5.2.1 Regional waste composition

The technical aspects of WtE are dependent on the technology and the feedstock. One of the proven aspects of decision-making is the selection of the technology which relates to the energy output and revenues. The availability of a single study characterizing waste across the country is lacking. Therefore, waste characterization data from various sources were aggregated Table S.3. For each region, a relevant study which provided primary data was selected.

The results indicate that the largest proportion of waste is the organics, followed by the plastics and residuals. This is consistent with all areas across the country. This can be attributed to the heavy reliance of Ghanaians on the transportation of raw food and other agricultural products to the customer and marketing centers. Thus, large quantities of potential biomass materials such as cassava, plantain and yam peels are retrieved at homes (Azasi et al., 2020). The IEA estimates that 20-50% of post-harvest losses occurs in SSA due mainly to a lack of cold storage facilities. This also accounts for large quantities of post-harvest losses recorded in Ghana. According to Ghana's Agriculture Sector Report (2020), the low availability of storage and warehousing accounts for the high postharvest losses (GIPC, 2022). In a broader framework, WtE could be reducing post-harvest losses by redirecting energy for cooling chain. This presents an opportunity for project developers focusing on processing of agricultural produce to integrate WtE systems such as the HPW plant (prosumer model).

As indicated in Table 2.2, the biochemical technologies include AD, LFGTE and compositing whiles thermochemical technologies include incineration, pyrolysis and gasification technologies. The main resources for biochemical assessment are the organic waste, also known as the organic fraction of Municipals Solid Waste (OFMSW). Within the CE framework, recyclables must also be considered. The plastic components may be directed to recycling or pyrolysis. Residuals include paper, leather and some plastics.

Although this study focused on the organic fraction of MSW, other forms of organic waste may be explored. This includes agricultural residues, such as cocoa husks, oil palm biomass, and palm kernel shells. It has been estimated in Ghana that 20 million tonnes of crop residues are available for energy generation per year as compared to 2.1 million tonnes of MSW (Kemausuor et al., 2014). Also, animal manure, energy crops, were have been showed to have the higher ranking in terms of bioenergy production as compared to MSW, forest and crop residues. However, challenges with the aggregation of these wastes were identified (Ossei-Bremang & Kemausuor, 2021). In a study in Turkey, the co-digestion of animal manure and MSW was found to be effective in achieving economic feasibility. The study also demonstrated that a minimum of eight decentralised biogas plants presents a feasible model due to economies of scale. Thus, a more detailed national waste resource assessment is required for future plants. Figure 5.5 presents the regional potentials for organics, plastics and residuals for RDF.

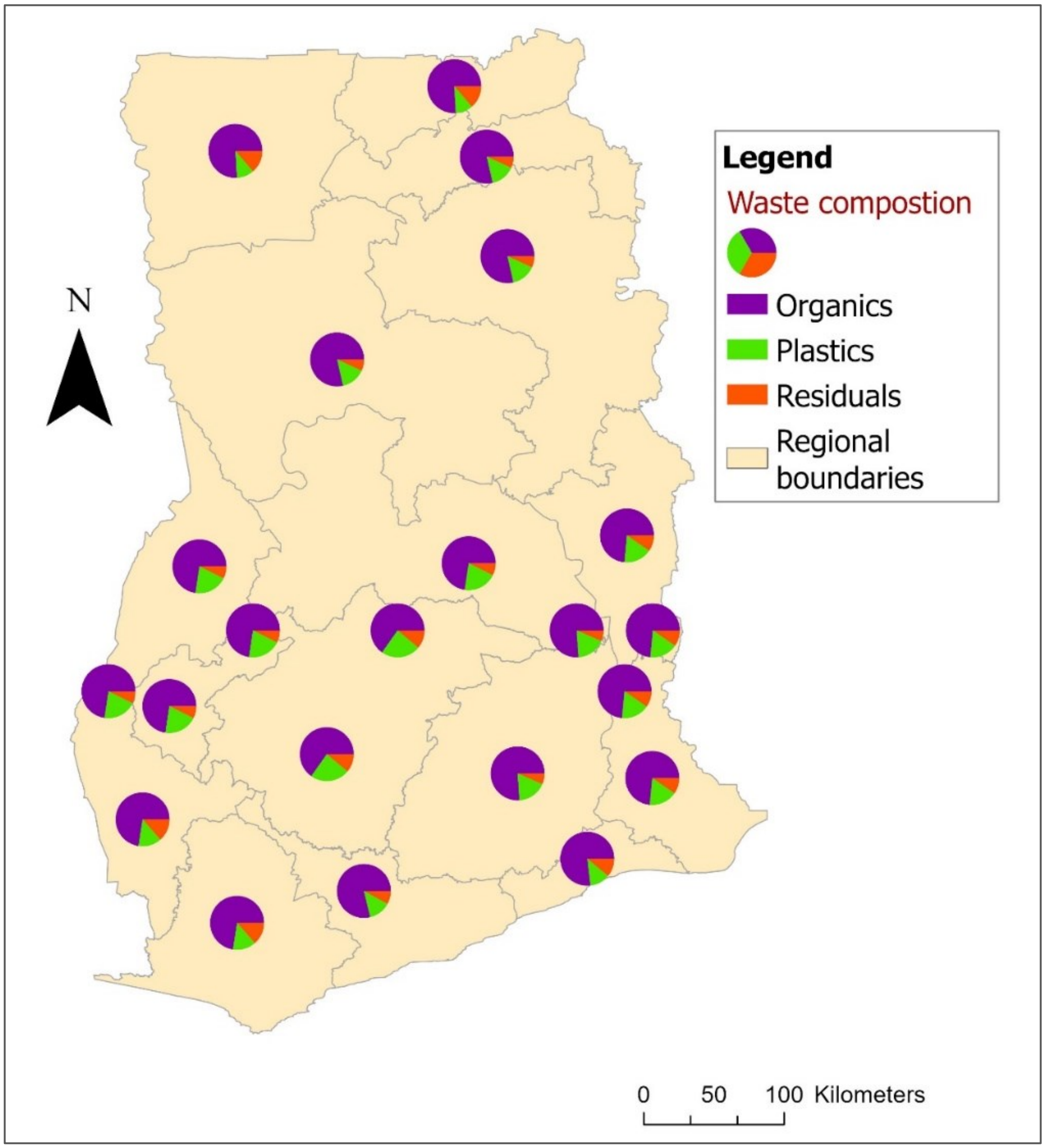

Figure 5.5: The potential for biochemical or thermochemical technologies based on regional data on waste composition.

*Sources and data: Table S.3

5.2.2 Industrial hotspots for marketing of AF

The manufacturing industry is one of the major potential customers to any upcoming WtE plant which aims to produce AF such as RDF, RFO, bio-CNG and hydrogen. The Ghana Industrial Census provides data on the manufacturing industries on regional basis. This has been geospatially represented in Figure 5.6. The Greater Accra region is particularly an attractive location for industries due to its proximity to the port of Tema. Also, Tema has been strategically developed since the 1960s as an industrial town and is equipped with several supporting infrastructures for industrial development. Secondly, the Ashanti region is the most populous region in Ghana and attracts mainly wood processing and agricultural centers (GSS, 2006).

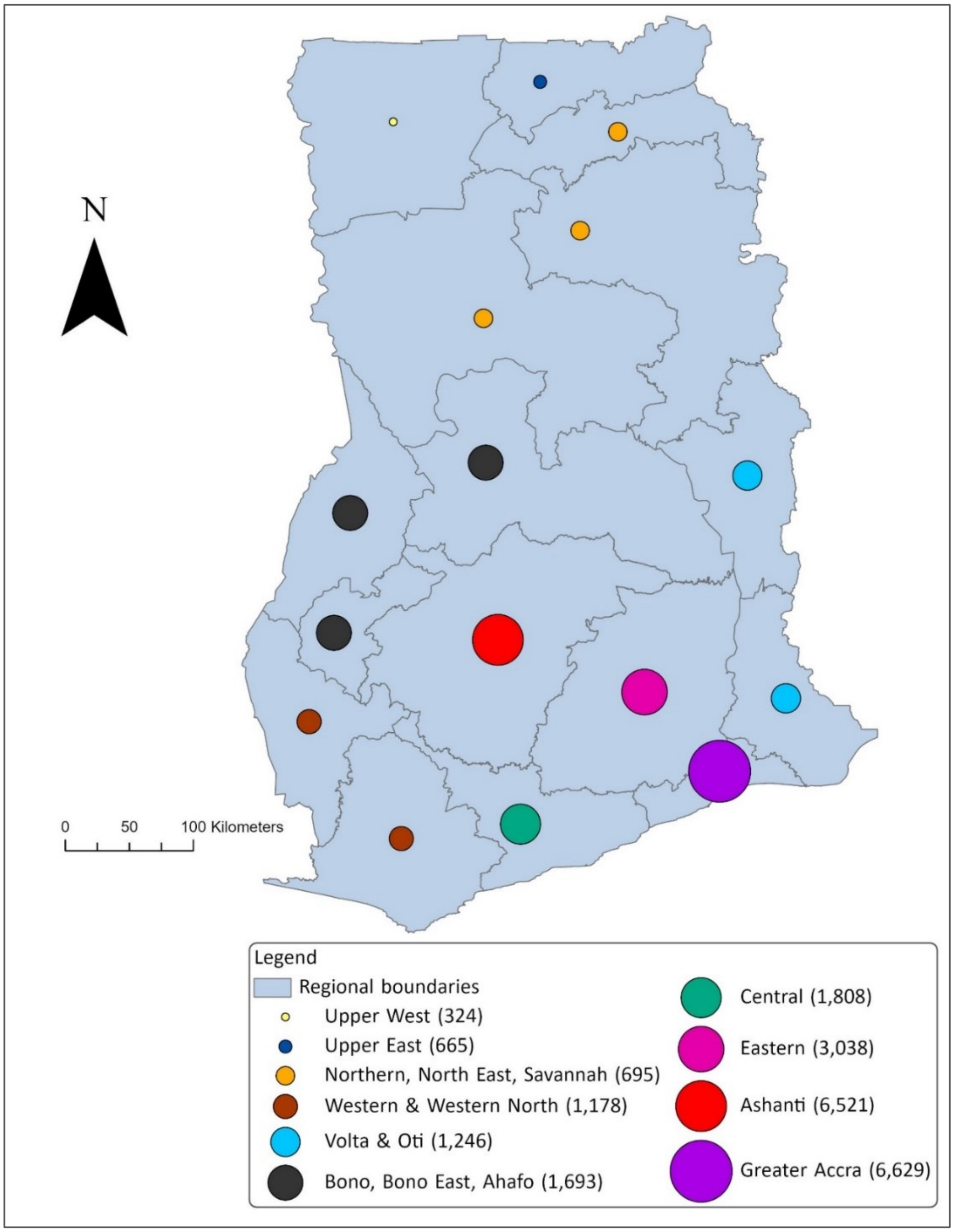

Figure 5.6: Number of industries per region indicating the location based potential demand for AF.

*Data source: Ghana Industrial Census (GSS, 2006)

5.3 Chapter discussion

This chapter evaluates the use of multiple criteria to select hotspots for HWtE implementation in Ghana. According to the selected criteria and alternatives evaluated, the most attractive locations are in the coastal regions of Greater Accra and Western Region and the Ashanti Region in the Middle belt. These are strongly linked to the joint impact of urbanization and high population which also affects waste generation and composition. The Greater Accra region has similar population as the Ashanti Region. However, the two regions differ in their vegetation coverage and their direct normal solar irradiation received. The Greater Accra region is geographically located within the coastal savannah vegetation zone. This means there is less diffuse horizontal irradiation as compared to the Ashanti Region which is located within the forest zone and has lower direct normal irradiation (Energy Commission of Ghana, 2019).

Generally, the urbanization dynamics in Africa means that in the next decade, waste management infrastructure are is a critical planning need (OECD, 2025). In PAPER IV the HWtE model is applied to an urban area (the biggest hotspot), the Greater Accra Metropolitan Area. The expanding population has resulted in the built-up area almost doubling between 2008 and 2017. This demonstrates the critical role that WtE may play in waste management and attaining the circular economy.

In PAPER IV, a Material Flow Analysis is conducted to assess the potential for various waste components from the mixed waste stream arriving at the proposed facility. The location affects the waste composition and ultimately the technical and products model. This is linked to Figure 5.5 which assess the potential for thermochemical or biochemical technologies. Many studies have attempted to propose various technical models to handle various waste compositions in Ghana. For instance, a LFGTE plant integrated with Solar PV is proposed for the Oti Landfill site in Kumasi (Asante et al., 2023). Several studies have used MCDA for the selection of the most appropriate technology for WtE (Adu et al., 2025; Afrane et al., 2021). However, in the use of the HWtE model, this study proposes that the selection of the technical model should be based on a Products model. Scenario analysis should be used in the feasibility assessment.

The decision-making process for MCDA allows for multiple outcomes based on selected criteria and input data (Shao et al., 2020). The MCDA should be used after the business model has been clearly evaluated using the products as described in Chapter 4. For instance, for a project seeking to prioritise the sale of compost to farmers, the location for waste feedstock and the location of demand centers must be prioritized. On the other hand, the proximity to coastal ports may be a priority for products which may be targeting international markets such as hydrogen. Also, another project seeking to prioritise job creation may assign higher weights to employment criteria. For instance, the Upper East, Upper West, Volta and Northern Regions have the lowest employment rates which compares to 5-10% of the employed persons in the Greater Accra Region (GSS, 2017). In effect, the priorities of the project may present varied hotspots for decision making.

To link Figure 5.6 with the hotspots in Figure 5.3, the marketing of AF is strategically located in the same hotspots. Specific products models and technologies may be associated with specific industrial hubs. For instance, RFO and RDF may be an attractive fuel options within the SUAME MAGAZINE industrial enclave in Kumasi. In a study to assess alternative energy sources, 82.5% of respondents were willing to adopt alternative sources of energy. This is due to unreliable supply from the national grid and the high cost of energy. Energy has been identified as the highest ranked challenge among Ghanaian industries. The penetration of the market in such industrial enclaves also reduces the operational cost due to transportation (Owusu, 2010).

According to the National Greenhouse Gas Inventory, the energy sector is the largest GHG emitter, contributing 45.7% (59.8MtCO_2e) to Ghana's total GHG emissions. This is due to the overreliance on thermal combustion of fossil fuels for energy generation. Also, solid waste disposal contributed 38% of GHG within the waste sector. This is mainly from landfill sites (EPA Ghana, 2022). This means that with the increasing population and urbanization, the implementation of WtE will significantly contribute to the country's efforts to advance its development agenda sustainably.

CONCLUSION & RECOMMENDATIONS

Trends in WtE research in Africa show a growing interest in circular economy solutions rather than stand-alone systems. This study begins with the assessment of the feasibility of the HWtE plant as a case study. Further to this, the strategy for replication is presented as scenarios and using MCDA to identify hotspots. This entire process entails a business case for potential investment decision-making.

The technoeconomic assessment of the case study plant indicates that although the metrics such as NPV and IRR show a potentially feasible project, the energy production cost is too high as compared to the current tariffs within the energy sector. With the energy sector in Ghana dominated by about 60% supply from thermal power plants which rely on fossil fuels, negotiations for a PPA for a potential WtE project must incorporate the potential environmental gains into determined tariffs. However, project developers must target incorporating significant local or international grants or subsidies into the project financing structure to improve the energy generation cost. In the technical designing, the incorporation of Solar PV is crucial to ensuring feasibility. Economies of scale should also be explored. The current promotion of WtE plants should go beyond schools and institutional systems to larger scale plants with well-integrated waste collection and segregation systems to improve feasibility.

Alternative fuels and materials (AF&M) also have the potential to contribute significant revenue to the overall revenue model. It is especially important to focus on plastic pelletising, compost production and RDF. Decisions on the final products of AD (electricity, bio-CNG or hydrogen) depend on a comparative economic feasibility and the market dynamics (such as availability of offtakers and cost of supply). Hydrogen is particularly a new product which may be attractive to inorganic fertilizer producers. A significant budget must be made for marketing and transportation since these are relatively new products on the market. Within the CE context, the implementation of this model in Ghana will require the strong integration of supply chain and logistics management through waste brokers and AF&M offtakers in Ghana. A large-scale operator with the capacity to develop a strong distribution network will enable the easy access and supply to industries and end users.

For the purposes of potential future implementation, the project financing, products and scale must be carefully considered. Three business model strategies are proposed: On-grid Prosumer, Supplier and Off-Grid Prosumer. The integration of energy and AF&M products is the most feasible strategy. The On-grid prosumer (Scenario 1) utilises part of the energy generated to internal operations including the production of AF&M whiles a part is exported to grid. The on-grid supplier (Scenario 2) generates electricity as a sole revenue product to grid. The off-grid prosumer (Scenario 3) converts all energy into AF&M production with no grid connection. Based on the internal energy demand of all the onsite systems, all generated electricity can be internally utilized by the plant without the need for grid transfer; howbeit with a higher LCOE. This scenario is particularly relevant when a PPA cannot be secured. Scenario 1 also provides the secure investment model by providing a base revenue through a PPA whiles also trading AF&M. As has been demonstrated, increasing plant capacity can potentially improve the LCOE. Once the marketing and market entry challenges have been surmounted, incorporation of AF&M into WtE business models is a sustainable option.

The environmental assessment focused on the comparison the processes as well as the avoided emissions from the AD, pyrolysis and RDF and segregation systems. The pyrolysis system showed lower environmental impact due to the production of char which has the potential to sequester carbon. Also, there is a high potential impact for human and ecosystem toxicity categories which require incorporation if risk mitigation measures. This is especially a potential hazard since the mixed waste in Ghana contains waste materials such as batteries which can leak its contents into waste. The plant must incorporate strict adherence to internal quality control measures to avoid potential human and ecosystem toxicity. Also, the estimated carbon savings of 3.52 tCO_2eq/ton will require strict standards and certifications to benefit from potential grants and incentives which may improve profitability and attractiveness. From the policy viewpoint, policies on waste segregation are needed to support the proposed scenarios. The presence of large fractions of inerts in mixed waste impedes the technical aspects of WtE systems.

The selection of the hotspots for future plants reveals that the capitals of the coastal regions of Greater Accra and Western Region are areas of interest, The Ashanti region is an attractive location in the middle belt of the country. Although the Northern regions have high incident solar radiation, their low populations make them unfavourable for HWtE plants. However, decision making methodologies focusing on criteria such as increasing clean energy access and reducing unemployment may find the Northern regions an attractive location for siting such system. The dual role of increasing population and urbanization influences the attractiveness of the location. However, these same locations have the highest density of industries which make them attractive locations for AF demand. Overall, MCDA is a proven methodology to determine the hotspots for siting of future plants depending on the interests of project developers.

Recommended strategies for implementation

- Pilot phase is required to test the market: For planned large scale projects, introduction in phases may be more beneficial to protect investments.
- Infrastructure: Investments in sorting, preprocessing, and material recovery systems are needed to ensure consistency in fuel quality. One of the major challenges associated with the adoption of AF for industrial applications is the inconsistency in quality. Quality control measures must be followed to ensure continued access to markets.
- The technical model may be altered. For instance, an onsite gasification system may be incorporated for additional energy recovery from RDF to enhance the energy output for the supplier model.
- Careful selection of plant location: This is required to ensure proximity to both markets and waste sourcing centers. The use of MCDA is recommended.
- Storage system: Large onsite storage is required for feedstock to mitigate potential inconsistent supply.
- Incorporation of local human resource: To avoid public outcry and backlash, it is important to engage local stakeholders and incorporate local human resource into the project team. This provides a sense of ownership and reduces conflict.
- Local licensing and approvals may bloat project implementation timelines. This should be incorporated in debt repayment plans.

Recommendations for future studies

- Detailed and up-to-date waste generation and composition data is needed. The work of Miezah et al., 2015 is 10 years old but is still extensively used as the most comprehensive data on nationwide waste generation and characteristics with a single unified methodology. The varied terms for organic waste such as biodegradable waste and fermentable waste requires clear definition since it is not clear whether organic waste includes waste types such as wood, faecal matter, soft paper, food waste etc. It is therefore important for researchers in Ghana to generate a universal definition of terms on waste composition to guide future research. Such definition of terms is contained in the EU framework Directive 2018/851 and may guide such an exercise (European Parliament and Council of the European Union, 2018). National agencies such as the Environmental Protection Agency may be a key stakeholder in delivering such a document.
- Trade flows analysis is required for all proposed products to ascertain the networks, routes, direction of flows, trends and flows, hotspots and clusters and supply chains.
- It is recommended that the toxicity content of locally produced compost from biodigestion of the organic fraction of MSW must be investigated to avert ecotoxicity concerns.

- It is recommended to investigate the potential for establishing technology enabled supply chains which involves aggregators, storage centers, transportation. Modern technology AI systems incorporating blockchain technologies may be a subject of future studies in the development of bioenergy supply chains.

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- The proposed hybrid waste to energy model (HWtE model) consists of the following components
    - Treatment of multiple waste streams (organics, plastics, residuals, digestate)
    - Multiple WtE technologies such as AD and pyrolysis systems
    - Solar PV system

- Within the context of the HWtE model the major product categories are energy, alternative fuels and materials (AF&M). The following products may be explored:
    - Energy : electricity, heat
    - Alternative Fuels : RDF, hydrogen, bio-CNG, RFO
    - Materials : compost, recyclables (plastics, scraps etc)
    - Others (potential) : emissions, laboratory

- Three business models can be explored by project developers based on the intended use of the energy generated. These are:
    i. On grid prosumer : generates energy for internal production of AF&M and exports excess energy to grid.
    ii. On grid supplier : generates energy for only grid supply
    iii. Off grid prosumer : generates only energy required for internal consumption for AF&M production

- The feasibility for projects are strongly influenced by the following parameters:
    - Project financing model
    - Products model
    - Scale/ capacity

- Feasibility can be enhanced by the following:
    - Larger capacity plants with energy generation at a minimum of 1.6 GWh/yr
    - Integration of larger capacity of Solar PV as compared to WtE systems. Although Solar PV is not a WtE technology, its role is financial rather than technical. It contributes to the reduction of the capital cost per kW of the total installed capacity
    - Incorporation of local tax reduction and subsidies such as tax holidays, tax exemption on importation of equipment and international grants and carbon markets
    - Multiple products rather than a single energy product

- MCDA methodology supports the selection of the hotspots for future plants. Based on technical, economic, environmental and social criteria, the Greater Accra and Ashanti Regions are the most attractive locations. MCDA supports various project priorities based on the selected criteria.
    - The Greater Accra Region is especially important due to high population, high population growth rate and urbanisation as well as high Global Horizontal Index (GHI).
    - Regions and municipalities with industrial hubs are attractive locations for AF.
    - The coastal regions are strategic location for products targeting on international markets.

- Environmental impact of the model of the case study WtE plant is significant; with carbon savings of 3.52 tCO_2eq per ton of waste treated compared to conventional landfilling. The following are to be considered:

- Carbon credits may bring in significant additional income once environmental protection measures are incorporated, local and international standards and regulations are met, and savings can be proven.
- Among the two WtE technologies, the technical design of the Pyrolysis system is the more environmentally friendly due to the development of a new product (fuel oil), its dependence on its own energy cycle, and closed system which reduces release of emissions.
- Apart from carbon emissions, human and ecosystem can be severely impacted by the activities of the WtE plant through toxicity levels. Directly, this includes contamination from release of liquid waste and digestate. With the conversion of digestate to compost, contaminants may be transferred into the food chain.

- For the integration of HWtE into circular economy in Ghana, the proposed circular model ensures:
    - Recyclables are recovered
    - Non-recyclables are treated in a HWtE system (organics, combustible plastics, residuals)
    - Solar PV supports energy generation capacity
    - Plant nutrients are recovered from organics through AD and composting
    - AF are transferred to industries for onsite energy generation

- There is a general lack of up-to-date locally available data on several aspects. Projects must commence with pilot systems and preliminary data collection.

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Personal Information

Name	:	Ekua Afrakoma Armoo
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Education

10.2021 – Present	Doctoral candidate - University of Rostock • Title of Thesis: Developing an economically viable business case for the development of hybrid waste to energy projects in Ghana.
10.2015 – 9.2017	Postgraduate studies- Technical University of Darmstadt Study Program: Tropical Hydrogeology and Environmental Engineering (TropHEE) (MSc) • Master dissertation topic: Reuse of Domestic Greywater: technical and financial feasibility study as a sanitation improvement strategy for Ghana.
7.2006 – 7. 2010	Bachelor studies- Kwame Nkrumah University of Science and Technology Study Program: Environmental Science (BSc) • Bachelor dissertation topic: The effects of anthropogenic activities on the water quality of River Wewe.

Work experience

3.2019- Present	Council for Scientific and Industrial Research Ghana - Institute of Industrial Research (CSIR-IIR) - • Projects Coordinator – Project and grant sourcing, project implementation and general research in circular economy and waste-food-energy nexus

3.4.2018 – 2.2019	Institute of Sustainable Energy and Environmental Solutions (NGO) • Senior Programs Officer – Water, Sanitation and Hygiene (WASH) – Project sourcing and strategic partnerships, facilitation of training programs and technology deployment
9.2016- 3.2017	German Federal Institute for Geosciences and Natural Resources (BGR) and Technical University of Darmstadt • Research Intern – Project “Groundwater for Northern Namibia (Cuve Waters)” – Geophysical logging using Gamma Ray Spectrometry and Magnetic Susceptibility to identify trends of geological deposition of sediment for aquifer formations.
10.2010 – 8.2011	Tema Metropolitan Assembly (T.M.A) - Waste Management Department • Waste management coordinator Solid waste collection coordination and coordination of maintenance works on the Central Sewerage System of Tema

Place and date: Rostock, 17.04.2025

ANNEX 1: BOOK CHAPTER 1 (PAPER I)

Bibliometric study of trends in waste to energy research in Africa.

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Abstract

"Waste-to-energy" (WtE) has been historically associated with incineration. However, this term has taken on a broader connotation and encompasses currently any processing method that generates energy or alternative fuels from waste. In this chapter, two articles conduct systematic reviews on WtE, one aiming at research in the management of municipal solid waste in Africa, while the other aims to promote the potential of emerging WtE generation technologies and innovations. The other articles research the background narrative for the "Hybrid Waste-to-Energy as a sustainable solution for Ghana" project, funded by the German Federal Ministry of Education and Research. The analyses provide a true reflection of the waste generation vis-a-vis collection models and their potential for energy generation in Ghana. These analyses could be used to replicate the model for similar communities in other countries. The research also focuses on effective WtE plant operationalization and acceptance. Capacity building and basic education play a vital role in enhancing the waste segregation and treatment, reducing the burden on waste management. Publicizing/disseminating the net social and economic benefits to the target communities should create additional benefits. The chapter is concluded with case specific business model based on a newly built WtE plant in Ghana.

Keywords

Municipal Solid Waste, MSW, Waste to Energy, Energy from Waste, bibliometric analysis, Africa

1. Introduction

The World Bank estimates that global waste production has increased by nearly 70% and is expected to rise to an estimated 3.4 billion metric tons per annum by 2050 if the current average daily generation rate of 0.74kg per capita continues, mainly due to increasing population growth, urbanization, economic expansion and changing consumer purchasing patterns (Silpa et al., 2018). The waste sector is the third largest contributor (20%) to global anthropogenic methane emissions largely originating from landfills and thus critical to the climate crises (United Nations Environment Program and Climate and Clean Air Coalition, 2021). To mitigate and adapt to the impacts of increasing global emissions, many countries have developed action plans known as the Nationally Determined Contributions (NDCs) under the Paris Agreement to meet the 1.5°C global warming target by the end of this century (United Nations Framework Convention on Climate Change, 2022). The European Union has taken bold steps towards mitigation through the European Green Deal; with a target to become the first climate-neutral continent by 2050 and slash greenhouse gas emissions by 55% compared to 1990 levels. Sustainable resource management will play a vital role in achieving this target. (European Commission, 2020).

Although most developing countries are signatories to the Paris Agreement and have gone ahead to develop their NDCs, countries in Africa are lagging in both research and the implementation of sustainable solutions to its complex waste management challenges (Ndou & Rampedi, 2022). One of the major challenges with waste management practices in developing countries is that waste is treated as an item to be disposed of in a linear consumption-to-disposal model rather than a circular resource recovery model (Sillanpää & Ncibi, 2019).

Municipal solid waste management (MSWM) in developing countries is characterized by landfilling or open dumping (Silpa et al., 2018). Although waste is generally abundant, it is not readily accessible for proper collection and treatment due to challenges such as inadequate waste segregation and collection services, poor infrastructure, few treatment facilities, weak enforcement of laws, etc. (Salami et al., 2019; Thabit et al., 2022). The unsegregated waste ends up contaminating the environment in drains, streets, and open dumps. Such waste is difficult to handle and treat even when collected. For instance, in Ghana, waste collection to landfills is at 21% while the remaining is burned, and disposed into open dumps or indiscriminate spaces (Mudu et al., 2021). Waste management is the single largest budget item for city managers in developing countries. However, the negative impacts of poor MSWM are enormous and cut across all aspects of human life including social, economic, environmental, health, economic, infrastructural, etc., and are more prevalent in developing countries (Hoornweg & Perinaz, 2012). This includes greenhouse gas emissions (Verma & Borongan, 2022) and contamination of groundwater from landfill leachate (El Maguiri et al., 2017), health risks including air pollution and contamination from open burning of both domestic and industrial waste, disease transmission due to vectors and informal waste collectors and scavengers, (Ferronato & Torretta, 2019), flooding due to choked drains and water ways (IBRD/The World Bank, 2010), transmission of diseases such as COVID-19 (Kalina et al., 2022).

Recovering energy from the waste is a well-established strategy for managing waste. However, the development of such systems is subject to extensive research based on major areas such as the technical, economic, environmental and social aspects.

Waste to energy research

In recent years, there has been significant global research and development focused on harnessing energy from various types of waste, employing a diverse range of waste-to-energy technologies. These innovations are crucial components of sustainable integrated waste management systems, aligning with both economic and environmental needs. (Loizidou, Maria, Konstantinos Moustakas, Mohammed Rehan, Abdul-Sattar Nizami, 2021). This valuable resource holds immense potential for bolstering the socio-economic development of numerous developing nations, particularly in Africa.

Global trends in energy recovery from waste (WTE) indicate that the most important technologies include gasification, incineration, anaerobic digestion, pyrolysis, and landfill gas recovery (Ndou & Rampedi, 2022; Tsai et al., 2020). Research into alternative energy sources such as hydrogen is growing at a very fast pace since the onset of Russia - Ukraine conflict. With natural gas prices increasing at an exponential rate, hydrogen from renewable sources is gaining increasing attention (Mbuk, 2022). Hydrogen is not a fuel in itself but an energy carrier. It has the good potential to store energy in the form of molecules and can be stored and transported as compared to other renewable energy sources such as solar and wind. It also has major applications in the energy, transport, and chemical manufacturing sectors (Reith et al., 2003; Yang & Wang, 2020). In the UK, there is a potential for over 22,000 tons of hydrogen from biomass to replace fossils in public transport in the West Midlands region per year. Economic analysis indicated that a cost-competitive business model must incorporate trade of CO_2 and the selling price is sensitive to the price of raw materials and the internal rate of return (Nouwe Edou & Onwudili, 2022).

However, it is crucial to note that research efforts in Africa have primarily focused on challenges related to waste management, especially waste collection and recycling with limited attention given to understanding WTE technologies (Alao et al., 2022; Simatele et al., 2017). There are limited successful cases or waste to energy systems in developing countries which requires enhanced efforts (Mutz et al., 2017). Unlike developed nations such as Japan, China, the USA, and Germany, where WTE technologies have been successfully adopted for commercial use, many African countries grapple with logistical, technical, financial, socio-environmental, and policy-related hurdles. The absence of comprehensive technical data on waste quantity and quality in developing countries poses a significant obstacle. Insufficient knowledge about waste composition and characterization can lead to misguided choices in equipment and technology, resulting in resource wastage, inefficiencies, and undermining the concept of zero waste (Dlamini et al., 2019; Oelofse et al., 2016).

For the economic aspects, WTE technologies require substantial capital investments in equipment. Many developing nations face financial limitations that hinder their ability to invest in waste-to-energy projects., financial incentives like feed-in tariffs, Carbon Reduction Credits, Tax exemptions, and Renewable Energy Credits have the potential to stimulate private sector investments in the waste-to-energy sector (Alao et al., 2022). Regulatory frameworks and policies need to be established through legislative actions, fostering public-private partnerships in the waste-to-energy market. Furthermore, African local authorities, agencies, and stakeholders should collaboratively identify opportunities to enhance the adoption of modern waste management technologies, unlocking additional economic potential from solid waste resources(Alao et al., 2022).

Given the diversity of WTE, research has seen many changes over several decades. One of the methods of assessing field-specific trends is bibliometric studies. Several authors have investigated various aspects of WTE trends on a global scale. However, there is a research gap in specific bibliometric studies on WTE research in Africa (continental scale) although some studies have been conducted at the country level such as Republic of South Africa (RSA), and in areas such as RDF, landfill gas, renewable energy. For instance Sarquah et al., 2022 carried out a global review of RDF research within the Scopus database identified that publications from Africa between 2015 and 2022 were less than 1%. RDF application is predominantly in the cement processes and electricity generation and Circular Economy and sustainability are recent themes. Afrane et al., 2022 also carried out review of Renewable energy research in Africa within the Web of Science database and concluded that the most recent emerging areas included green hydrogen and economic growth.

This article therefore seeks to assess the trends in WTE research in Africa and to provide an outlook based on the identification of relevant themes, collaborations and institutions. Africa is noted to be lagging in WTE research. The study further aims to provide evidence to stimulate increased relevant research into WTE in Africa by identifying gaps and suggesting future direction.

2. Methodology

Bibliometrics is an important tool for reviewing trends in research in various fields including MSW research. The PRISMA Checklist and Flow diagram guided the methodology for this study (Liberati et al., 2009). The Elsevier Scopus database was used because it is the largest database of scientific peer-reviewed literature and is popular with similar bibliometric studies. The dataset was downloaded in June 2023. The study focused on publications from all 54 countries in Africa and considered the period from 1975 to 2022. The chosen timeframe allows for an exploration of historical trends, developments, and recent advancements in the field. These included articles resulting from collaborations between African authors and authors from other countries. To define the field of interest, an advanced search query was utilized to only include documents in the English language and within the period: 1975 to 2022. The analysis was conducted in three stages as depicted in Figure 1. The search string below was used in the SCOPUS database:

> *"Municipal Solid Waste" OR "MSW" AND "energy" OR "Waste to Energy" OR "Waste-to-Energy" OR "Energy from Waste" AND AFFCOUNTRY(Africa) OR AFFILCOUNTRY(Nigeria OR Kenya OR Sudan OR Ghana OR Morocco OR Senegal OR Tanzania OR Ethiopia OR Mali OR Uganda OR Algeria OR Somalia OR Madagascar OR Niger OR Tunisia OR Cameroon OR Angola OR Zimbabwe OR Rwanda OR Namibia OR Gabon OR Zambia OR Mozambique OR Chad OR Liberia OR Togo OR Libya OR Djibouti OR Botswana OR Burundi OR Malawi OR Lesotho OR Benin OR Mauritius OR Eritrea OR Mauritania OR Guinea OR Eswatini OR Seychelles OR Comoros OR Egypt) OR AFFILCOUNTRY ("South Africa" OR "Democratic Republic of the Congo" OR "Cote D'Ivoire" OR "South Sudan" OR "Burkina Faso" OR "Central African Republic" OR "Guinea-Bissau" OR "Cabo Verde" OR "The Gambia" OR "Equatorial Guinea" OR "Sierra Leone" OR "Republic of the Congo" OR "Sao Tome and Principe").*

The search query identified an initial hit 385 documents. The dataset was then downloaded as a CSV file for screening with EXCEL. Repeated and irrelevant entries were excluded, and additional searches were performed for incomplete information to standardize the formats. 378 entries remained as the main dataset for the bibliometric analysis which was performed using VOSviewer® software in combination with EXCEL. VOSviewer is a popularly used software for creating network maps of large numbers of scientific publications for visualization and analysis of network data (Van Eck & Waltman, 2010). The bibliographic study considers a range of evaluation factors, encompassing quantitative aspects such as research areas, publication years, publication count, study locations, language, journal distribution, authors, and institutions. Additionally, the qualitative aspect concentrates on subject-based areas and term analysis. Both the quantitative and qualitative analyses were performed using Microsoft Excel and VOSviewer.

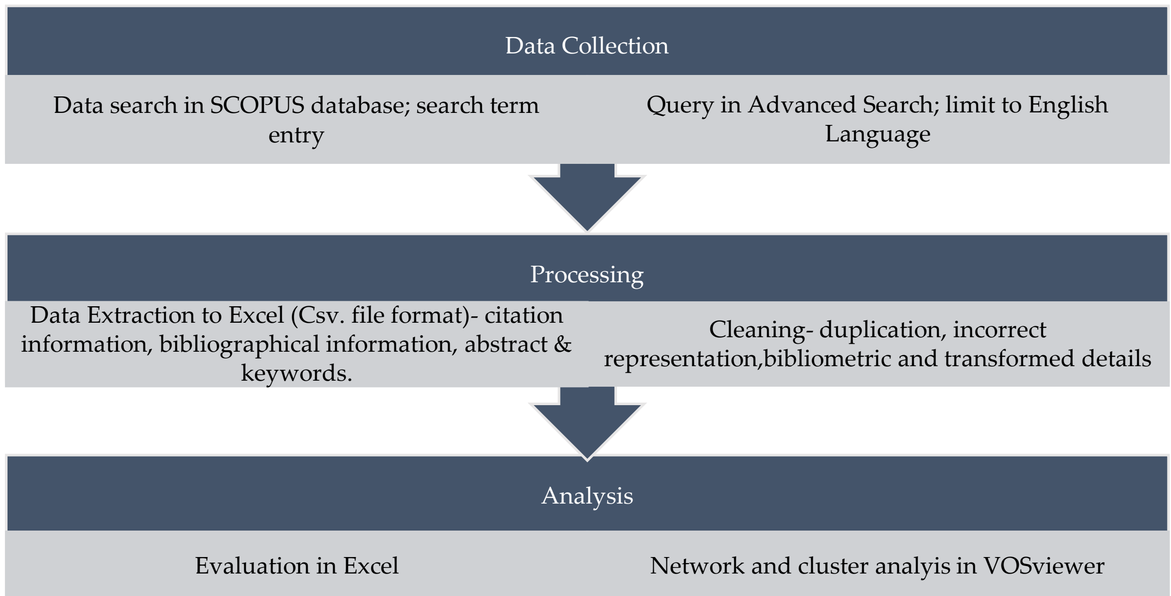

Figure 7:Rrepresentation of research methodology for the study

3. Results and discussion

3.1 General characteristics and trends of research publications

The dataset, comprising 378 documents, comprised diverse types of literature, including, conference papers, book chapters, books, data papers, journal articles (including review papers), and editorials. Among these, journal articles (including review papers) and conference papers dominated the research landscape, accounting for 75.70 % (286 documents) and 17.2% (65 documents), respectively. Followed by book chapters at 6.1% (23 documents). Books constituted 0.5% (2 documents), data papers comprised 0.3% (1 document), and editorials made up 0.3% (1 document). Figure 2 provides a concise overview of the trends in waste to energy research over the past 47 years.

Although the first paper was published in 1975 on "The energy potential of MSW in South Africa", it took another 20 years before consistent research began within the area (Connor, 1975; Letcher & Kolbe, 1994). However, the number of articles began to shoot up from 2005 which is consistent with global trends (Ndou & Rampedi, 2022). Both the 1995 and 2005 spikes could be attributed to the impact of two international treaties - the 1992 United Nations Framework Convention on Climate Change (the Earth Summit) and the Kyoto Protocol. They sparked the environmental movement in most parts of the world (United Nations, 2018). The Kyoto Protocol and the subsequent Kyoto Mechanisms particularly kick-started the Clean Development Mechanism (CDM) and joint Implementation projects across many countries (Bogner et al., 2007; Rowlands, 2001). Although the CDM itself is deemed to have failed, several projects were implemented and its principles of sustainability and carbon trade continue to be refined and applied in various contexts (Couth & Trois, 2012; Mutz et al., 2017). It must be noted however that, although CDM projects might have ignited a lot of interest, there were tremendous challenges with implementation even in advanced African countries like RSA (Mbazima et al., 2022).

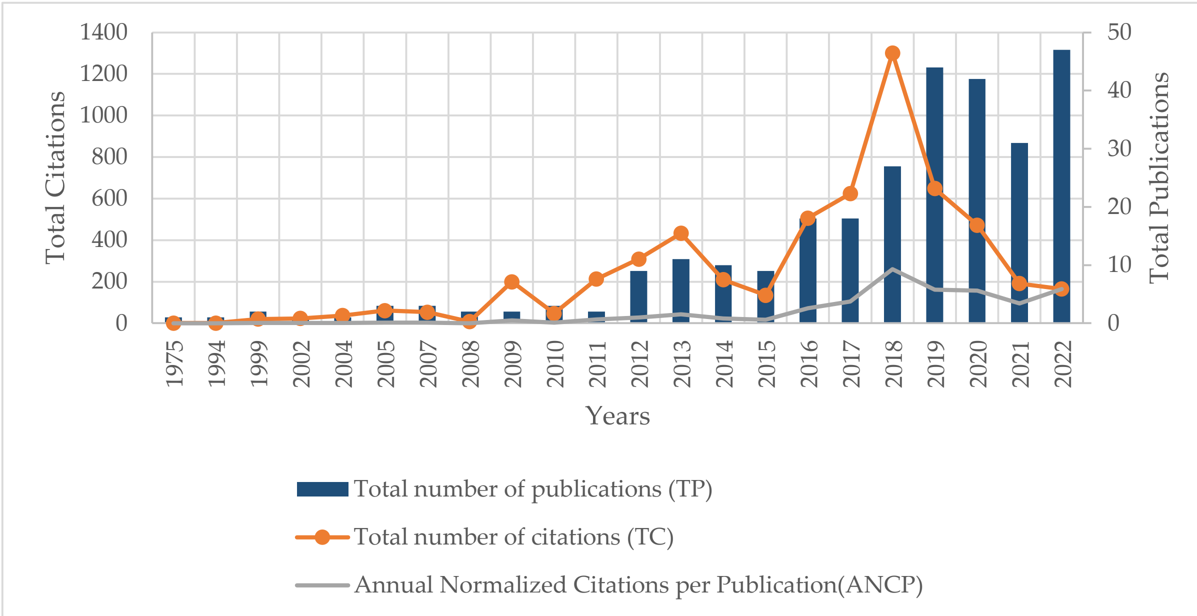

Figure 8: Trends of publications (TP: Total Publications, TC: Total Number of Citations, ANCP: Annual Normalized Citations Per Publication.

3.2 Thematic areas of research

3.2.1 Publications by subject area

The research on WTE in Africa spanned six main subject areas: energy, chemistry, engineering, chemical engineering, mathematics, and physics. Among these, engineering emerged as the dominant subject area, with 58 publications, followed by chemical engineering with 23 publications. Energy, chemistry and mathematics & physics accounted for 6, 5, and 2 publications, respectively (Figure 3).

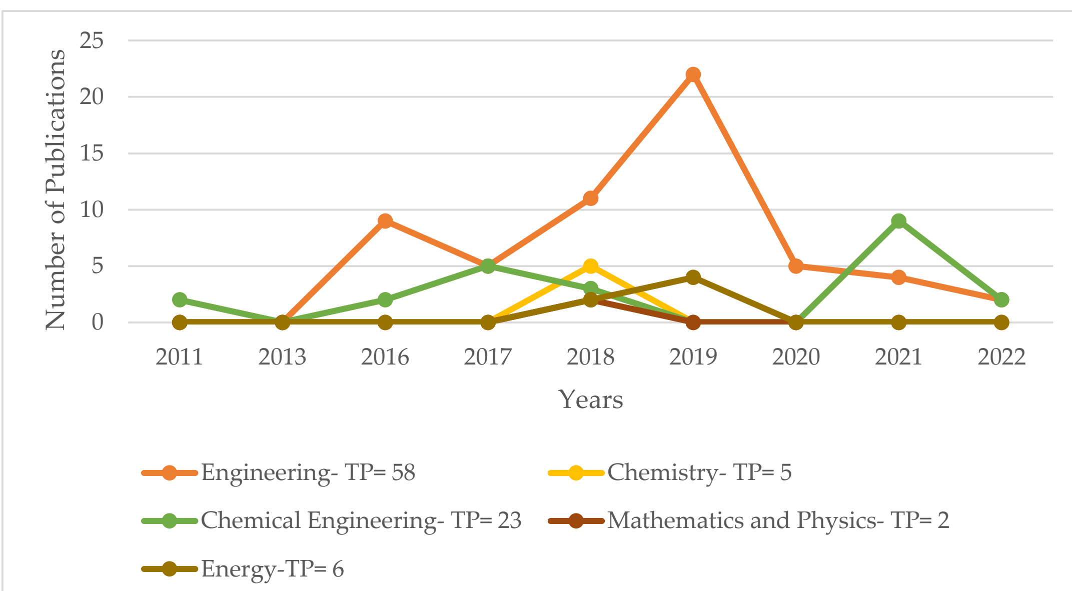

Figure 3: Number of publications within the different subject areas (2011-2022).

This is an indication that researchers are currently focusing much on the technological aspect, designing various systems for waste conversion and energy recovery of which the engineering community plays a central role in advancing these technologies and optimizing their performance, at the detriment of the type and composition of energy produced. Additionally, the prominence of these subject areas may also be influenced by funding priorities, government policies, and the specific research interests of institutions and researchers (Chand Malav et al., 2020; Williams et al., 2023). For example, if a country or region places a strong emphasis on sustainable waste management and renewable energy generation, it may lead to more research publications in these fields.

3.2.2 Major thematic areas based on keywords

The study investigated the key concepts and hotspots explored within the field of interest. To achieve this, keyword analysis was employed to explore the knowledge structure, identify emerging trends, and highlight main topics within the research areas. VOSviewer, utilizing the co-occurrence of keywords tool, was used for this analysis. Through cluster analysis, the main research streams and trends were identified. A total of 2409 keywords were extracted from the publications using both author and index keywords. 405 keywords met the criterion of occurring at least three times. From Figure 4, there are eight distinct clusters from which the authors distinguished into the following themes within waste-to-energy research based on the various keywords in each cluster. The technical and economic aspects have been thoroughly research as compared to areas assessing impact of such as health and environment (Medina-mijangos & Seguí-amórtegui, 2020).

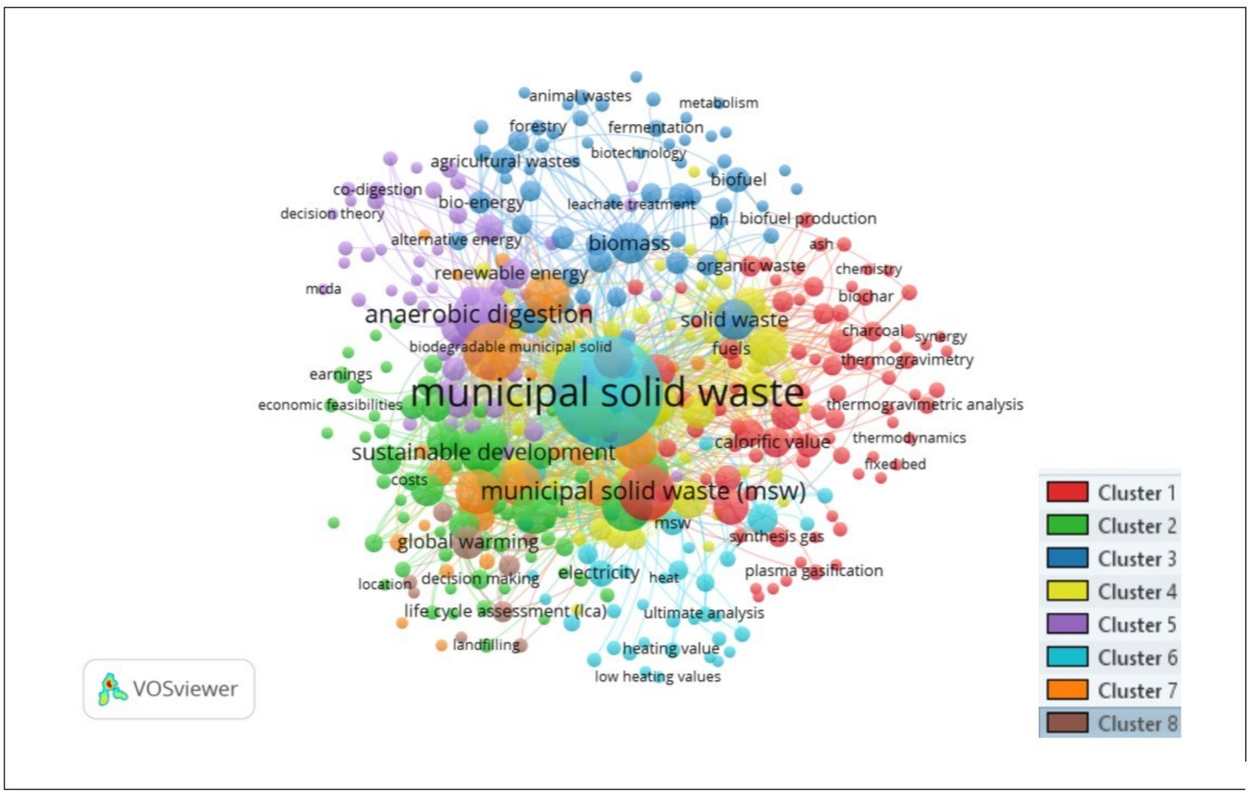

Figure 4: Clusters representing the major subject areas of research in Africa

3.2.3 Emerging trends in subject areas (last 10 years)

Over the last ten years, the period from 2016 to 2020 saw a major diversification in the research topics in waste to energy including technologies, valorization, economics and investments as well as environmental aspects (Table 1 and Figure 5). In the past 5 years, the focus has emerged on sustainable management such as hybrid technologies and circular economy. This is consistent with the findings of (Negrete-Cardoso et al., 2022; Tsai et al., 2020) showing that circular economy is an important emerging field in the management of MSW and energy plays an important role in achieving the circular economy, especially in the post COVID-19 era.

Table 1: The subject area clusters and thematic areas

Major subject area (cluster)	Number of keywords within the cluster
1-Thermochemical conversion methods	89
2- Economic value and circular economy	66
3- Bio-conversion methods	62
4- Environmental aspect and emission control	56
5- Renewable energy from waste	54
6– Research methods	39
7– Sanitation and waste recovery	28
8– Human health	11

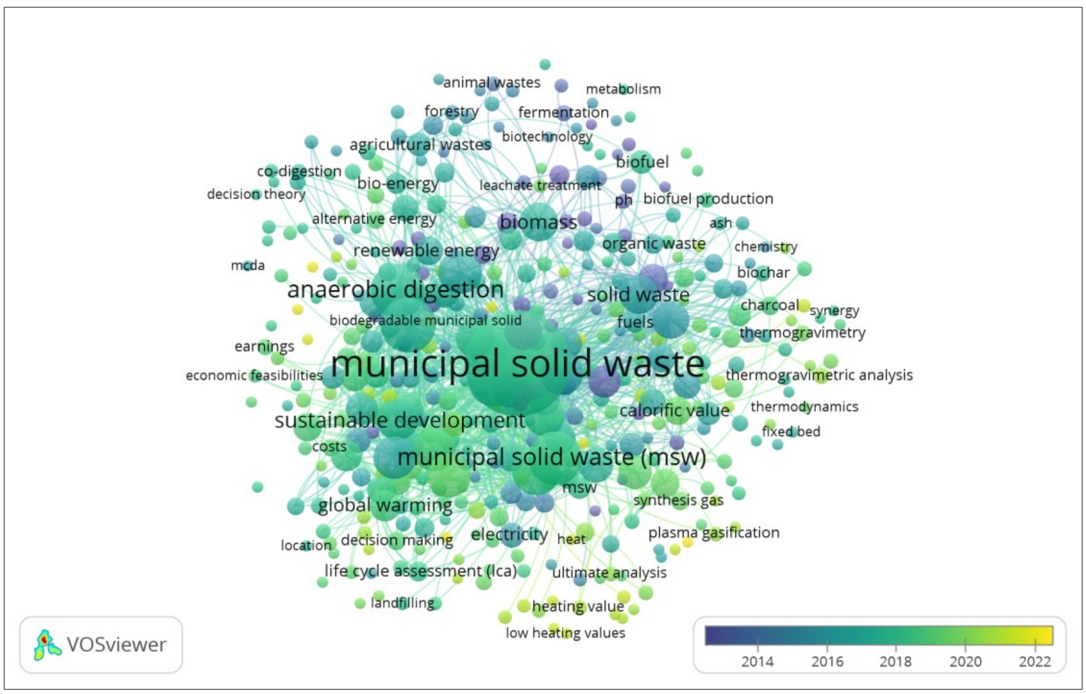

Figure 5: Keywords incidence in years

3.3. Country Analysis

The contribution of different territories to the body of knowledge in WTE research in Africa was analyzed in VOSviewer. Although the research focused on Africa, collaborations between authors and institutions outside Africa was significant (Figure 6). A total of 57 countries were represented. Although the research was based on Africa, African countries contributing only 33.33% of total countries represented indicating that there was significant co-authoring with institutions outside Africa.

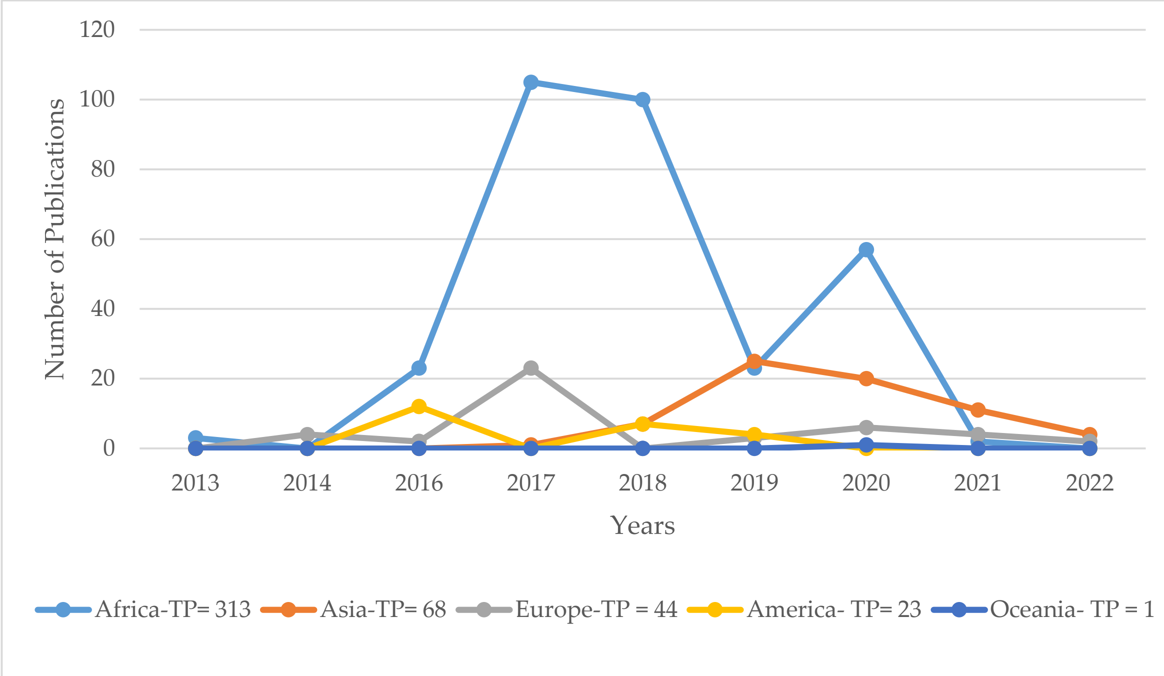

Figure 6: The contributions of various continents to research based on the number of documents within the dataset

Among African countries, South Africa (86), Nigeria (68), Egypt (32), Morocco (26), and Mauritius (16) were the top five contributors. A positive growth trend in waste-to-energy research in Africa is observed, backed by a significant number of works recorded in recent years (2019-2022), comprising 18.26 % of the total publications (Figure 7).

Geographically, all regions (North, East, West, South, and Central) are represented in the top 10 countries. However, most studies are still country specific. In the entire data, countries such as ESwatini, Comoros, Seychelles, Madagascar, Chad, South Sudan, Namibia, Djibouti are not represented at all. This could be attributed to either a language barrier since Africa is mainly divided along Anglophone or Francophone language lines (Ebong, 2022). This research only focused on publications in English thus most Francophone countries may rather publish in French. Also, political and economic instability may have contributed to low availability of funding for research.

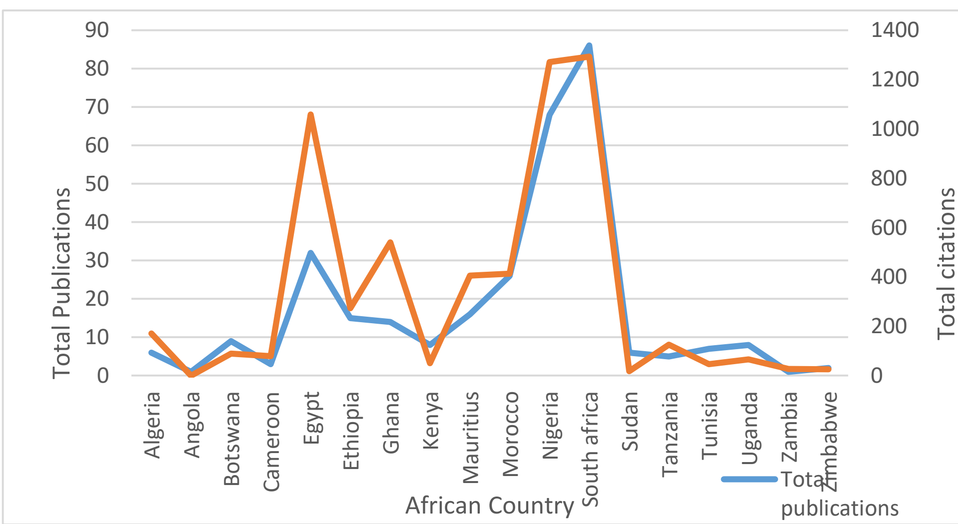

Figure 7: The contribution of African countries to waste-to-energy research within the continent based on the number of citations and related documents.

3.3.1 Collaboration Analysis

The study investigated country collaboration using VOSviewer's co-authorship tool, which revealed 42 documents meeting the criteria of a minimum of 2 documents and 1 citation per country. Figure 3 shows collaborative efforts among 57 countries.

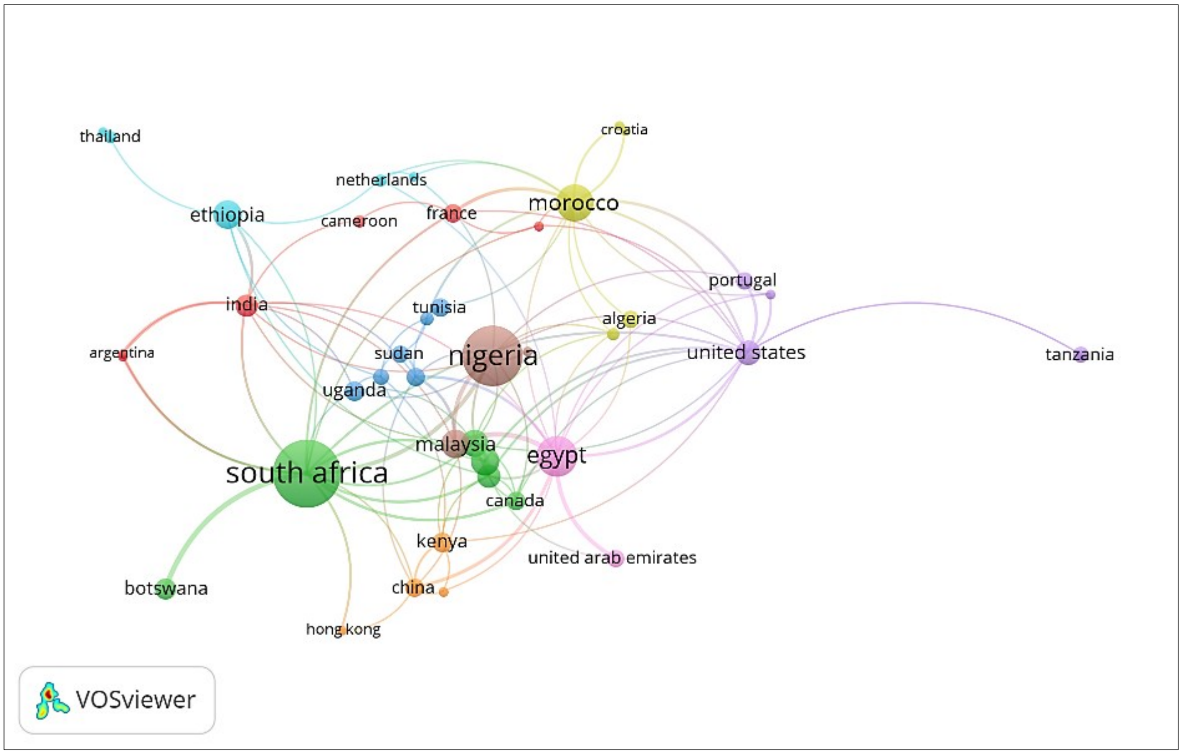

Figure 8: Country collaborations including those outside Africa

3.3.2 Analysis of Sources, Authors, and Institutional Contributions

The publications were categorized into two source types: journals and conference proceedings. A total of 174 distinct sources were identified, and the top seven journals include Renewable and Sustainable Energy Reviews, Waste Management, Waste Management and Research, Applied Energy, Biomass and Bioenergy, Energy Sources, and Solid Waste Technology and Management. In terms of affiliation, 52 institutions contributed to the field of Waste -to-Energy research. Among 783 authors, 153 authors had a minimum of 2 publications during the analysis period. A similar work by (Afrane et al., 2022) on renewable energy in Africa using the Web of Science database also revealed that Renewable And Sustainable Energy Reviews has journaled the most number of publications on energy in Africa (Table 2). Since this is a review publication source, it is inferred that most of the publications on energy and renewable energy in Africa focus on reviews.

An analysis of affiliation based on co-author information revealed a total of 52 institutions, including sub-institutions such as departments, faculties, and centers. These institutions have made contributions to the field of MSW research, both through collaborations and as single institutions. The distribution of these institutions across various countries can be found in Table 3. Only institutions with a minimum of 2 publications are represented in the table.

In the field of study, a total of 783 authors has made contributions. Among them, 153 authors had a minimum of 2 publications during the analysis period. The h-index and affiliation information of these authors were obtained from the Scopus website. Table 4 presents the top six authors who have achieved at least 10 publications in this domain.

Table 2: Characteristics of the Top Journals of the Publications Analyzed.

Journal Name	TP	TC	CPP	Cite Score [1]	SJR [1]	SNIP 2022
Renewable and Sustainable Energy Reviews	16	1072	67	26.3	3.232	3.631
Waste Management	9	498	55.33	15.1	1.745	1.912
Waste Management and Research	8	187	23.38	7.4	0.866	1.328
Applied Energy	5	259	51.8	21.1	2.907	2.758
Biomass and Bioenergy	5	174	34.8	10.8	1.045	1.305
Energy Sources	5	30	6	4.7	0.471	0.807
Solid Waste Technology and Management	5	3	0.6	0.6	0.146	0.187

Note: TP= Total Publication, TC= Total Citations, CPP= Citation Per Publication, SJR= Scimago Journal Ranking, 2022 figures from Scopus database, SNIP= Source Normalized Impact per Paper

Table 3: *Countries and Institutional Contributions; TP= Total Publications*

Country	Institutions	TP
Nigeria	University of Ibadan	6
	Landmark University	13
	Federal University of Technology	6
	University of Lagos	2
Egypt	Cairo University	4
	Ain Shams University	4
	Suez Canal University	5
South Africa	Council for Scientific and Industrial Research	3
	University of Johannesburg	25
	Cape Peninsula University of Technology	7
	University of Stellenbosch	6
	Tshwane University of Technology	5
	Durban university technology	2
	Vaal University of Technology	2
	Regional Office for Southern Africa	2
	University of South Africa Gauteng	2
	University of Cape Town	2
Botswana	The Botswana International University of Science and Technology	2
Tanzania	University of Dar es Salaam	2

	The Nelson Mandela African Institution of Science and Technology	2
Malaysia	University of Malaya	2
Ghana	Kwame Nkrumah University of Science and Technology	2
Mauritius	The University of Mauritius	4
Ethiopia	Wollo University	2
Portugal	University of Porto	2
Argentina	Fundación Bariloche	2
Tunisia	Higher Institute of Information and Communication Technologies	2
Morrocco	Chouaïb Doukkali University	4
France	Lille University	2
India	National Institute of Urban Affairs (niua)	2
Brazil	University of Sao Paulo	2
China	Harbin Institute of Technology	2
Tunisia	Higher Institute of Information and Communication Technologies	2

Table 4: *Top Six Authors with 10 or more Publications from 2001-2022*

Author Name	TP	TC	h-index	Current Affiliation	Country
Ayodele, Temitope Raphael	12	459	29	The University of Ibadan	Nigeria
Elagroudy, Sherien A.	10	174	12	Ain Shams University	Eqypt
Ibikunle, R. A.	11	123	8	Landmark University	Nigeria
Mbohwa, Charles	16	86	27	University of Johannesburg	South Africa
Muzenda, Edson	16	221	23	Botswana International University of Science and Technology	Botswana
Titiladunayo, Isaac Femi	10	123	7	Federal University of Technology, Akure	Nigeria

Note: TP= Total Publications, TC= Total Citations

3.3.3 Citation analysis

An analysis was performed on the highly cited publications in the field of MSW research from 1975 to 2022. The study examined various factors, including total citations (TC), research conducted in specific territories/ areas, annual averages, sources, and year of publication (YP).

Remarkably, a significant number of these highly cited works were found in the Egyptian Journal of Petroleum, predominantly authored within Egypt's territory. Notably, Table 5 revealed that the most cited research was published in 2018, amassing an impressive 577 recorded citations. This publication, which originated from Egyptian territory, was featured in the Egyptian Journal and credited to the Egyptian Petroleum Research Institute, with an average of 21.37 citations per year.

In terms of geographical scope, east and central Africa recorded no entry. It is expected that the establishment of the first large-scale waste-to-energy plant in Ethiopia will stimulate increased interest and more research into the impacts of such interventions in East Africa (UNEP, 2017). Table 6 also confirms 6; with the top 3 countries also appearing in the top 10 most cited articles.

Table 5: Top 5 sources for publication, total citations, and the average publication year

Year	Title	TC	TC/Year	Source	CA
2018	Solid waste issue: composition, disposal, recycling, and valorization	577	21.37	Egyptian Journal of Petroleum	Egypt
2011	A comprehensive review of biomass resources and biofuels potential in Ghana	206	103	Renewable and Sustainable Energy Reviews	Ghana, and the United Kingdom
2016	Liquid biofuels from food waste: current trends, prospect and limitation	160	8.89	Renewable and Sustainable Energy Reviews	India
2018	Current updates on waste to energy (WtE) technologies: a review	145	5.37	Renewable Energy Focus	Ethiopia, and Italy
2012	Enzyme research and applications in biotechnological intensification of biogas production	140	15.56	Critical Review in Biotechnology	Zimbabwe
2013	An Overview of Energy Recovery from Municipal Solid Wastes (MSW) in Malaysia Scenario	135	12.27	Renewable and Sustainable Energy Reviews	Malaysia, and Nigeria
2009	Comparison of Municipal solid waste management systems in Canada and Ghana: A case study of the Cities of London, Ontario, and Kumasi, Ghana	129	64.5	Waste Management	Ghana, and the United Kingdom
2017	Life cycle assessment of waste-to-energy (WtE) technologies for electricity generation using municipal solid waste in Nigeria	121	6.72	Applied Energy	Nigeria
2017	Electricity generation from municipal solid waste in some selected cities in Nigeria: An assessment of feasibility, potential, and technologies	107	5.94	Renewable and Sustainable Energy Review	Nigeria

Note: TP= Total Publications, TC/year= Total Citations per year, CA= Country of Authors

Table 6: The top 10 most cited articles, the areas of research, and the total citations per year

Reference	Area of research	Year	Source	Country	Total Citations	TC/ year
(Tizaoui et al., 2007)	Landfill leachate treatment	2007	Journal of Hazardous Materials	RSA	278	19
(Scarlat et al., 2015)	Energy Potential of Municipal Solid Waste	2015	Renewable and Sustainable Energy Reviews	RSA	215	31
(Osibanjo & Nnorom, 2007)	Electronic waste (e-waste) management	2007	Waste Management and Research	Nigeria	201	13
(Salem et al., 2008)	Landfill leachate treatment	2008	Desalination	Algeria	158	11
(Achiba et al., 2009)	Compost	2009	Agriculture, Ecosystems and Environment	Tunisia	156	12
(Asase et al., 2009)	MSWM systems	2009	Waste Management	Ghana	122	9
(Mohammed et al., 2013)	Renewable energy resources	2013	Renewable and Sustainable Energy Reviews	Sub-Sahara Africa	117	13
(Kofoworola, 2007)	Recovery and recycling practices	2007	Waste Management	Nigeria	100	7
(Giwa et al., 2017)	Sustainable energy	2017	Renewable and Sustainable Energy Reviews	Nigeria	99	20
(Idowu et al., 2019)	Landfill classification systems	2019	Waste Management	Sub-Sahara Africa	91	30

Conclusion

The study provides an insightful and comprehensive analysis of research on municipal solid waste-to-energy in Africa over the past 47 years. It sheds light on key aspects such as document types, subject areas, research concepts, country/ territory contributions, collaboration patterns, sources, authors, and citation trends. The findings highlight Africa's significant role in WTE research and reveal the growing interest and collaboration within the field. The major challenges identified is the low contribution of most countries on the continent to this research area indicating a need for increased research funding and support. This study serves as a valuable resource for researchers and policymakers seeking to advance sustainable waste management and energy generation in the African context. Also, the growing interest in circular economy indicates that this may be a sustainable solution for countries seeking to solve Municipal Solid Waste management challenges.

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ANNEX II: BOOK CHAPTER 2 (PAPER II)

Business Case for Hybrid Waste to Energy System for Ghana

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Abstract

This study aims to develop a business case for a hybrid renewable energy plant located in Ghana which has the capacity to treat 50 tons of municipal solid waste daily through Anaerobic digestion and pyrolysis and integrates a solar photovoltaic (PV) system. The plant is estimated to generate 810 MWh of electricity annually. The study developed a techno-economic model for assessing the viability using RETSCREEN software. The plant shows a positive net present value (NPV) and an internal rate of return (IRR) of 20.1%, despite a levelized cost of energy (LCOE) of e0.331/kWh, which exceeds the average End User Tariff (EUT) of e0.887/kWh. Sensitivity analysis identifies key variables, including electricity exported to the grid and debt financing parameters. Scenario 2 introduces grant-based financing and reduced capital expenditure (CAPEX) by eliminating the segregation system, reducing the LCOE to e0.145/kWh, but still above current tariffs at the same capacity. A business case for this waste-to-energy plant under the current worse case economic conditions of the country will rely mainly on a large plant with a minimum capacity of 1.6 GWh/yr. With decreasing global costs of solar PV, the technical plant design should have at least 50% solar PV capacity.

1. Introduction

Recent health and geopolitical tensions have negatively impacted the global energy system which depends heavily on fossil fuels. Price fluctuations for key fuel commodities, on the one hand, is commonplace but has plummeted within the last year which may lead to over 75 million vulnerable people potentially losing access to electricity. On the other hand, renewable energy is fast becoming an important energy commodity in most countries (International Energy Agency 2022). The capital cost for renewable energy projects is generally regarded relatively high with low operation and maintenance costs as compared to alternatives such as crude oil and coal (Pueyo et al. 2016). However, over the last decade, technological advances have resulted in renewable energy technologies becoming more cost competitive. The global weighted levelized cost of energy (LCOE) for solar PV for instance dropped from 700% more than fossils in 2010 to 29% less as at 2021 (International Renewable Energy Agency 2023). The slow growth within the renewable energy sector is affected by actors such as interest rate fluctuations, uncompetitive tariff regime, high cost of capital, fragile economic growth patterns, and inadequate interest and government funding into research and development. The factors affecting feasibility are context specific and include the seasonal availability of feedstock and governmental subsidies (van den Berg and Duong 2018).

Financing for energy projects may be sourced from internal resources of the investor, external equity or debt from a lender. Often, a combination of any of these is used (Harvey 2020). To consider the feasibility of investments in the energy sector, the LCOE is one of the most important indicators. It is calculated as the average generation cost throughout the project's lifespan, determines the project's viability relative to other projects and is generally linked to the capacity of the plant (Weinand et al. 2023).

Hybrid energy systems which integrate two or more technologies have been studied by various authors and at different scales. Examples of various combination which have been studied include: anaerobic digestion (AD) and solar PV (Odoi-Yorke et al. 2023; Buragohain et al. 2021; Agyenim et al. 2020); AD and gasification (Mabalane et al. 2021; Hadidi and Omer 2017; Esfilar et al. 2021; Asante et al. 2023); AD, aerobic composting, gasification and incineration (Xiong et al. 2016); solar PV and biodiesel (Adaramola et al. 2017); Concentrating solar power (CSP) and AD (Petrollese and Cocco 2020) as well as solar thermal and flue gas condensation through waste incineration (Behzadi et al. 2021). In all these studies electricity is the main product with some studies also considering compost and heating. Most studies have focused on technoeconomic feasibility assessment. For instance, in Moroccan cities, a hybrid anaerobic digestion and solar thermal system was found to be the most feasible option with an Internal Rate of Return (IIR) of 10.14% (El Ibrahimi et al. 2021). In three North African countries (Tunisia, Algeria and Morocco), co-digesting agro-industrial waste with organic fraction of MSW (OFMSW) in a hybrid solar- biogas plant was found to be feasible with IRR between 10 and 20% based on seasonal availability of feedstock. Although the estimated CO_2-eq emissions during the lifetime of the project was quantified (26–411 MT), the economic returns were not incorporated into revenues and feasibility which could be due to the project being economically feasible from the sale of the primary product (electricity) (El Ibrahimi et al. 2022).

One important source of energy is MSW. Conversion of waste to energy is known as waste to energy (WtE) or Energy from Waste (EfW) (Hoang and Fogarassy 2020). The recovered energy is considered a form of renewable energy and thus has positive environmental impacts as compared to fossil fuels and creates a bioeconomy for economic gains as well (Anyaoha and Zhang 2022). WTE technologies are available depending on the type, quantity and characteristics of feedstock, required energy method, economic conditions, environmental standards and specific factors (Mutz et al. 2017). The most commonly used WtE technologies are thermal, biochemical and chemical technologies although thermal technologies dominate (incineration, gasification/pyrolysis and landfill gas recovery) (Tozlu et al. 2016).

Like conventional power plants, the investment cost for waste energy power mainly consists of engineering, construction, and equipment, as well as infrastructure costs (e.g., fuel supply system and grid connection). Some studies have revealed that WTE systems are not financially sustainable without subsidies and external support. Revenues to be obtained from electricity sales does not directly cover both CAPEX and OPEX. Additional products such as Carbon Credits may be important to achieve this (Mutz et al. 2017). A landfill gas to energy project was modelled in South Africa and it was concluded that although the project had the potential to produce 6.6GWh of electricity to 2952 households, the plant was not economically feasible. Feasibility could only be attained through the sale of Certified Emission Reduction (CER) which could bring in revenues of over $15,000,000 as at 2020 (Njoku et al. 2020).

Several large WtE plants are springing up in Africa. Ethiopia has recently commissioned a WtE plant which processes 1,400 tons of MSW per day into electricity to cover 30% of the Addis Ababa's household energy needs (UNEP 2017). Also, Safisana is a 100 kW hybrid solar-biogas plant in Ghana providing grid connected electricity and compost (Agyenim et al. 2020). Through funding support from the German Government, a 400 kW pilot WtE plant is being constructed in Ghana with capacity to treat 50 tons/day of mixed MSW through a hybrid solar PV-biogas-pyrolysis system to produce electricity, compost and other recovered materials (Tena 2023).

This hybrid model is the first of such projects to be established in Ghana (Tena 2023). Over the past two decades, the installed capacity of Ghana's energy system has been dominated by fossils and biomass. In 2021, 61% was sourced from Natural Gas and oil with 34% from biomass and the remaining accounted for by solar and hydro (Energy Commission 2022). Although the generation share of renewables is expected to increase to 1% in 2032 mainly due to an expansion in installed capacity of solar plants, waste to energy still remains at 100 kW; mainly from the SAFISANA plant (Agyenim et al. 2020, Ghana Grid Company 2022). Out of the total 21,466.26 GWh electricity generated in 2021, the sources were composed of 35% hydro, 64.52% thermal, 0.25% renewables (solar and waste) and 0.2% from emergency imports (Ghana Grid Company 2022).

This study therefore seeks to develop a business case for the new hybrid waste to energy plant in Ghana by assessing the techno-economic feasibility of the three renewable energy systems. As with all renewable energy projects, the economic feasibility must be proven in order to establish the basis for future projects. The business case will support decision making for policy makers for the management of waste in Ghana. Furthermore, the business case will provide evidence to investors and project developers on critical direction to stimulate further investment. Since this is a pilot plant which is currently under construction, all referenced data for the assessment is related to the plant design and the preliminary operational phase. The scope of the project specifically covers a total installed capacity of 400kW with 50 tons of mixed municipal solid waste (MSW) being received from the city of Kumasi.

2. Methodology

Study approach

For the hybrid power project under study, the feasibility analysis is carried out in the RETScreen® Clean Energy Management software focusing on the technical and financial aspects which are detailed in sections "Data collection" and "Financial analysis" respectively. The RETScreen Expert software enables decision making for planning, analysis and monitoring of energy projects. The platform analyses the benchmark, feasibility and/or performance of energy projects or a portfolio of facilities and provides results based on technical, economic and environmental aspects. It also allows the assessment of several technologies, project designs as well as different scenarios. The software is workbook based with each sheet containing specific formulas to produce output results based on the case specific data put in (Minister of Natural Resources Canada 2005).

Figure 1 provides a representation of the entire study approach which involves three stages: data collection at the plant and technical as well as financial analysis in RETScreen. Finally, based on the results of the financial analysis, a business case is presented which provides guidance regarding the conditions under which a viable investment can be made feasible.

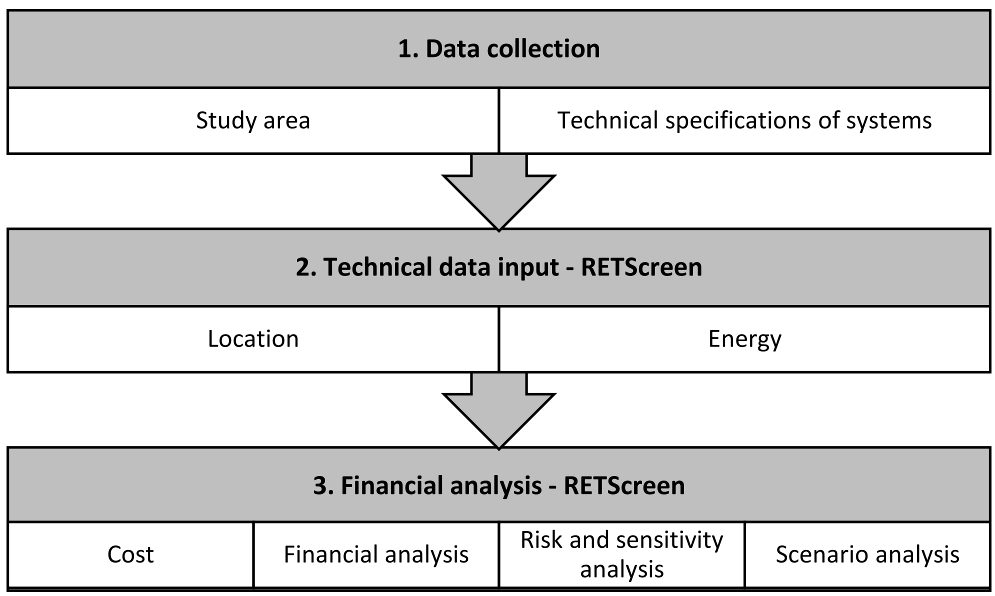

Figure 1 Schematic of study approach

2.1 Data Collection

Study area

The hybrid waste to energy pilot plant is situated specifically at Gyankobaa which is a small rural community located within Atwima Nwabiagya Municipality of the Ashanti region which is 25 km from the location of the plant. It is specifically located on Longitude −1.8 and Latitude 6.6. The Municipality has an estimated population of 103,698 with an annual growth rate 2.6%. The main economic activity is farming and livestock rearing. The electricity coverage is about 70% with 24 communities without access to electricity (Ministry of Finance 2019). The general waste management situation in Ghana is characterized by unsegregated waste which is mainly disposed of in landfills which is the same within the Atwima Nwabiagya Municipality although the rural population is expected to contain more organics as compared to the urban municipalities (Miezah et al. 2015; Ofori 2016).

Technical design

The data input in RETScreen began with the input of the location data. The weather data was automatically generated from the NASA database incorporated into the software. In the energy worksheet of RETScreen, three tabs are created for each of the three systems with a total installed capacity of 400 kW: 200 kW solar PV system, 1000 m^3 biogas system linked to a 100 kW Combined Heat and Power (CHP) plant and a plastic pyrolysis system also linked to a 100 kW CHP plant (Fig. 2). Since most of the facilities within the plant are already installed, the scope of this study focuses on the technoeconomic study rather than the design of the system. Thus, all technical details from the plant are adopted without further calculations.

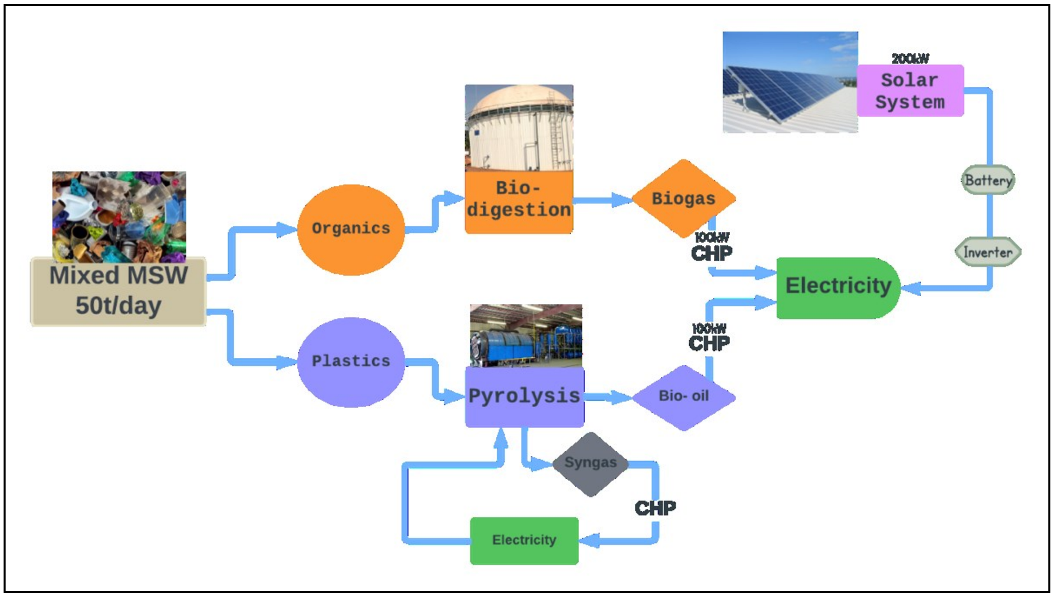

Fig. 2*: A representation of the technical design for the hybrid power plant*

<u>Solar PV system</u>

The solar photovoltaic system consists of roof mounted solar panels, battery, inverter and cables. In order to calculate the output of the solar system, RETScreen uses location specific data from the closest climate data location from the NASA database. Based on the selected location, the closest data location is 25 km away from the plant site.

The PV modules are roof mounted with a fixed solar tracking mode. Based on the solar irradiance data received at the selected location, maximum energy output from the modules is received at a tilt angle of 5 °C. Talesun TP6L72M mono-Si module is already installed at the site. This is because it is more locally accessible, and the technical specifications are adequate. Table 1 presents the technical specifications of the module. The miscellaneous losses from the module is assumed to be 10% since it is roof mounted. Also, the area is relatively rural and surrounded by thick forest and farmlands with low atmospheric dust although it is expected to be slightly higher during the dry season months from November to March each year. The module lifespan is assumed to be 25 years.

Table 1 Specifications of the components of solar PV system

Parameter	Specification
Manufacturer and module	Talesun (TP6L72M)
Type	Mono-Si
Solar tracking	Fixed (Roof mounted)
Tilting	5%
Power capacity	200kW
Efficiency	20.1%

Nominal operating cell temperature	45°C
Solar collection area	995
Inverter capacity	150
Inverter efficiency	95.5%
Capacity factor	14.1%

Anaerobic digestion (AD) system

The plant is expected to receive 50 tons of mixed MSW per day. The waste is sorted using both manual and mechanical procedures. A recent study on three plants in Ghana using similar sorting processes indicate that about 48% of organics is expected from the waste received at the plant (Sarquah et al. 2023). The organic waste is transferred to a 1000 m^3 biodigester which is expected to produce biogas at a rate of 45 m^3/h. The biogas is then transferred to a cleaning chamber and finally, the methane is directed to a 100 kW Combined Heat and Power (CHP) engine with an efficiency of 35% to be converted into electrical energy for the grid. A transformer is located onsite to convert the electrical energy for the grid. The plant is expected to operate 335 days/year with 30 days for both planned and unscheduled repair and maintenance works. The energy output from the AD system is calculated as in Eq. (1):

$$E_{gen} = P \times T \times E\text{ff} \quad (1)$$

where, E_{gen} is the energy generated from the system, P is the Power capacity of the CHP (kW), T is the operational hours per year (hrs/yr), Eff is the conversion efficiency of the CHP (%)

Pyrolysis system

The pyrolysis system is expected to receive 1 ton of mixed plastic waste per day. The pyrolysis process typically produces bio-oil, syngas and tar (Bassey et al. 2023). The pyrolysis system in this study is designed to be self-sustaining in terms of energy demand. Thus, the syngas is directed into a 50 kW CHP to power the pyrolysis process. The bio-oil is directed into a 100 kW CHP to produce electricity for the grid. The energy generation from the pyrolysis system is calculated as with Eq. (1).

Energy exported to grid

The energy exported to grid (E_{grid}) is calculated as a balance between the total energy generated (TE_{gen}) and the internal energy demand (E_d). E_d is mainly from the segregation system as well as minor onsite uses such as the office building. The national end-user tariff was applied to the internal energy consumed during the financial analysis. The energy output from the plant is calculated within the RETScreen software as in Eq. (2):

$$TE_{gen} = \sum E_{pv} + E_{AD} + E_{pyr} \quad (2)$$

where: E_{pv}, E_{AD}, E_{pyr} is the energy output from the Solar PV, AD and Pyrolysis systems respectively.

Since the plant was not under full scale operation during the period of the study, the complete log of energy consumption was not obtained. The total internal energy demand is therefore calculated using the Eq. (3).

$$E_d = P * T \quad (3)$$

where P is the power rating of the equipment and T is the total operating hours per year.

Therefore, the total energy exported to grid is calculated as in Eq. (4):

$$E_{grid} = TE_{gen} - E_d \quad (4)$$

2.2 Financial Analysis

The financial analysis was carried out on the finance worksheet of the RETSCREEN software. The project costs values were input in the cost worksheet and automatically exported to the finance worksheet. The parameters are grouped into two based on the level of control from the project managers: Internally and externally controlled parameters. Reference is made to a Power Purchasing Agreement between the Government of Ghana and Jacobsen Jelco Ghana Limited as an Independent Power Producer which provides insight into typical Power Purchasing Agreements in the local context and gives an indication of the cost buildup for energy projects in Ghana (Parliament of Ghana 2014)

Internally controlled parameters

The main factors to be considered here are the Capital costs, Capital financing (Debt to Equity, Debt rate and Debt term) and Operation and Maintenance (O&M) Costs. All costs are escalated at the rate of inflation as specified in section "external economic parameters".

The equipment was procured as turnkey systems from local suppliers which includes consultancy design supply and installation. This ensures access to local personnel for repair and maintenance. The Capital Cost (CAPEX) is the sum of the costs of the individual systems and assumes that for each of the systems, a Turnkey installation is done. The capital costs are calculated as in Equation 5:

$$C_{pv} + C_{bio} + C_{py} + C_{seg} + \text{land} \quad (5)$$

Which are the costs of the individual systems as follow: solar PV, AD technology, Pyrolysis and segregation system respectively. The Capital Cost of Equipment was made up of 12% for the solar PV and 29% each for the AD, pyrolysis and segregation systems (Table 2).

Table 2: Summary of the financial parameters used for the analysis

Parameter	**Value**
Initial equipment costs	€1,710,000
Land	€150,000
Project lifetime	20 years
Discount rate	12%
Debt to equity ratio	85%
Debt interest rate	2%
Debt term	15%
Operation and Maintenance	2% of CAPEX
Electricity export escalation rate	25%

The operation and maintenance costs are estimated to be 2% of the CAPEX which involves cleaning, servicing and periodic replacement of minor worn-out cables etc. One of the reasons for the low O&M is the rural nature of the area making cost of operations relatively low.

External economic parameters

The external factors considered for the financial analysis indicates influences from national and international factors which may affect the feasibility of the plant. These factors are usually beyond the control of the stakeholders but may have a high impact on operations. Global economic situations such as the COVID-19 pandemic and the Russia Ukraine conflict has hugely affected most economies and the energy sector including Ghana (International Energy Agency 2022). The details for the calculation of the parameters are provided in the following sections (Table 3).

Table 3 Summary of external economic parameters

External economic parameters	Source of value	Value
Escalation of cost	Average 25-year Inflation	16.12%
Income tax	Corporate Income tax (with tax holidays)	18%
Electricity export escalation rate	Average 25-year increase in BGC tariffs	25%
Incentives and grants	Land and import duties (20% of Capex)	20%

Inflation

All costs are escalated at the local inflation rate. Based on the projected lifetime of the project, the historical inflation of the country is used to forecast potential future trends. Figure 3 shows the 25-year trend of Ghana's annual inflation rate based on data from The World Bank (2023). The average inflation rate for the period was 16.12%; the highest of within the period being 41% in 2001 while a low 7% is observed in 2019. This average figure is a reflection of all possible local economic conditions with a potential to impact the feasibility of the plant.

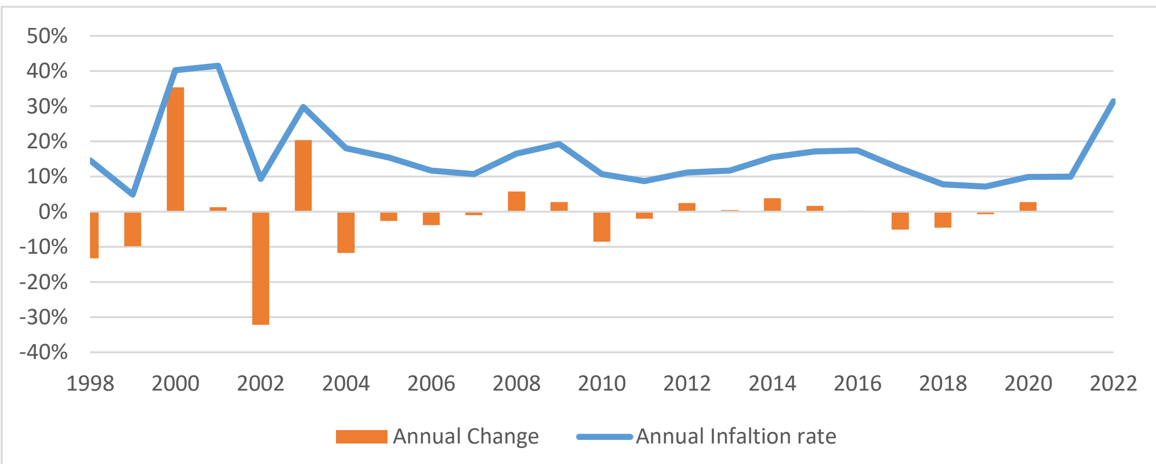

Fig. 3*: The 20-year trend of inflation in Ghana*

Revenues and rate of escalation of revenue

The potential sources of revenue for the plant are the sale of products such as electricity, tipping fees and district heating (Asante et al. 2023). However, due to the distance of the plant from the regional capital and the rural nature of the surrounding communities, tipping fees will become a major disincentive to attract waste management companies to dispose of waste at the plant. Also, district heating is not available in Kumasi.

The revenue estimations for the plant are based on the local tariff for Bulk Generation Charge (BGC) as published by the Public Utilities Regulatory Commission (PURC) in June 2023. The PURC is mandated to set realistic tariffs for public utilities including electricity to enhance competition and international standards. Bulk Generation Charge (BGC) which is the aggregated cost of power generated by the Independent Power Producers (IPPs) and the Volta River Authority (VRA). The End User Tariffs is obtained by a sum of the Bulk Generation Charge, Transmission Service Charge and the Distribution service charge (Acheampong et al. 2021). The proposed power plant is considered an IPP and thus revenues will be assumed to be based on the BGC tariffs. The most recent tariff released by the PURC for the second quarter of 2023 is GHp104.3646/kWh which translates into EUR0.088/kWh at the average interbank exchange rate for May 2023 from the Bank of Ghana (PURC 2023, Bank of Ghana 2023).

The rate of escalation of the revenues used in this study is 25%. This was obtained from the average of the year-on-year increments between 2018 and the second quarter of 2023. From Fig. 4, the cumulative change is greater than 17times the 15-year period although some years remained constant, the post COVID economic crises which is evident in most countries has caused a drastic increase in tariffs with 137% since 2021. This can be seen as the worst-case scenario whiles best-case scenarios occurred in 2015–2017 and 2011–2012. The long-term average figures give a realistic representation of both worse case and best-case scenarios. Also, trends indicate that End User Tariffs are relatively stable around election years with no major reviews such as 2012, 2016, 2020 (PURC 2020).

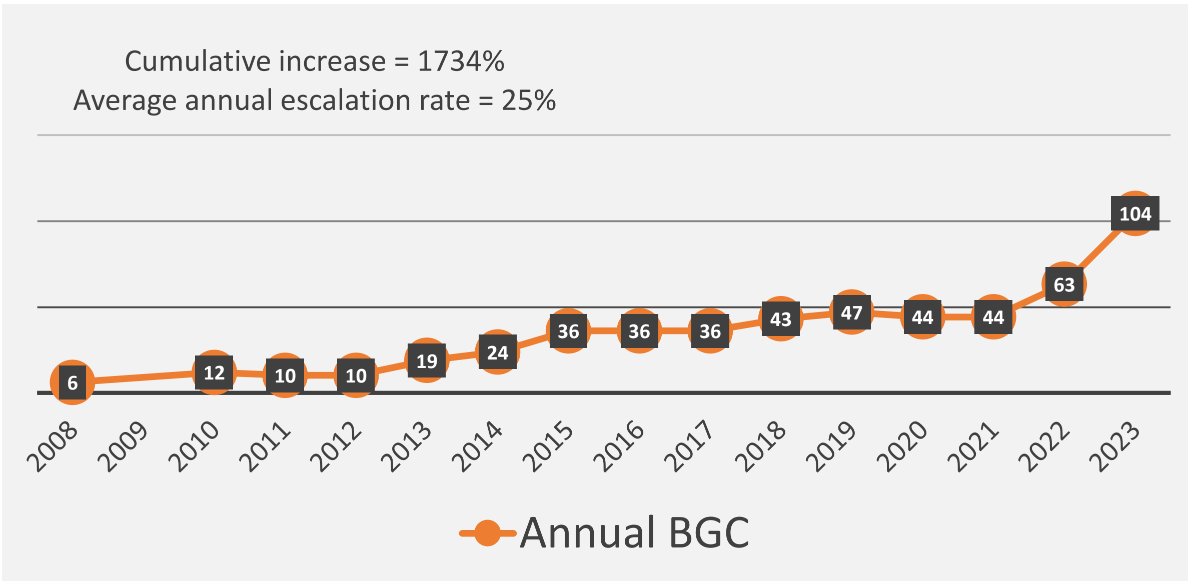

***Fig. 4**: The 25-year annual trend of escalation of tariffs for Bulk Generation Companies in Ghana (PURC 2020, 2023).*

The tariff pricing in Ghana is based on the Automatic Adjustment Formula (AAF) which was originally introduced in 2002 and reviewed in 2011. In applying the AAF, the PURC performs a comparative analysis of actual and projected Hydro-Thermal Generation Mix, Ghana Cedi-US Dollar Exchange Rate, Inflation Rate and Fuel Prices (such as natural gas) (Acheampong et al. 2021). Thus, the tariffs are a reflection of both local economic situation (inflation) as well as international market prices (fuel prices) and also various sources of energy. The use of the tariff in the escalation rate will therefore incorporate such internal and external influencing factors.

<u>Tax–average for project lifespan</u>

All corporate entities are required to pay Corporate Income Tax according to the Income Tax Act 2015 (Act 896). Companies within the waste management sector receive a tax holiday of seven years within which the applicable rate is 1%; and 25% from the 8th year onwards (Ghana Revenue Authority 2023). Over the 20 years expected lifespan of this project, the average annual tax rate is calculated as 17%.

<u>Financial viability indicators</u>

The viability of the proposed system will be assessed with Net present value (NPV), Levelised Cost of Energy (LCOE)/Energy Production cost and the Internal Rate of Return (IRR) based on the analysis results from provides results RETScreen. The RETScreen software calculates the NPV as the value of all future cashflows, discounted at the discount rate at present. The present value of all cash inflows is compared to the present value of all cash outflows over the investment period. A positive NPV generally indicates the potential feasibility of a project. The LCOE is the electricity export rate required to attain an NPV of whiles the IRR is calculated as the after-tax internal rate of return (IRR) on assets (%), which represents the true interest yield provided by the project assets over its life after income tax. It is calculated using the after-tax yearly cash flows and the project life.

2.3 Risk and Sensitivity analysis

This is carried out in the risk worksheet of the RETScreen software. A comparative analysis of the performance of financial viability indicators to the changes in various parameter enables the development of business case and provides basis for the future direction of the project.

Based on the results of the sensitivity analysis, two scenarios are assessed for the best case to attain economic viability. The technical design of the three technologies and the externally controlled parameters remain the same for both scenarios.

- Scenario 1—as described above
- Scenario 2—the internally controlled parameters are changed to improve viability of the project to develop the business case

3. Results and Discussion

3.1 Technical Performance

The expected daily solar irradiation data as against precipitation is represented in Fig. 5 with an average daily solar radiation of 4.34 kWh/m^2/d. The total energy potentially generated from the plant is 810 MWh/yr.

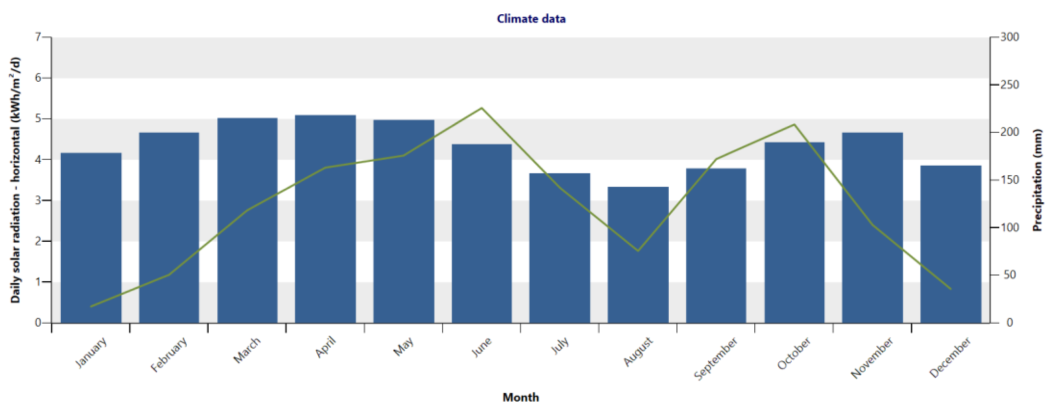

***Fig. 5**: The average monthly solar radiation as against the precipitation*

3.2 Financial Viability

Based on the BGC tariff for May 2023, the total revenue expected in the first year is €70,457. The cumulative cashflows for the 20-year period indicate that positive cashflows begin in the 5th year although the debt financing period is 15 years. This is an indication of a good debt repayment potential with a low risk to the lender. The NPV is positive, IRR is 20.1% and LCOE is €0.331/kWh. The average residential and commercial End User Tariff (EUT) as announced in May 2023 is €0.127 (PURC 2023). Comparing the LCOE, the BGC tariff and the EUT, the cost of energy production is too high to sell the power and make the plant financially sustainable. The sensitivity analysis indicates that the most sensitive variables are the electricity exported to grid, debt financing (debt to equity, debt rate and debt term) and the tariffs. However, the tariffs are beyond the control of the project. Thus, adjustments must be made to the internally controlled variables to provide a viable business case for the plant. Although the current externally controlled variables such as inflation are relatively high, the model provides us with a more optimistic approach to focus on the parameters which can be controlled by the project developer (see Fig. 6).

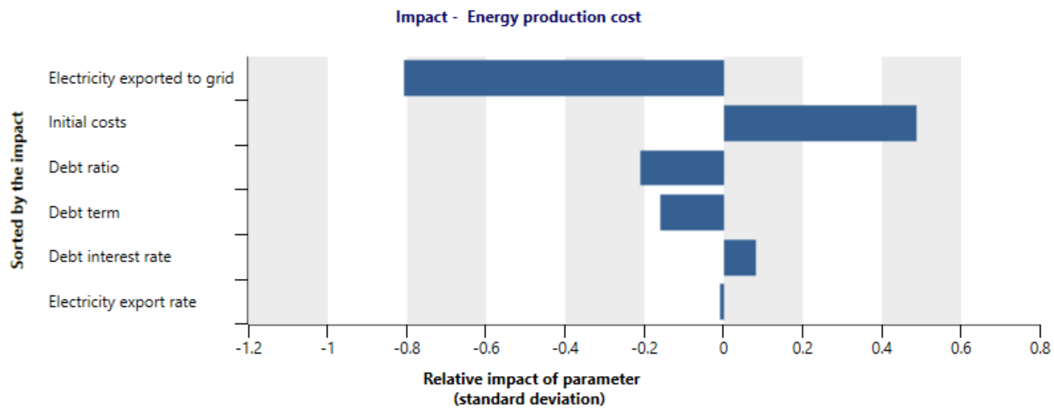

***Fig. 6**: The risk analysis indicating the impact of various variabilities on the LCOE*

Scenario 2

In the Scenario 2, the following adjustments are made to the internally controlled variable.

- The source of the financing is assumed to be a grant with no debt.
- The CAPEX is reduced by removing the cost of the segregation system. The segregation system can be removed by sourcing already segregated organic and plastic waste, for instance from abattoirs and food processing industries. The Safisana system for instance receives only source segregated organic waste from market centers and industries (Agyenim et al. 2020). Also, source segregated plastic is gradually becoming very common in Ghana (Fiati 2021). With greater engagement with the municipality, the high cost of the segregation system can be removed for source segregated waste to be directed to the plant.

With the adjustments, the LCOE reduces to EUR 0.1447/kWh, which is still above the current selling price of the power (BGC Tariff). However, sensitivity analysis provides details into the various scenarios under which the plant can have an energy production cost matching or below the applicable tariffs. The most viable option is to increase the CAPEX by 16.7% whiles also increasing the energy exported to grid by 100% (see Fig. 7).

	Electricity exported to grid (MWh)								
	0.00	202.53	405.06	607.59	810.13	1,012.66	1,215.19	1,417.72	1,620.25
	-100.0%	-75.0%	-50.0%	-25.0%	0.0%	25.0%	50.0%	75.0%	100.0%
-100.0%	8,697,050.00	8,697,050.00	8,697,050.00	8,697,050.00	8,697,050.00	8,697,050.00	8,697,050.00	8,697,050.00	8,697,050.00
-83.3%	8,697,050.00	8,697,050.00	8,697,050.00	8,697,050.00	8,697,050.00	8,697,050.00	8,697,050.00	8,697,050.00	8,697,050.00
-66.7%	8,697,050.00	96.64	48.32	32.21	24.16	19.33	16.11	13.81	12.08
-50.0%	8,697,050.00	209.74	104.87	69.91	52.44	41.95	34.96	29.96	26.22
-33.3%	8,697,050.00	329.34	164.67	109.78	82.34	65.87	54.89	47.05	41.17
-16.7%	8,697,050.00	452.94	226.47	150.98	113.23	90.59	75.49	64.71	56.62
0.0%	8,697,050.00	579.06	289.53	193.02	**144.77**	115.81	96.51	82.72	72.38
16.7%	8,697,050.00	708.77	354.38	236.26	177.19	141.75	118.13	101.25	88.596
33.3%	8,697,050.00	843.06	421.53	281.02	210.76	168.61	140.51	120.44	105.38
50.0%	8,697,050.00	979.60	489.80	326.53	244.90	195.92	163.27	139.94	122.45
66.7%	8,697,050.00	1,117.52	558.76	372.51	279.38	223.50	186.25	159.65	139.69
83.3%	8,697,050.00	1,256.70	628.35	418.90	314.17	251.34	209.45	179.53	157.09
100.0%	8,697,050.00	1,396.54	698.27	465.51	349.13	279.31	232.76	199.51	174.57

***Fig. 7**: The sensitivity analysis for scenario 2: comparing the LCOE (€/MWh) with changing CAPEX (initial cost in €) and electricity exported to grid (MWh)*

This may be a feasible option considering the cost of the various systems in the cost buildup (Fig. 8). Comparing the relative the cost buildup and the expected energy output, solar PV is the viable technology to expand at a relatively lower investment cost.

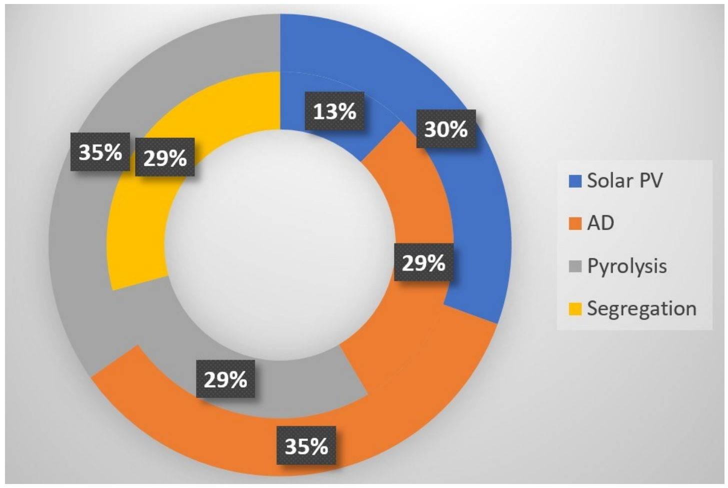

Fig. 8*: The relative contribution of the various systems to the cost buildup (inner band) and the energy production (outer band)*

The cost of solar PV systems is reducing at a high rate each year and the LCOE for solar PV projects reduced from USD0.445/kWh in 2010 to 0.049/kWh in 2022 (International Renewable Energy Agency 2023). Since the procurement for the plant was done in 2019, the rate of reduction in the installed cost of Solar PV systems globally provides an opportunity for such systems (IEA et al. 2021). Programs such as the Scaling Solar Program is targeted at increasing private investment in Africa by removing major barriers for large scale investors such as documentation, cost uncertainties and risks. The program has led to the establishment of projects in Zambia (100 MW), Ethiopia (250 MW) and Senegal (60 MW) with Togo, Madagascar, Cote d'Ivoire, and Niger set to receive similar benefits through grants. The large capacities of these projects, coupled with enhanced support from the program to investors ensured that the solar PV projects were awarded at relatively lower prices of about USD 60 and 78 MWh at the time (2015–2016) which was far below average prices in Africa. In 2018, the program supported lower prices of USD25/MWh (2019) in Ethiopia and USD 40/MWh in Senegal (2018) (IRENA and AfDB 2022).

This indicates that in order to improve the economic feasibility of the hybrid model, which relies only on revenues from the sale of electricity, the capacity must be expanded to produce at least 1.6 MWh/yr. Also, this expansion must be in favor of solar PV system (Gigure 1.34). However, the major limitation with this scenario is the dependence on grant support. The market for off-grid renewable energy in West Africa for instance depends largely on debt and equity rather than grants. However, most capital for energy project in Africa are financed through either debt and grant (IRENA and AfDB 2022). Public policy and financing play a critical role in stimulating investments and reducing the risks associated with financing renewable energy markets in Africa. Public concessional financing provides lower debt rates and more flexible debt terms as compared to independent investors. Private investments through Independent Power Producers (IPP) can be improved through public policy, public investments and risk sharing instruments. Thus, public financing is encouraged to drive such technological advancements.

Conclusion

The study assessed the technoeconomic feasibility of a hybrid waste to energy plant located in the Ashanti region of Ghana utilizing a combination of three technologies: solar PV, anaerobic digestion and pyrolysis. It is a novel model in Ghana in terms of the technical design. The plant receives 50 tons of unsegregated Municipal Solid Waste per day from the surrounding municipalities. A business case is developed to assess the economic feasibility of the current plant and the best scenario under which feasibility can be obtained. The RETScreen expert software was used. The results indicated that the plant is economically unsustainable whiles producing only 820 MWh of electricity to the grid per year. The most viable business case can be obtained when the capacity of the system is expanded to export at least 100% more electricity to the grid per annum at only 16.7% increase in the installed cost. Based on the installed cost for the three technologies, the recommended expansion should be done in favor of solar PV which is more likely to be done at such a low investment cost. Also, the although the country's economy has been strongly affected by recent global situations such as COVID-19, the model is still feasible within the current unfavorable externally controlled variables such as inflation and taxes. Thus, it can be concluded that the hybrid design is a feasible model which must be adopted in the developing country perspective although the capacity considerations are the capacity consideration must be carefully considered in the technology combination.

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Achieving Techno-Economic Feasibility for Hybrid Renewable Energy Systems through the Production of Energy and Alternative Fuels

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Abstract

In developing countries like Ghana, the conversion of waste into energy is gaining greater interest among policy makers and researchers. The present study investigates the feasibility of producing electricity and/or fuels from a hybrid waste-to-energy pilot plant located in the Ashanti Region of Ghana. The plant integrates three technologies: anaerobic digestion, pyrolysis and solar PV. The plant has the potential to produce both energy and fuels such as green hydrogen, refuse derived fuels, bio-compressed natural gas and compost. Thus, this study compares the financial feasibility of three scenarios—generating electricity and fuels, generating electricity alone and generating fuels alone—by modelling their energy output and financial performance using RETSCREEN expert 6.0.7.55 and Microsoft Excel 2019 softwares. The results indicate that the multiple products of electricity and fuels provide higher investment interest with a Net Present Value in excess of EUR 13 million and a payback period of 12 years compared to the electricity-only model. Also, converting electricity into fuels alone also provides substantial benefits which can be explored. However, the Levelized Cost of Energy, ranging from 0.3 to 0.68 EUR/kWh, is far above the average residential End User tariff. Overall, this study provides an important methodology for assessing the potential products of future projects.

Keywords:

municipal solid waste; green hydrogen; refuse-derived fuels; compost; electricity; bio-CNG; techno-economic analysis; waste to energy; renewable energy

1. Introduction

As Africa pivots towards agenda 2063, the IEA estimates that Africa will lead the next phase of global energy demand due to its increasing population, urbanization and industrialisation. More importantly, Africa has in stock a vast expanse of vital natural resources including solar power and natural gas, as well as minerals such as uranium, chromium, cobalt, copper, manganese and platinum, which are very crucial for the global drive of renewables. Renewables, as well as natural gas, are ear-marked to transition the continent from a biomass-based energy economy to a more sustainable and reliable energy consumption [1]. Renewable energy (RE) has recently become very attractive, with competitive prices and more accessible technologies. In 2022, the weighted average Levelized Cost of Energy (LCOE) for solar PV became 29% lower than the cheapest fossil fuel, compared to it being 710% higher in 2010 [2].

Municipal solid waste (MSW) is an important resource for producing RE, although it has become one of the banes of most developing economies due to poor management [3]. One of the most popular strategies to effectively manage MSW is to convert the waste to energy known as waste to energy (WTE) or Energy from Waste (EfW) strategies [4]. WTE recovers the energy from waste and converts it into value-added bio-products. The energy is considered a form of renewable energy and thus has a positive environmental impact compared to fossil fuels, and also creates a bioeconomy for economic gains [5]. WTE technologies are available depending on the type, quantity and characteristics of the feedstock, the required energy method, economic conditions, environmental standards and specific factors [6]. The most commonly used WTE technologies are thermal, biochemical and chemical technologies, although thermal technologies such as incineration, gasification, pyrolysis and landfill gas recovery are more dominant [7]. Hybrid RE systems (HRES) integrate two or more technologies. These systems combine complimentary benefits from each technology and, in some cases, reduce the risk of dependence on only one source of raw material or resource [8,9]. Some configurations are solar and anaerobic digestion (AD) [10,11,12]; AD and gasification [13]; AD, aerobic composting, gasification and incineration [14]; AD and solar thermal systems [15], pyrolysis and AD [16]; Concentrating Solar Power and AD [17]; and solar PV and hydrogen [18].

The business model for most 100% renewable energy projects depends on the revenues from the sale of electricity [19]. Studies from the Finnish biogas branch indicate that non-energy products such as recycling nutrients (manure), gate fees and transportation fuels are key to ensuring an attractive return on investment from biogas plants [20]. Additional bio-products can be potentially produced from WTE plants with major applications for domestic, industrial and transportation uses [21]. These include bio-Liquified Petroleum Gas (bio-LPG) [22], biomethane [23], bio-compressed natural gas (bio-CNG) [24], Refuse-Derived Fuel (RDF) [25], hydrogen [26], carbon credits [27] and recycling nutrients (compost) [28].

In the EU, alternative fuels such as the RDF derived from waste and biomass contribute, on average, over 40% of the thermal energy used by cement industries. Germany and the Czech Republic substitute over 60% of conventional fuels in cement plants with waste with a potential to increase that to 80% by 2027 [29]. The Netherlands substitutes as high as 83% [30]. In Togo, alternative fuels such as RDF have the potential to significantly reduce the energy consumption of cement plants by 15 EUR/ton and improve their sustainability through reduced emissions [31]. In producing and substituting RDF, the main beneficial component is the fuel savings from production costs and emission reductions [32]. Although the main driver is the direct economic benefits, other important impacts include the reduction in greenhouse gas (GHG) emission, reduction in exploitation of virgin materials and sustainable waste management [29]. Also, for any RDF plant to be economically feasible, the revenue model must include gate fees, product sales (RDF, recyclables and compost) and additional financing support through the Capital Investment (CAPEX) from the municipality. The study further concluded that an appropriate MSW management system will depend on factors such as land availability, a local or foreign market for the recyclables and the energy product, as well as local social, economic and environmental issues [33].

Hydrogen (H_2) has also become very relevant within the global energy market. It is not a fuel in itself but an energy carrier. It has the potential to store energy in the form of molecules, which can be stored and transported more easily than other renewable energy sources such as solar and wind. Many countries have developed roadmaps to create a H_2 economy [34]. It also has major applications in the energy, transport and chemical manufacturing sectors [35]. H_2 is commonly identified by three major colours, based on the life cycle GHG emissions of the input energy. The colour coding specifically refers to the following input energy sources: grey (fossil fuels), blue (fossil fuels with carbon capture) and green (renewable energy). Colours such as brown (coal), yellow (solar-powered electrolysis) and purple (the nuclear-powered electrolysis of thermolysis have also been used [36]. Biogas is an important renewable source for the production of green H_2 [37,38]. Steam methane reformation (SMR) is one of the most common and advanced technologies for the production of H_2 [39,40]. In a recent study by Tamilselvan and Selwynraj [41], SMR gave a high yield of 10.15 kg/h using methane with a 99% purity when compared with other methods. In the context of West Africa, H_2 production from biogas produced from food waste has been proven to be feasible for both Ghana and Nigeria [42,43].

Digestate is an important byproduct of the AD process [44]. It is also an important fuel for plant growth as it provides energy for various metabolic activities, encouraging plant growth. It creates a circular economy when it is further processed into organic compost products, and it has been incorporated into many WTE plants [45]. Some studies consider compost a recyclable product, which is not its conventional categorization, but, in technical terms, the nutrients being returned to the soil constitute recyclable material [46]. Globally, the renewable energy sector is affected by factors such as interest rate fluctuations, uncompetitive tariff regimes, the high cost of capital, fragile economic growth patterns and inadequate interest and government funding into research and development. The factors affecting its feasibility are context-specific and include the seasonal availability of feedstock, governmental subsidies, the price of products, etc. [47]. An evaluation of five case studies in South Africa revealed that flexibility in terms of multiple revenue sources/products and feedstock types increases the financial feasibility of a biogas project [48]. Subsidies support the feasibility of WTE systems since the revenues to be obtained from RDF and electricity sales do not directly cover both CAPEX and operation costs (OPEX) [6]. Additional products such as carbon credits may be important to achieve this. In a recent study, Njoku et al. [49]

modelled a landfill-gas-to-energy project in South Africa and concluded that although the project had the potential to produce 6.6 GWh of electricity to 2952 households, the plant was not economically feasible and feasibility could only be attained through the sale of Certified Emission Reductions (CERs) which could bring in revenues of over USD 15,000,000 as of 2020. Like conventional power plants, the investment cost for WTE power mainly consists of engineering, construction and equipment, as well as infrastructure costs (e.g., the fuel supply system and grid connection) [49].

In Africa, the development of such renewable technologies and systems is rather slow. For instance, RDF has been researched since the 1970s, with countries such as the US, China, Germany and India leading in research outputs. Sub-Saharan Africa, on the other hand, is one of the least researched regions and requires improved efforts [50]. Countries such as Ghana have made significant strides in energy access but with low advancement in RE.

The Local Context—The Energy Sector and Hybrid Renewable Energy Systems

Ghana is the second most electrified country in sub-Saharan Africa (84%), with a total reliable power capacity of 4738.6 MW. However, the generation mix is dominated by fossil fuels (68.8%). Other sources are hydropower (29.1%) and renewable energy sources, including solar, wind and biomass (2.1%) [51]. An overdependence on fossil-fuel-based energy is subject to high insecurities in terms of supply and price fluctuations in the global market, resulting in large system disturbances [52].

Governmental interest in renewables is increasing, with several large-scale renewable energy projects having been launched in recent years. This includes the 50 MWp Bui Solar Power Plant, the Volta River Authority and 13 MW Kaleo solar project [53]. Renewables are also gaining increasing attention among researchers. Notably, a study on the feasibility of a hybrid solar PV and gasification system used the Oti landfill as case study. In this study, three distinct scenarios were considered: (i) a standalone WTE plant, (ii) a standalone solar photovoltaic (PV) plant and (iii) a hybrid combination of the two. Remarkably, all renewable energy plant scenarios demonstrated investment potential. The solar PV plant emerged as the most financially attractive option, with a Net Present Value (NPV) of GHC 324.79 million, a payback period (DPP) of 4 years, an Internal Rate of Return (IRR) of 44%, and a Debt Payback Index (DPI) of 2.7 [54]. In a separate investigation, the techno-economic feasibility of employing hybrid solar–wind–diesel–battery systems for electricity generation in remote areas of southern Ghana was explored [55,56]. The findings underscored the critical role of the government and policymakers in ensuring the affordability of electricity for both households and commercial consumers. A sensitivity analysis revealed that factors such as the cost of fuel significantly impact the LCOE for Wind–DG–Battery systems. In the Ghanaian context, fuel costs are influenced by variables like exchange rates, crude oil prices and inflation. Variables like inflation, discount rates and interest rates can be regulated through precise governmental economic policies. In a cooperative approach, studies have argued that there is the critical need for creating the necessary economic environment that encourages sustained investment in the renewable energy landscape. These studies demonstrate that hybrid renewable energy systems are a promising solution for Ghana's energy needs. A study was conducted to develop a reliable and cost-competitive autonomous energy supply system with renewable energy resources. As a reference site, a university campus in northern Ghana was chosen. The optimal configuration consisted of 92 PV panels, 9 wind turbines, 32 batteries and 1 diesel generator. The proposed method was applied to a cluster of villages in Bonsaaso, located in the Amansie West District of the Ashanti Region of Ghana [57].

Across Africa, many WTE plants are springing up which have the potential to sustainably manage municipal waste. For instance, the new Reppie WTE plant in Ethiopia processes 1400 tonnes of MSW per day into electricity to cover 30% of the city's energy needs [58]. Also, Safisana in Ghana has a capacity of 100 kW from hybrid solar–biogas and provides grid-connected electricity and compost [11]. With funding support from the German government, a 400 kW pilot WTE plant is under construction in Ghana, which will treat 50 tonnes/day of mixed MSW through a hybrid solar PV–biogas–pyrolysis plant to produce electricity, compost and other recovered materials [59]. This is the first of its kind in Ghana and is expected to contribute to the country's renewable energy resources [60]. This is a major step in the development of WTE plants in Ghana because WTE research has mainly been based on theoretical feasibility assessments without the physical pilot plants for case study investigations [12,61]. The establishment of a pilot plant is relevant for the whole of sub-Saharan Africa because it provides a basis for the assessment of the feasibility of WTE plants in general. The hybrid model being implemented in Ghana is also relevant to recent advancements in hybrid WTE and the feasibility of alternative fuels and other products with economic value. With the current economic challenges in the country, feasibility studies provide preliminary information to attract potential investments.

The current study therefore aims to carry out an assessment of the financial feasibility of the new pilot plant in Ghana by comparing three scenarios with various technical combinations of electricity and fuel products. This will form the basis for decision making for the replication of the pilot model in other parts of the country, as well as the continent.

The scenarios were selected based on the following reasons:

i. Hybrid renewable energy plants have conventionally focused on electricity as the main product and, in most cases, the only product. For instance, in a review of 100% RE systems it was revealed that 97% of all RE energy research focused on electricity [19]. Ghana's National Energy Statistics 2022 reveal that biomass contributes 34%, petroleum 50% and electricity 17% to energy consumption. Thus, fuels remain an important source of energy, especially for residential 39%, transport (38%) and industrial consumption (16%) [62].

ii. Ghana, through the Energy Sector Recovery Programme (ESRP), placed a moratorium on the signing of new power purchasing agreements due to overcapacity in its energy system [52]. This is an indication that electricity may not be the only universally desired product from WTE projects. Such plants may sometimes require the energy to be converted to fuels to create value for the market.

iii. Waste segregation in Ghana is estimated to be at only 2%. Thus, previous projects, such as Safisana, have invested additional resources into public education and other social research activities to receive highly segregated organic waste for AD systems. However, this does not provide a holistic solution to the remaining fraction of the waste. Also, the Integrated Recycling and Compost Plant (IRECOP), Kumasi Compost and Recycling Plant (KCARP) and Accra Compost and Recycling Plant (ACARP) dispose of residual waste at landfills after organic waste and plastics have been recovered [63]. The case study plant being considered in this study has the capacity to use all waste fractions that are practically available to produce various products.

The outcome of this study thus becomes relevant in selecting the best model that creates a balance between environmental gains for sustainable waste management and financial investments and returns.

2. Materials and Methods

This study used a combination of primary data from the plant under construction as well as secondary data from the literature mainly to estimate the expected operational performance conditions of the plant. The main reference point for this study are the following three scenarios and five products: electricity and fuels (bio-CNG, green H_2, RDF and compost). RETSCREEN EXPERT software version 6.0.7.55 was used to model the energy (electricity) output from the plant. Once this was established, the financial analysis was carried out entirely in Microsoft Excel 2019 software by creating a financial model. The Excel workbook that has been developed will become an important decision-making tool to support project developers in continuously analysing the feasibility of similar systems across the country or introducing new products into the case study plant. Similarly, authors such as those in [13] have carried out a techno-economic study of a hybrid AD and gasification system in South Africa using MS Excel.

2.1. Study Area

The pilot plant is located at Gyankobaa; a small rural community in the southern parts of the Atwima Nwabiagya Municipality of the Ashanti Region of Ghana. The municipality has 64 settlements covering a land area of 184 sq. km, with a 64.7% rural population. It is specifically located at longitude 6.6 and latitude −1.8. The municipality has an estimated population of 103,698, with an annual growth rate 2.6%. The main economic activities are farming and livestock rearing. The electricity coverage is about 70% with 31,109 people, mainly in 24 communities, without access to electricity. The plant is designed to receive 50 tons of MSW per day from the Atwima Nwabiagya Municipality as well as from adjoining districts within a radius of 30 km from the plant location, such as Amansie West, Atwima Mponua, Atwima Kwanwoma, Asokwa, Kwadaso, Suame and Ahafo Ano South [64].

2.2. Technical Description of the Pilot Plant

The plant site receives 50 tons/day of mixed MSW. Onsite segregation is carried out to produce each product as detailed in the following sections. MSW in Ghana typically includes waste from household and commercial activities such as market centres, restaurants and offices, but not medical, agricultural or industrial activities [65]. The MSW collection trucks arriving at the plant deliver waste into a bunker, after which the waste is transferred into a semi-automatic segregation system. The segregation carried out is similar to that of other waste management plants in the country, such as IRECOP, ACARP and KCARP. Waste is separated into three pathways: organics, plastics and residuals, as demonstrated in Figure 1. Other components such as scrap metals, e-waste and glass are stored and transferred to recycling facilities. Waste characteristics carried out in the study area indicates 48% organics, 20% plastics and 30% residuals [63]. This is comparable to that recorded by [66], which noted 43.1% organics and 17.8% plastics.

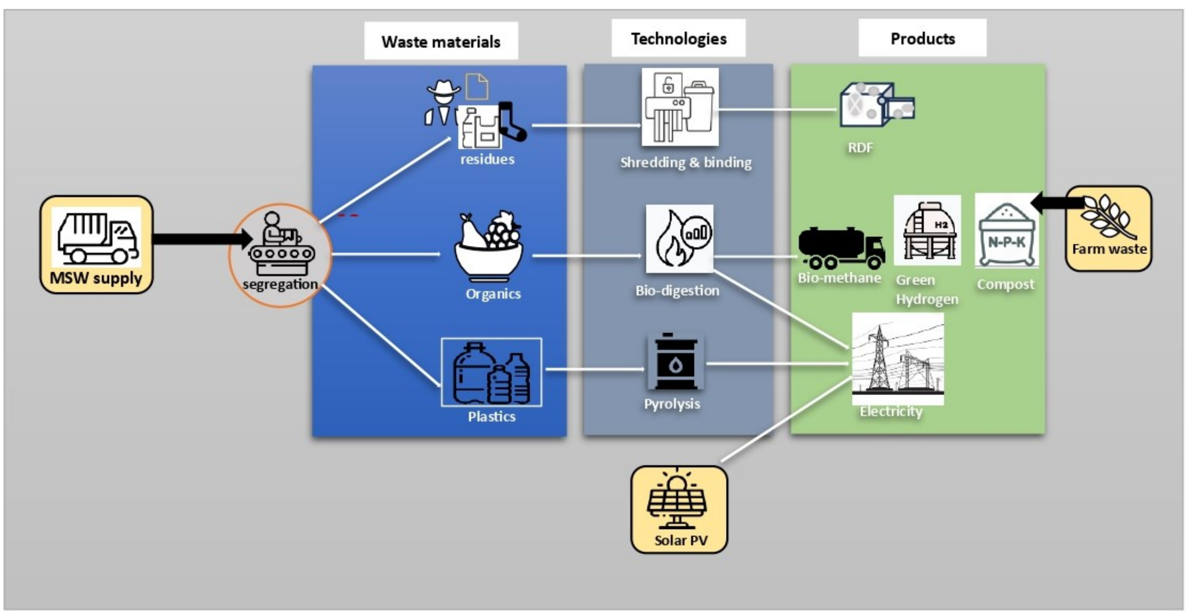

Figure 1. Process flow within the plant to produce products.

2.3. Description of Scenarios

The scenarios and fuels were selected based on the technical production capacity of the plant and the availability of local, regional or international markets for the products. In terms of electricity, an off-taker agreement/ Power Purchasing Agreement (PPA) could be secured with the public energy agency, the Electricity Company of Ghana, which has been mandated to enter into such agreements with power producers [67]. The fuels, on the other hand, will require bulk direct purchase agreements with potential buyers/off-takers.

Below is a description of the scenarios considered, with the framework represented in Figure 2:

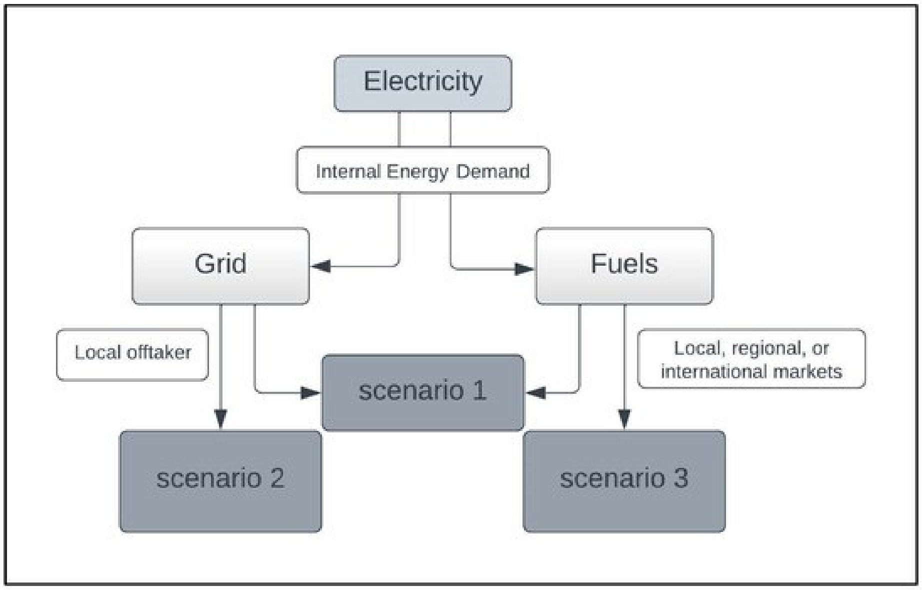

Figure 2. *Representation of the scenarios, indicating their relationship to each other.*

- Scenario 1 (Electricity and Fuel)—this provides an integrated option for the plant, with both a PPA for electricity exported to the grid and other fuels. This is the base case scenario, because the pilot plant has been constructed to test various options to provide key locally applicable data for academic research activities and technological advancement. In the very uncertain and relatively young market for fuels such as green H_2, a secure source of revenue from a PPA provides greater security for an investor while also providing an opportunity for them to invest in cleaner fuels for industrial activities. It also presents a higher investment cost and internal energy demand due to it needing more equipment.
- Scenario 2 (Electricity only)—this considers electricity as the only product from the plant. It is assumed that a long-term power purchasing agreement (20 years) is secured, in which the off taker takes on all the energy produced for grid supply. In this scenario, all the methane produced from an AD system is converted to electricity and the digestate is given at no cost to local farmers. No additional activities are required, thus generating the smallest investment and operational cost scenario.
- Scenario 2 (Fuels only)—this considers producing four types of fuels for local and international markets: bio-CNG, RDF, green H_2 and compost. The pilot plant will be committed to meeting the specifications of the buyers as much as financially feasible. Although this provides greater flexibility in terms of a wider spread of markets, including local and international consumers, the risk is higher with greater competition from other suppliers. However, long-term purchase agreements may be secured with buyers to reduce such risks and provide substantial price competitiveness. This model will require more investment in market research and business case development to reduce the risk. The compost product, for instance, will face significant competition from other local waste processing facilities such as KCARP in Kumasi and IRECOP, Jekora Ventures Limited (JVL) and Safisana in Accra [63].

2.4. Computation of Energy Output

Electricity from a plant is produced in all three energy systems, AD, pyrolysis and solar PV, after which a proportion is exported to the grid. The energy exported to grid is calculated as the net from the gross energy produced minus the internal consumption. The internal energy demand for each scenario is calculated as

$$E_{grid}=E_{Tot}-E_{Int} \quad (1)$$

$$E_{Int}=E_{hr}\times T \quad (2)$$

where E_{Tot} is the total electricity (energy) produced from the AD, solar PV and pyrolysis systems, E_{grid} = electricity exported to grid, E_{Int} is the total energy demand, E_{hr} is the average daily energy consumption, and T is the total operation hours per annum.

RETSCREEN® expert software was used to estimate the total energy output from the system. RETSCREEN software provides a platform for assessing the technical and economic feasibility of renewable energy systems by providing a spreadsheet-based model. It provides a simple decision-making tool for policy makers, planners, project financiers and equipment vendors, thereby reducing project risk [68]. It has been used by several authors to estimate the energy output as well as carry out detailed feasibility analysis, including financial analysis [69,70,71]. Since the electricity is generated by three technologies, E_{ToT} was computed within the software by creating three separate tabs within the energy worksheet. Below are the details for each technology.

2.4.1. Solar PV System

In order to simulate the solar PV system, the exact specifications of the system installed on-site were used. The RETSCREEN software requires the climate specific data of the site for a minimum of one year. However, at the time the data were collected, the system was undergoing optimization tests, with the data collected spanning only 3 months. Thus, the inbuilt data from NASA for the specific site was adopted for the study, which calculated the daily solar radiation horizontal (kWh/m^2/d). The detailed specifications of the system were then input into the energy worksheet. The solar PV system consists of panels, a battery, an inverter and cables. A Talesun TP6L72M mono-Si module with an efficiency of 20.1% has been roof-mounted at the site because it is more locally accessible and its technical specifications are adequate. One unique design is that the solar panels have been used as roofs for the open shed which houses the segregation and composting equipment. This significantly reduced the construction cost. Based on the solar irradiance data received for the selected location, the modules have been tilted at an angle of 5° for maximum energy output. A Sinexcel PWG2 inverter, with a capacity of 150 kW and a 95.5% efficiency, is attached. The miscellaneous losses from the module are assumed to be 10% due to the area being relatively rural and surrounded by thick forest and farmlands with low atmospheric dust. Irrespective of this, dust is expected to be slightly higher during the dry season months from November to March each year. The module lifespan is expected to be 20 years. In this study, the energy exported to the grid varies under scenarios 1 and 3 due to the internal energy consumption of the different equipment used.

2.4.2. Anaerobic Digestion (AD) System

For energy production from waste, the segregated organic waste is transferred to a 1000 m^3 biodigester to produce biogas at a rate of 45 m^3/h. The digestor is a continuous stirred reactor. Cow dung is added to the biodigester as it serves as an inoculum to introduce microorganisms for the biodigestion process. Thus, no additional microorganisms have been introduced into the system.

For scenario 3, the biogas is diverted to produce three products, but the quantity required to produce electricity is estimated first, after which the remaining biogas is diverted to produce green H2 and, subsequently, bio-CNG.

Biogas typically contains methane (CH4), carbon dioxide (CO2), hydrogen sulphide (H2S) and other trace elements. It must undergo cleaning to produce pure CH4. Once cleaning is complete, the biomethane may be divided into two portions: green H2 (and bio-CNG) and electricity, based on the scenario.

To produce electricity, purified CH4 is directed to a 100 kW Combined Heat and Power (CHP) engine with an efficiency of 35%. A CHP is very relevant for such systems because it provides additional heat energy, which is redirected to the digester to provide heat for the biodigestion process [72]. Planned and unscheduled repair and maintenance works are expected to occur, at most, 30 days per year.

The electrical energy output from the AD system is calculated as shown in Equation (3) [73]:

$$E_{AD} = (V_{CH4} \times LCV_{CH4}) \times P \times T \times Eff \quad (3)$$

where E_{AD} is the energy generated from the AD system per year (kWh/yr) and V_{CH4} is the volume of CH_4 (m^3) based on the volume of biogas allocated. This is calculated as the product of the quantity of biogas and the % CH_4 content in biogas. *LCV* is the Lower Calorific Value of the CH_4 (kWh/m^3), which is 9.94 kWh/m^3 under normal temperature and pressure conditions [74]. *P* is the power capacity of the CHP engine (kW). *T* is its operational hours per year (hrs/yr). *Eff* is the conversion efficiency of the CHP engine (%).

2.4.3. Pyrolysis System

The pyrolysis system typically produces bio-oil, syngas and tar [75]. For this study, segregated mixed plastic waste is transferred to the pyrolysis reactor at a rate of 1 ton per day to the undergo thermal decomposition. The use of a CHP engine in pyrolysis has been adopted by several authors and provides additional heat energy to aid the process [76]. The syngas is directed into a 50 kW CHP engine to produce electricity for the pyrolysis process, thus making the system self-sustaining. The bio-oil is directed into a 100 kW CHP engine to produce electricity for the grid. The energy generation from the pyrolysis system is calculated as

$$E_{pyr} = P \times T \times Eff \quad (4)$$

where E_{pyr} is the energy produced from the pyrolysis system (kWh), *T* is the total operation hours per year (h), and *Eff* is the efficiency of the CHP engine, which is 35%.

2.5. Output of Fuels

The fuels are obtained from three main sources—biogas, digestate and residual waste.

2.5.1. Green Hydrogen (H2)

Green H_2 is produced from CH_4 through steam methane reformation (SMR) under scenarios 1 and 3. SMR is the most commonly used technology for H_2 production due to its cost effectiveness and the lower temperature and energy requirements of H_2. It involves the conversion of hydrocarbons and steam to H_2 and CO_2, with the aid of a catalyst such as nickel. The most significant strength of SMR is its high conversion efficiency of 74–85% compared to other methods such as biomass pyrolysis (35–50%) and electrolysis (40–60%), while, on the other hand, it produces high amounts of CO_2, which is a GHG with a large climate impact [77]. It has been proven that H_2 production through SMR has a direct positive relationship with its reforming efficiencies, which are also dependent on the CH_4 content of biogas [42]. H_2 production is achieved via a reformer reactor and a shift reactor to fulfil the major reactions outlined in Table 1. Other reactions occur alongside these reactions and have been clearly outlined by [78]. The reactions are aided by a nickel catalyst with dry reforming and shift reactions occurring simultaneously. A boiler is used to produce steam, which is the main source of fuel for the reactor due to the energy contained in the water molecules. This is similar to the process used by [42].

Table 1. Reactions for steam methane reformation using biogas.

Description of reaction	Reaction [39,78,79]	Equation (5)
Dry reforming of methane within the reformer reactor	$CH_4 + CO_2 \rightarrow 2CO + 2H_2$	(5a)
Water–gas shift reaction	$CO + H_2O \leftrightarrow CO_2 + H_2$	(5b)
Steam reforming of methane	$CH_4 + H_2O \rightarrow CO + 3H_2$	(5c)

The quantity of H_2 to be produced can be computed as the final reaction of Equation (5a–c), as represented by Equation (6) below [42]. The reactions also greatly depend on the reformer and boiler efficiencies, which are assumed to be 80% each [80].

$$Q_{H2} = V_{CH4} \times \rho_{CH4} \times Eff(boiler) \times Eff(reformer) \times 0.5 \quad (6)$$

where Q_{H2} is the total H_2 produced (kg); ρ_{CH4} is the density of the CH_4 (kg/m^3), which is considered to be 0.717 kg/m^3; V_{CH4} is the volume of purified CH_4 at 95% purity; and $Eff_{(boiler)}$ and $Eff_{(reformer)}$ are the efficiencies of the steam boiler and reactor for the dry and steam-reforming reactions. It is assumed that 1 m^3 of steam-reformed CH_4 is equivalent to (0.5 × ρCH_4) kg of H_2 gas.

H_2 is a free gas that must be stored appropriately before transportation to potential markets/off takers. At the plant under study, storage will be accomplished through high-pressure compression into cylinders at 350 bar. The final volume of the compressed H_2 (m^3) is determined by the equation

$$Q_{H2compressed} = (Q_{H2} \times Eff_{compression}) \quad (7)$$

where $Eff_{compression}$ is the compression efficiency, which is assumed to be 95% [18].

2.5.2. Bio-CNG

Green H_2 is converted to compressed CH_4 gas, which has similar properties to compressed natural gas (CNG). The Sabatier reaction explains the process as the reaction of H_2 and CO_2 to produce methane and water under elevated temperature and pressure conditions in the presence of a catalyst. A nickel catalyst is used in this study. The efficiency of the methanation reaction was taken as 70% [81]. The reaction is represented below [81,82]:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (8)$$

2.5.3. Compost

The focus of this study is to convert digestates into a commercially viable product for the local market. In scenario 2, the digestate, which will otherwise become a waste material, is converted into an important fuel for plant growth through the composting process. In the context of this study, the raw materials for the production of compost are digestate and farm waste from adjacent farms.

On site, a holding tank has been constructed to hold the fresh digestate during its release from the biodigester. It then undergoes mechanical separation to separate its solid and liquid portions. In total, 80% of the liquid digestate (LD) is directed back to the biodigester to provide additional moisture for the process, while the remainder is used for periodic watering of the compost piles in the compost shed. The windrow composting process is used because it requires little equipment, labour or energy, as described by [83]. The solid digestate (SD) is first transferred into the composting shed, where it is uniformly mixed with farm waste (FW) from the nearby farm in a ratio of 1:4 for SD and FW, respectively [84]. FW serves as a bulking agent, which is needed to enhance the physical and chemical properties of SD [28]. The mixture of FW and SD is thoroughly mixed manually and heaped into piles of about 1.5 m tall. It is watered with 0.5 L/kg of LD on the first day and subsequently at a rate of 1 L/kg every 7 days for 60 days. Since this is an aerobic process aided by microorganisms, frequent airing of the piles and daily temperature monitoring is carried out to avoid anaerobic conditions and promote homogeneity. After maturation, the compost is screened and bagged to make it ready for the market.

The quantity of compost produced can be theoretically derived using the equation

$$Q_{comp} = (Q_{SD} + Q_{Bulk}) * \%loss \quad (9)$$

where Q_{SD} is the quantity of *SD*, Q_{Bulk} is the bulking agent and %loss is the loss of weight due to the composting process.

Also, a market study was carried out in November 2023 to assess the key characteristics of similar products on the Ghanaian market. Key organic fertiliser suppliers were contacted for similar products. Nine products were selected based on their raw materials (organic fraction of MSW or digestate) and the process used (aerobic decomposition/composting). One bag of each selected product was purchased from the open market. The following data were collected: the price, weight and the location of the manufacturer and raw materials.

2.5.4. Refuse-Derived Fuel (RDF)

RDF is produced from the residual fraction (RF) of the waste obtained after the segregation process, and it contains items such as plastics, leather, paper/cardboards, etc., which have no direct recycling facility in the country. Although the digester and pyrolysis system are available to process the plastics and organics, some plastic particles still find their way into the residual fraction. The RF undergoes shredding and binding to produce bales for their direct supplying to off takers. Thus, the estimated quantity of RDF to be produced per annum is calculated as

$$Q_{RDF} = Q_{RF} \times CF \quad (10)$$

where Q_{RDF} is the quantity of *RDF* (tons), Q_{RF} is the total percentage of the residual fraction (tons) and *CF* is the combustible fraction in %.

2.6. Financial Analysis

The following indicators were used to determine the financial feasibility of the three scenarios: Net Present Value (NPV), Internal Rate of Return (IRR), LCOE and simple payback period (PBP). The LCOE is applicable to scenarios 1 and 2, and the IRR and NPV to all scenarios. The results are compared to determine the most feasible option for investment decision making. All currency conversions from Ghana Cedis (GHC) to Euros (EUR) were sourced from the official currency conversion website of the European Commission. In some cases, the results were also compared to previous studies in USD, using the same source for conversion. As of November 2023, when this analysis was carried out, EUR 1.00 was equivalent to GHC 12.60 [85]. The general parameters and assumptions used in the financial analysis are outlined below:

2.6.1. General Assumptions

- CAPEX—the capital cost of all infrastructure and equipment, which is spread over a construction period of 3 years. For the purposes of this study, detailed investments such as land and road construction are considered as support from the government. The CAPEX considered here refers to equipment and installation costs.

$$CAPEX = \sum C_{AD}, C_{pv}, C_{pyr}, C_{comp}, C_{seg}, C_{lab}, C_{infras} \quad (11)$$

- which represents the sum of the costs of *AD*, pyrolysis, composting, segregation, laboratories and other infrastructure, such as the bunker and shed. In the context of this study, the laboratory is assumed to be used only for research purposes for the facility and not income generating.
- Capital Financing—this is determined by the following factors: the debt-to-equity ratio, cost of equity and cost of debt. The cost of debt also depends on the maturity and grace period of the loan and the interest rate. For this study, the interest rate used was 3.05 %/annum, the grace period = 0 and the debt-to-equity ratio was 70:30 [86].
- OPEX—the pilot plant is currently undergoing operationalization tests and full-scale operation has not yet begun. Thus, although all the development-related costs are taken from the plant, its operational conditions are not yet verified or optimized. The OPEX is divided into the fixed and variable cost [87]. Human labour is needed to operate the segregation system and composting, while the energy systems remain largely independent, except for periodic and unscheduled maintenance that needs to be carried out. The OPEX was calculated as

$$\sum_1^{20} FC + VC \quad (12)$$

where *FC* is the fixed cost, which incorporates costs from labour, interest on debt, insurance, equipment replacement costs and scheduled maintenance. *VC* is the variable cost, which incorporates internal energy consumption, tax, materials, unscheduled maintenance and miscellaneous costs.

- Operation hours per annum (t)—the total operational hours per year is taken as 8040 hrs/yr.
- Lifespan—20 years.
- Annual inflation provides a good reflection of the rate of escalation of the prices of goods and services within the country. Thus, inflation provides a good basis for projecting the annual escalation of the selling prices of the products under study. It is taken as the average of the last 25 years, since the recent economic situation in the country presents a worse-case scenario with poor performance due to the impact of COVID-19. According to inflation data obtained from the World Bank, the average for the period is computed as 16.12% [88].
- Cooperate Income tax (CIT)—according to the Ghana Revenue Authority, the CIT for waste management companies is 1% within the first 7 years and 25% from the 8th year onwards [89].
- Discount rate—10%.
- Revenues—the revenues were obtained through a calculation of the product of the quantity of products and their market price in Euros (EUR). For electricity, the price used is adopted from the tariff at which the ECG buys power from the Independent Power Producers (IPPs), known as the Bulk Generation Charge (BGC). As of May 2023, the tariff was 0.088 EUR/kWh [90].
- Annual escalation rate of revenues—this was calculated based on the historic figures obtained for the escalation of tariffs for BGCs based on PURC tariffs since 2006. The average annual rate of increase was calculated as 25%.

2.6.2. Financial Feasibility Parameters

The LCOE calculates the total cost of producing one kilowatt hour (kWh) of electricity over a project's lifespan and is computed as the ratio of the total lifecycle cost to the total lifecycle energy production. It is important for assessing the cost viability of various projects utilizing different supplies of electricity over a long period, such as in this study. It is calculated using Equation (13) below by creating a model in Microsoft Excel [12].

$$LCOE = \frac{\sum_{t=1}^{n} \frac{CAPEX_0 + OPEX_t}{(1+r)^2}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{13}$$

where $CAPEX_0$ is the total capital cost of the project disbursed during the construction period, $OPEX_t$ is the O&M cost over the project's lifespan (EUR), E_t is the total energy generated over the project's lifespan (kWh/y), r is the discount rate (%) and t is the project's lifespan (y).

The NPV is the difference between the current value of cash inflows and outflows. The NPV function within Microsoft Excel was used to automatically calculate the NPV using the CAPEX, discount rate and the net cashflows over the project's lifespan. The IRR is also computed in Microsoft Excel using the net cashflows over the project's lifespan.

3. Results

A financial model was created for each scenario, in Microsoft Excel, on a separate spreadsheet. The pilot plant was established to provide adequate locally applicable data for the advancement of WTE systems across Africa. The following results are important in achieving this objective.

3.1. Technical Results for the Scenarios

The installed capacity of the solar PV and pyrolysis systems remains the same for all scenarios, while the AD capacity changes for each (Table 2). This is because the fuels (green H2 and bio-CNG) that are obtained from biogas in scenarios 1 and 3 account for the differences in the capacity of the AD system. Scenario 2 has the highest capacity and results in the lowest installed cost/kW.

Table 2. The installed capacity and cost/kW of the three energy technologies for each scenario.

Technology	Scenario 1		Scenario 2		Scenario 3	
	Installed Capacity (kW)	Installed Cost (EUR /kW	Installed Capacity (kW)	Installed Cost (EUR /kW)	Installed Capacity (kW)	Installed Cost (EUR /kW)
Solar PV	200	1050	200	1050	200	1050
AD (CHP)	100	5000	300	2333	0	0
Pyrolysis (CHP)	100	5000	100	5000	100	5000
Total capacity	400		600		300	
Average Installed cost		3683		2794		3025

Under Scenario 1, 50% of the output from the solar PV system is directed back to the plant for internal energy consumption. The energy outputs for each system and scenario are presented in Figure 3. For the base case (scenario 1), 810 MWh/yr of electricity is expected to be produced, with 562.72 MWh/yr exported to the grid. The difference represents the 50% of the output from the solar PV system redirected for internal use. Under scenario 2, 100% of the biogas produced is expected to be directed to the CHP engine to produce electrical energy. The AD system alone produces 844 MWh/yr of energy resulting in a total of 1373 MWh/yr from the whole plant which is expected to be exported to grid. From an installed capacity of 600 kW, the average installed cost is 2794 EUR/kW. This represents the lowest installation cost of the scenarios due to the need for a larger-capacity CHP plant with a relatively lower cost/kW, thus reducing the cost/installed capacity ratio. On the other hand, in Scenario 3, only fuels, 100% of the biogas produced is used for fuels (green H_2 and subsequently bio-CNG).

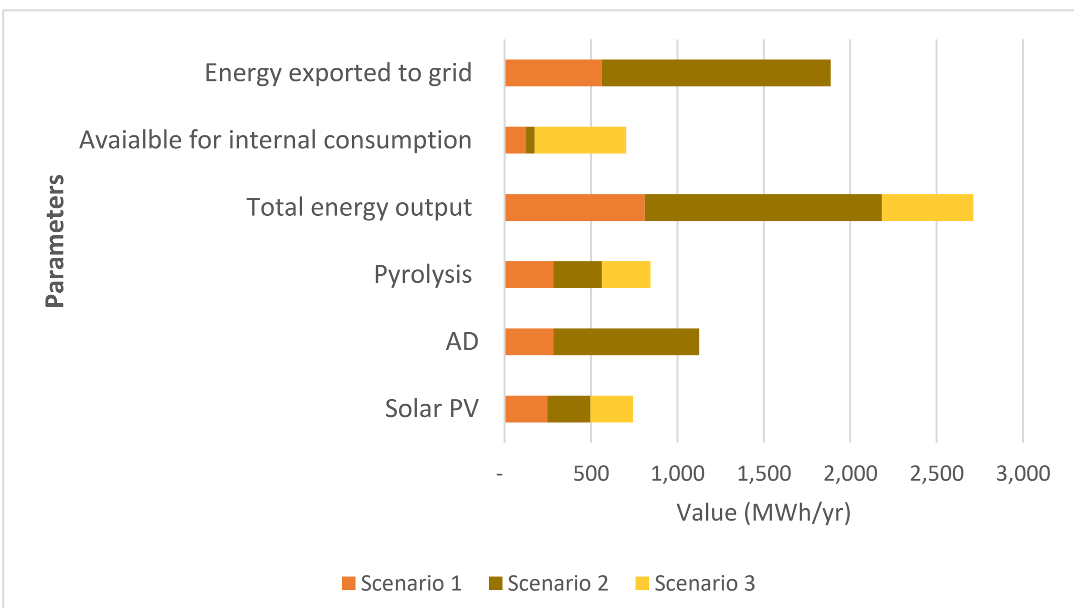

Figure 3. *Comparison of the technical variations and energy output for each scenario.*

3.2. Financial Analysis

The first step in the development of the financial model is the estimation of the revenues and Operation and Maintenance (O&M) costs for the three scenarios. Revenues depend on the quantities and prices of the products. Although the quantities change per scenario, the prices remain the same for all scenarios.

In order to determine the market value of the compost product that will be developed, a market study was carried out. From Table 3, the proposed price for the compost product is recommended to be set to the same as the average price, 0.19 EUR/kg.

The O&M costs are important in determining the final earnings before tax. In the proposed model, the project manager is expected to make annual debt repayments to the lender. Thus, the fixed cost (which includes debt repayment) is higher than the variable cost. The total O&M costs are 14%, 3.86% and 13% for scenarios 1, 2 and 3, respectively.

Table 3. *Results of the market study on common compost products on the market.*

Product name	Manufacturer	weight / bag (kg)	Price/ bag (GHC)	Price/ kg (GHC)	EUR/ kg
Asaase Gyefo	Safisana	30	40	1.33	0.10
Fortifier	JVL	50	50	1	0.08
Asaase Nufusuo	Farmers Hope	50	250	5	0.4
ACARP	ACARP	50	85	1.7	0.14
Grow Plenty	Green Gro Ghana	25	40	1.6	0.13
IRECOP	IRECOP	50	65	1.2	0.1
Super soil	S&M organics	50	250	5	0.4
Best fertiliser	Best fertiliser company limited	25	35	1.4	0.11
Green organic fertilisers	GML Green Energy Ghana Limited	30	90	3	0.24
Average values		**40**	**100**	**2.36**	**0.19**

The financial analysis of all scenarios has been summarized in Table 4. Scenario 1 is the best performing, with an NPV which is more than four times the investment cost. The PBP is also best performing under scenario 1, while scenario 2 is the worst performing. The LCOE for scenario 3 is very high because it involves only energy for internal consumption, which has the lowest capacity of 300 kW.

Table 4. *Summary of the financial performance of each scenario.*

Parameter	Scenario 1	Scenario 2	Scenario 3
NPV	13,795,828.29	1,701,413	9,954,464.83
IRR	24%	12%	21%
LCOE	0.57	0.336	0.691
PBP	12	17	13

4. Discussion

The results of this study clearly indicate that the combination of fuels and energy is a more economically feasible option. The average LCOE of the three scenarios is 0.51 EUR/kWh. Equally high LCOEs have been recorded in some studies. In a study in 2018, the average LCOE for bioenergy and solar PV was 0.054 and 0.075 EUR/kWh [85,91]. A recent review by [92] of 161 case studies across the globe indicates that 0.878

EUR/kW has been recorded in countries like Pakistan, while an LCOE of 0.26 EUR/kWh may be realistic in countries such as Germany, Spain and New Zealand, where household electricity prices are comparatively higher and includes taxes; meanwhile, Ghana lifeline consumers receive subsidized tariffs [93]. However, reported values for HRES in Ghana include 0.264 EUR/kWh [12] and 0.32 EUR/kWh [56], which are similar to scenario 2. On the other hand, ref. [94] recorded 0.64 EUR/kWh, which was over 400% higher than the End User tariffs (EUTs) at the time of that study, but it is similar to what has been recorded in this study for scenarios 1 and 3. Considering that the average residential EUT for electricity in Ghana is 0.27 EUR/kWh, as reported in May 2023, the lowest LCOE is about 20% higher [93]. Also, in the same study, the capacity of the system was 30 kW. This is consistent with the results obtained in this study, where the lower-capacity systems recorded very high LCOE values.

It has been proven that the capacity of renewable energy systems affects their cost [91]. The LCOE in Table 4 clearly indicates that the cost of renewable energy is closely linked to the capacity of the system. This also provides an indication that the LCOE may improve at a higher capacity. Thus, the small capacity of the current plant makes its economic feasibility unrealistic, especially under the current economic conditions of the country where average inflation is 16.12%. In the assessment of the financial feasibility of WTE, solar PV and hybrid plants, it was concluded that the standalone system is the best investment option because of its low operational cost compared to the other options [54]. However, that study considered electricity as the only product. This is similar to what has been recorded in this study, where scenario 2 (electricity only) had the lowest LCOE, which is still far above global prices and also the average EUT.

Considering the LCOE, the cost of internally generated power is too high and it cannot compete, even if it is directly supplying heavy industries, with tariffs ranging from 0.22 to 0.39 EUR/kWh [93]. For special load consumers, the End User tariffs are equivalent to 0.39 EUR/kWh, which is about 40% less than the cost of self-production. Thus, from an economic standpoint, it is more economical to purchase power from the national grid for internal uses when only fuels are being produced (scenario 3), compared to self-production. On the other hand, this is not the most environmentally friendly option because the energy from the national grid contains only 2% renewable energy, excluding that from hydropower [62]. Also, the added benefits associated with the environmentally sound management of waste must be considered since self-production allows more waste to be processed onsite. Overall, 16,750 tonnes of MSW is expected to be treated at the plant per year, which mitigates numerous societal challenges. In order to incentivize potential investors, governmental policy instruments such as subsidies, lower tariffs for renewable energy, tax exemptions, lower lending rates and concessional financing will improve the feasibility of such projects [95].

In order to expand capacity in future projects, the solar PV system will be the more cost-effective option compared to the other systems. The cost/kW of the solar PV system, as recorded in Table 2, is about half that of the AD and pyrolysis systems. According to IRENA, the cost of renewable energy technologies has seen tremendous price reduction in recent years. The installed costs for bioenergy and solar PV in 2022 were 2085 EUR/kW and 845 EUR/kW, compared to 2209 and 3898 EUR/kW in 2010, respectively. This is attributed to soaring global fossil fuel prices as well as recent technological advancements [2,85]. As evidence to this, the technologies in this plant were procured in 2021, demonstrating that technologies have seen a further drop since then, which will become relevant when making projections for future projects. The lowest average installed cost was seen under scenario 2 (2794 EUR/kW), which is due to the higher installed capacity largely from the AD system. In order to direct 100% of the biogas towards the production of electricity, a 300 kW capacity CHP engine is required. On the other hand, scenario 3 considers 100% of the biogas as being directed to fuels, with 300 kW of electricity produced (representing 100% of all energy produced) to drive the internal energy demand for the fuel production. This implies that in both scenarios 1 and 3, energy is converted to fuels, which store the energy for other uses [96]. The electricity produced is specifically redirected to the plant for internal use, for purposes such as segregation, the compression of gases and minor consumption for offices and laboratories and not for grid connection. Thus, the installed capacity is 300 kW, which is sourced from solar PV and pyrolysis, producing 529 MWh/y of energy for fuel production. Overall, the electrical potential of biogas (2.28 kWh/m^3) is similar to previous studies by [97], where each cubic meter of biogas had an electrical energy potential of 2.04 kWh. The slight difference may be due to the experimental nature of their work as compared to this study, where actual data were being collected.

Since the project site is located in a largely rural area, with about 70% of the population engaged in agriculture or related activities, compost is likely to be a very viable product. Preliminary tests on the biodigester reveal that digestate is released from the biodigester at an average rate of 6 m^3/h. In a 2018 market study of compost prices in northern Ghana, the average cost/kg adjusted to the current 2023 exchange rate was 0.04 EUR/kg, compared to the 0.19 EUR/kg in this study. This is a reflection of the state of the country's inflation, which is calculated to be 16.12% per annum in this study [98].

Equity investors usually assess project risk and feasibility based on returns of at least twice the value of the debt being offered [86]. For scenarios 1 and 3, the IRR is more than twice the discount rate, showing high feasibility. Scenario 3 also performs relatively well based on its NPV and IRR, although the LCOE for the energy being used at the plant makes it unrealistic to source energy at such a high cost for producing fuels. One option for future projects will be to source energy from the national grid for internal consumption, since its EUT is far lower than the cost of self-producing power.

The financial model developed required detailed considerations of the O&M costs (Figure 4). The O&M costs in this study are relatively higher than those recorded in other studies. The fixed costs and variable costs for scenario 2 were the lowest because solar PV systems have low O&M costs, which are calculated as 4% of the CAPEX, but highest costs were seen for Scenario 3 due to the high energy demand for the production of the fuels. This is higher than the 1% stated by [54], but within range from the study [99]. This is due to the consideration of costs such as insurance, annual debt repayments including interest, and equipment replacement costs in year 10 and 15. Although it is quite high, it provides significant risk reduction for the project developer. The variable costs in scenario 2 are the lowest due to no costs for materials and transportation of goods and a low possibility of unscheduled maintenance works.

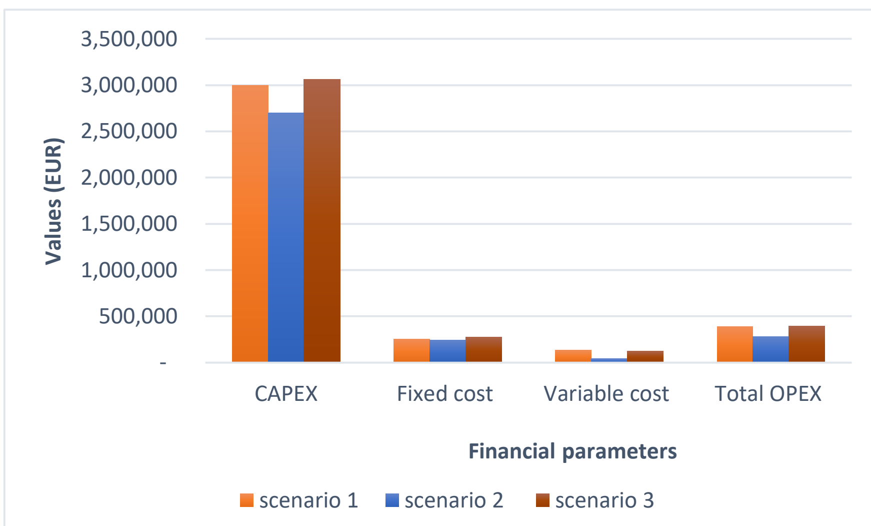

Figure 4. *The breakdown of capital costs and operational costs for each scenario.*

This study considered the CAPEX as being financed by an independent investor with a debt-to-equity ratio of 7:3. Overall, this resulted in a good NPV, which makes the investment attractive. From an investment point of view, the current model (scenario 1) is more attractive because it provides a higher NPV over a shorter payback period. It also reduces the risk of the investment by spreading the revenue sources between government PPAs and an open market trade in fuels. On the other hand, in a situation where public policy does not allow such PPAs to be signed, the trade in fuels also provides substantial benefits to the investor, although the repayment period for the debt must be carefully bargained with the lender. From an environmental point of view, scenario 2 does not provide a holistic solution to local waste management challenges because residual items must be sent back to the landfill, where a fee must be paid. An additional EUR 12,000/y is estimated to be paid as the cost to dispose of the RF, which could otherwise bring in additional income. The low revenue and operational cost ratio resulted in low earnings before tax (EBT), mainly as a result of debt repayment. Also, the negative impact of emissions during transportation to and from the landfill cannot be overlooked [100].

Conclusion

Hybrid renewable energy systems are gaining more attention among policy makers and governments as a means to solve current energy challenges in a sustainable manner. In Ghana, the management of MSW still continues to plague the country, with less than 2% of the waste being segregated. The government has recently supported the construction of a hybrid WTE plant in the Ashanti Region, which uses three main technologies to produce electricity. However, due to the onsite segregation of the waste received at the plant, an innovative model of producing electricity and fuels from the same site but from multiple technologies is presented. The current study carries out a comparative financial feasibility assessment of various income-generating models for the plant, which are (i) the base case—fuels and electricity, (ii) electricity only and (iii) fuels only. The results indicate that the LCOE is too high compared to the End User tariffs for electricity in the country, for all scenarios. However, the NPV and payback period make scenario 1 more attractive and provide less risk to the investor. The fuels-only scenario also provides substantial benefits in terms of the NPV and IRR but with a 10-year debt payback period, which is not very attractive. The electricity-only scenario is the least attractive because of its low revenue to cost ratio. Overall, the current model must be replicated but at a larger scale to improve the LCOE and make it more financially attractive. It is therefore highly recommended that in conducting financial feasibility studies for similar projects, the scenarios developed in this study be used to identify the best applicable technical model. This is relevant for obtaining long-term financial sustainability from multiple products, especially in situations where PPAs cannot be obtained from utility providers. However, this study did not consider any potential environmental aspects, including benefits and incentives such as carbon credits.

Author Contributions

Conceptualization: E.A.A. and S.N.; methodology: S.N., E.A.A., M.M., E.B. and F.K.; curation of results: S.N., M.M., F.K. and F.B.A.; writing and review: E.A.A., M.M. and E.B.; supervision: S.N., F.K. and M.M.; funding acquisition: S.N. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Data are contained within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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Hybrid Waste-To-Energy Solutions Within a Circular Economy Framework Towards Sustainable Urban Waste Management in Ghana

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Abstract

Cities in developing countries continue to struggle with mounting waste management challenges. Within a circular economy framework, energy recovery is mostly nonexistent. Against that background, this study aimed to design and assess the viability of a hybrid waste-to-energy facility for the Greater Accra Metropolitan Area (GAMA) in Ghana by 2030. The proposed plant integrates solar PV, anaerobic digestion and pyrolysis to treat unsegregated municipal solid waste. Three cases were developed for different product combinations. Material flow analysis was performed with STAN software 2.7.101. The results indicate that 1.6 million tons of MSW will be generated, to be potentially converted to 271 GWh of electricity, 6400 tons of hydrogen or 4400 tons of bio-compressed natural gas per year, along with additional products: compost, refuse-derived fuel and bio-oil. The economic indicators show that all cases are potentially viable in terms of the net present value (EUR 397 to 1030 million), internal rate of return (14–22%) and levelized cost of energy (0.11–0.18 EUR/kWh). As such, this study proves that waste to energy is a viable waste management solution for large metropolitan areas, with the potential to supply energy, alternative fuels and material products within a circular economy, though it requires the buy-in of policy makers.

Keywords:

waste to energy; circular economy; Greater Accra Metropolitan Area; hybrid renewable energy systems; material flows; municipal solid waste

1. Introduction

The global population hit 8 billion by the end of 2023 with 57% living in urban areas. [1]. Meanwhile, the population in sub-Saharan Africa is estimated to hit 1.2 billion by 2030 [2]. Against that background, UN Sustainable Development Goal 11 urges all countries and stakeholders to work to achieve sustainable cities and communities by 2030. Cities in most developing countries, however, are battling with challenges of waste management as their population growth continues to outpace the level of infrastructural development. Nearly 40% of the 2.3 billion tons of municipal solid waste (MSW) generated globally in 2020 was not sustainably managed. Today, in sub-Saharan Africa and Oceania, less than 60% of generated waste is collected [3]. Meanwhile, recent research links waste management to the circular economy, sustainable production and recycling. However, achieving local management of waste in highly populated urban settlements presents peculiar challenges, and failed attempts may result in great negative impacts; as such, a robust strategy is required [4].

It is estimated that Africa will generate 244 million tons of waste per year by 2025, with only a 55% collection rate. The informal sector and community-based organizations contribute immensely to the collection of waste, but recycling is estimated at only 4% [5]. Urbanization has been linked to increasing consumption and waste generation; for instance, Kenya and Ghana imported as much as 3.57% and 2.9% of the USD 5.7 billion global trade of goods in 2022, respectively [6,7]. Moreover, another major reason for increasing waste generation is the increase in the import of substandard goods, including used clothes from the developed world, under the guise of donations, 40% of which end up as waste. On the contrary, urbanization in sub-Saharan Africa (SSA) has been positively linked to a reduction in the incidence and depth of poverty. This can conditionally occur with adequate planning, policies and sustainable infrastructure [8]. In an opposite case, poor waste management in Yaoundé, Cameroun has been attributed to the lack of citizen participation in sustainable approaches, while city authorities have failed to enforce laws and implement both local policies and international treaties [9]. A key issue is that waste management is capital intensive, and it requires sound infrastructure to meet health and safety standards.

With most African countries facing economic challenges, investment in waste management is not given enough priority [5]. An exception is South Africa, the most developed country in Africa, which produces 12.7 million tons of waste per year and implements a robust waste management strategy, with huge investments targeting its continuous improvement [10].

In West Africa, the population of Ghana has experienced a five-fold increase over the past 60 years, with an average annual growth rate of 2.1% between 2010 and 2021. In 2021, 50.9% of the 30.8 million national population resided in urban areas, 47% of which resided in only two out of the sixteen regions: Ashanti and Greater Accra [11]. In that context, characterized by population increases in urban areas due to migration, the site selection for waste management infrastructure such as landfills is difficult, a matter further complicated by competing land uses [12,13]. As a result, only 51.4% of urban households engage with waste collection services, and the figure is as low as 5.8% for rural households [11].

The country administratively runs a decentralized governance system with sixteen administrative regions, which are further divided into 261 Metropolitan, Municipal and District Assemblies (MMDAs) [14]. One of the key responsibilities of the MMDAs is waste management. This has proven to be a challenge, especially in metropolitan and municipal areas such as Accra and Kumasi [15,16]. The major reasons include a lack of resources and financing, the sociocultural framework of the society, such as its belief systems and citizen participation, and weak institutional law enforcement [17].

Several studies have established various strategies that can be adopted by municipalities to improve the current situation. These include source segregation and recycling [18,19], energy recovery from organic waste [20], composting [21], biochar from organic waste [22], conversion to fuels such as RDF [23] and hydrogen [24], pyrolytic bio-oil [25] and composite materials for road construction [26]. All these treatment strategies provide a one-sided approach, while treating only some types of wastes. Nonetheless, within the broader context, such mini strategies can be encapsulated into a city-scale circular economy [27].

The circular economy is being promoted all over the world to respond to growing concerns about waste management and the need for climate action. It provides a sustainable approach, which follows natural principles of recovery and recycling of resources within a large system such as city, national or global boundaries. Material and energy recovery have a role to play in closing the loop in a circular economy [28]. The EU Framework Directive establishes a five-step waste hierarchy, which presents an order of preference for managing and disposing of waste: prevention, preparing for reuse, recycling, recovery and disposal. The principles of the circular economy are to as much as possible maintain the materials we have within a circular system, where they cease to exist only after all possible steps have been exhausted [29].

One of the key aspects of circular economy is the creation value and markets for resources within the cycle. This value creates a push and pull effect, ensuring the continuous cycle of materials within the system. A circular city requires business models with various scopes: collective citizen actions, the city governance level, local service providers or international networks [30]. At the core of those, the recovery of materials and energy is crucial for every circular economy. Two African countries have implemented ambitious waste-to-energy (WTE) projects within the last decade, to deal with their increasing waste, which must be scaled up. In Ethiopia, a 25 MW WTE plant started operations in 2019 and supplies 30% of the city's energy needs [31]. In Ghana, a pilot hybrid WTE plant is under construction and is expected to generate 810 MWh/year of energy for grid supply with other potential alternative fuels [32,33]. Within a circular economy framework, these projects make a contribution toward the achievement of sustainable cities.

In Ghana, the circular economy currently exists on a small scale, especially in urban areas such as Accra and Kumasi, for the recycling of plastics and scrap metals. An extensive network of formal service providers, informal collectors popularly known as waste pickers, and middle men (large-scale storage warehouses) recover materials and subsequently trade those with local manufacturers of plastic products or exports [15,34]. This is part of the global circular economy system because most of the plastic products originate from imports, and some of the reclaimed plastic waste processed into intermediary products (plastic pellets/scrap) is returned to the international market for further product manufacturing [35,36]. However, considering similar circular economy models across the globe, further action is required in terms of waste reduction, source segregation and recycling, energy recovery and emission tracking. Cities such as Phoenix, Amsterdam, Toronto, London and Cape Town have led the way with ambitious projects [30,37].

Justification for and objective of this study

In the face of the challenges associated with waste management, several studies have sought to investigate various solutions to Ghana's waste management problems. As compared to developed countries, Ghana as a developing country has challenges involving a lack of funding and poor awareness on the role of the circular economy in supporting sustainable waste management through waste to energy [38]. Most studies have focused on the technologies or small-scale models for communities within cities or in rural areas. In a hybrid setup of integration of technologies, off-grid [39], micro-grid [40] or grid-tied systems are available, as outlined in previous studies. Also, in some instances, schemes such as net metering have been studied [41]. However, utility-scale WTE projects involving large metropolitan areas have scarcely been researched in the context of Ghana. A recent study investigated the feasibility of a 47 MW hybrid waste-to-energy system for the Kumasi Metropolis, integrating solar PV and gasification technologies, to be sited at the Oti Landfill. The study, however, failed to access the levelized cost of electricity (LCOE), which is an important consideration in the economic analysis of energy projects [42]. This general lack of relevant research within the scope of waste to energy and the circular economy provides little support for decision-making or directing broad governmental policies.

The objective of this study was to develop a technical design for a hybrid renewable WTE system for the Greater Accra Metropolitan Area in Ghana and assess its techno-economic viability within a broad circular economy context for GAMA. Achieving a circular economy within a city in Ghana will require three major initiatives: (1) government policy (regulation, planning, procurements and markets), (2) citizen participation (values, attitudes and knowledge) and (3) development of the physical environment (infrastructure, waste management, energy and material security) [30]. This study, therefore, aimed to directly support the policy and planning direction of the government in terms of enhancing the physical environment within the city and amassing greater citizen participation. It also sought to develop a technical, economical and environmentally viable city-scale model for waste management infrastructure.

Large-scale material recovery and composting plants are already operational [43,44]. However, the conversion of WTE or alternative fuels is almost nonexistent. This study assessed the current system and plugged in WTE to create a more sustainable model. The overall business case for the WTE system was evaluated to determine whether it would attract potential investment. Our model integrates the current actors with a new system through a chain of activities starting from waste segregation at the source of consumption and proceeding through waste collectors, preprocessors, recyclers, manufacturers, recovery plants and return to consumers.

Many previous studies have proven the energy recovery potential of waste in Ghana [45,46,47]. For instance, it has been estimated that 13,000 GWh of energy can be recovered from waste by 2030 [48]. However, the government has failed to prioritize achieving this goal. Appropriate policies and strategies are required at the national and local government levels to ensure that the country gradually transitions to sustainable outcomes [49].

The WTE system within the circular economy framework will follow a similar technical design to the pilot plant, which integrates solar PV, anaerobic digestion and pyrolysis. It will produce two additional categories of marketable products based on the estimated input waste: electricity and alternative fuels [33]. Energy and alternative fuels have a major role within the circular economy in driving the manufacture and transportation of materials. As the population increases and industrial development means the demand for energy increases, WTE can provide significant energy, which may relieve the current dependence on fossil-based generation and its negative environmental and economic impacts [50].

2. Materials and Methods

This section follows the methodology outlined in Figure 1, based on similar studies [39,51].

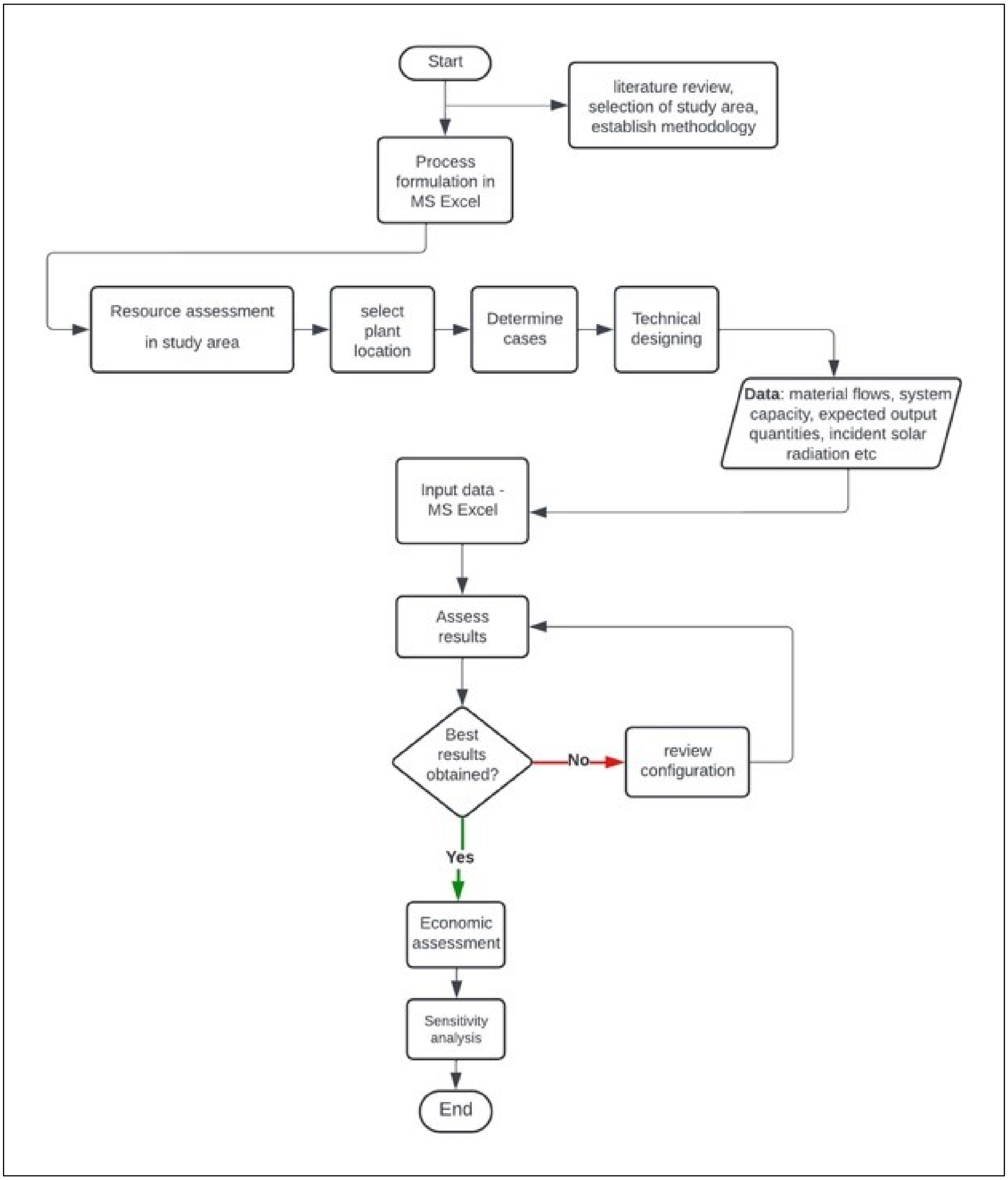

Figure 1. Flow chart of methodology roadmap.

2.1. Study Area

This study focused on the Greater Accra Metropolitan Area (GAMA), which consists of 25 out of the 29 MMDAs within the Greater Accra Region. The capital of Ghana, Accra, falls within the Accra Metropolitan Assembly (AMA), which is one of the MMDAs in GAMA (Figure 2). The impacts of migration and urbanization have resulted in the geographical expansion of the population beyond the AMA to adjoining municipalities and districts, to form the GAMA or the city of Accra. A recent study revealed that the built-up area within the GAMA increased from 27% in 2008 to 46% in 2017 and is expected to reach 73% by 2030 [52]. The term “metropolitan area or city” encompasses the metropolis and 23 adjoining municipalities and districts. Some studies have also described it as a sub-region [13,16].

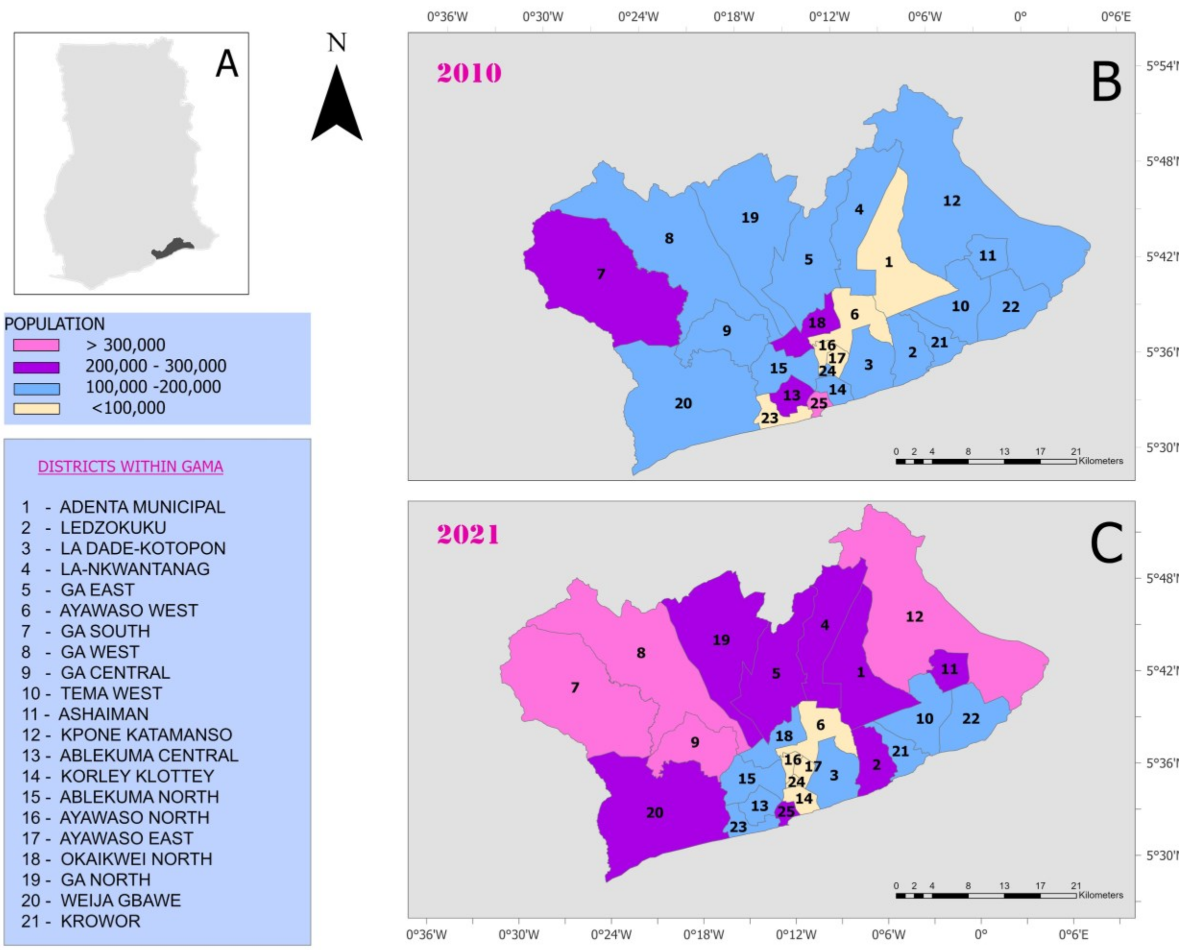

Figure 2. *Population in the study area, showing the increasing population and geographical expansion between 2010 and 2021. Map (**A**)—location of study area in the Greater Accra Region of Ghana; Map (**B**)—population in 2010; Map (**C**)—population in 2021.*

The expansion of research beyond the AMA to the larger GAMA is key to attaining relevant data for development planning of the waste management infrastructure. Currently, the most critical waste management infrastructure, landfills, are sited outside the AMA in the peripheral municipalities encompassing the GAMA. Most of these MMDAs’ locations have resulted from the not-in-my-back-yard (NIMBY) syndrome in terms of landfill site locations [53]. The Kpone and Nsumia landfills, for instance, are located 50 km beyond the AMA.

Residents of the GAMA generate 0.7 kg per capita each day [54,55]. The city is currently being supported by the C40 cities Finance Facility to implement a project targeted at increasing recycling and composting and decreasing waste disposal to landfills and subsequent greenhouse gas emissions. This targets the recovery of 192,297 tons of waste and 140,000 tons of CO_2 emissions per year, impacting 750,000 households [56]. Waste management is currently characterized by numerous players, involving waste collection and transportation, transit and recovery centers, recycling companies, treatment facilities and waste dumps/landfills. The collection of waste is the most challenging aspect of waste management within the city. Source segregation exists for some plastics and scrap metals and has an active value chain involving a network of collectors, plastic pelletizers, transporters, storage warehouses, bulk buyers and recycling industries [19,57]. Smart technologies have been introduced to improve the efficiency of collection and distribution. This includes the Bolabird and Jumeni mobile application, which allows waste producers to request collection services on the application. The Bolabird application, furthermore, provides a platform for trading recyclables for rewards once the consumer segregates those at source. Such innovative approaches may enhance future efforts when scaled up. Other companies such as Jekora Ventures Limited, Asadu Royal Limited and Zoomlion have introduced smart payment systems integrating mobile money platforms, to facilitate revenue collection for enhanced service delivery.

The total MSW disposed of in landfills in Accra was estimated at 1170 t/d [15]. The Kpone landfill site alone received an average of 931 t/d between 2013 and 2017, although it was designed to receive 400 t/d [58]. This led to its closure and decommissioning more than 5 years before its planned lifespan. Today, the Ayidan engineered landfill site is under construction and is expected to provide a more environmentally friendly disposal site.

However, the crux of the problem still remains, with 51.5% of the collected waste directly transferred to the landfill or waste transfer stations to be either transferred for recycling and composting or sent to landfill. A 2017 study developed a mass balance for the city. It is estimated that recycling and composting treat 6.7% and 7% of the total generated waste and 9.1 and 9.5% each of the collected waste, respectively. Surprisingly, the data also reveal that 30% of all waste directed to recycling goes to the landfills due to poor material quality. In total, 85% of all generated waste in Accra is either buried in landfills or, in the case of the uncollected waste, deposited in open spaces or drains or burnt [15].

<u>Selection of Plant Location</u>

This study aimed to assess the design and development of a WTE plant to replace the existing unsanitary/non-engineered landfill practices within the GAMA. Currently, the Ayidan landfill is located at longitude −0.4 and latitude 5.8. Furthermore, the Kumasi Compost and Recovery Plant (KCARP) in Kumasi is sited within 5 km of the Oti landfill in Kumasi. A feasible approach may be to divert current waste disposal from landfill to a new plant. However, considering the current rate of urbanization within the city, it is unlikely that a large portion of land will be secured for such uses by 2030. Nonetheless, the selected location is suitable for the required purposes of such a site based on economic, environmental and sociocultural criteria, according to [59].

2.2. Technical Design of the Plant

The proposed plant under consideration in this study will be referred to as the GAMA plant. The design will follow a similar design to the pilot plant. A previous publication offered a technical description of the pilot plant being scaled up and replicated in this study [33]. When a waste truck arrives at the plant, waste is off-loaded into a bunker. A pay loader transfers the waste onto a segregation conveyor, after which the waste undergoes manual and mechanical sorting. The onsite segregation is similar to the process in a typical material recovery facility (MRF) [60]. After sorting, each waste fraction is directed to a specific treatment system: organics to the anaerobic digester (AD), non-recyclable plastics to pyrolysis and residuals to the RDF. About 5.6% of inert substances (e.g., ceramic, ash, sand, glass) are expected to be transferred to a landfill or for other land reclamation uses. The purified biogas is then converted to electricity or fuels: hydrogen or bio-CNG. The digestate from the AD is processed into compost. Figure 3 presents the technical design for the proposed plant.

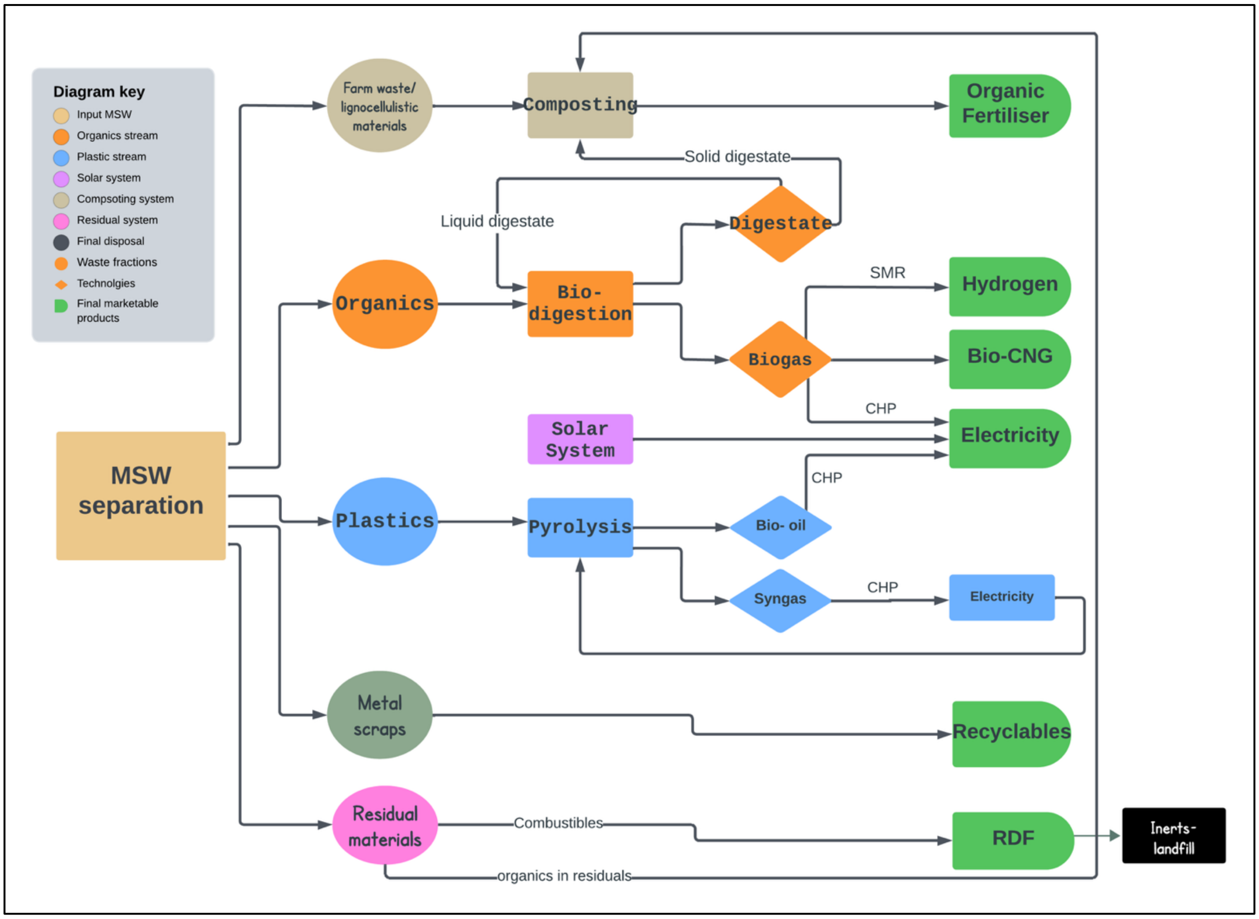

Figure 3. Plant design showing the various systems and directions of material flows and products.

The independent systems within the plant and their expected outputs are as follows:

1.	Energy	-electricity
2.	Alternative fuels	-RDF, bio-CNG, hydrogen, bio-oil
3.	Plant nutrients	-compost
4.	Recyclables	-scrap metal, etc.

2.3. Resource Assessment

The GAMA plant will also utilize hybrid renewable energy technologies that integrate solar PV, anaerobic digestion (AD) and pyrolysis. Two key resources will feed the plant: (1) MSW and (2) incident solar radiation for the solar PV system. The following sections describe the estimation of the key resources for the proposed GAMA plant.

2.3.1. Quantification of MSW for the Proposed Plant

In order to achieve a sustainable city, it is proposed that the waste now being disposed of untreated at the landfill site should be diverted to the proposed plant and only the untreatable or complex waste be transferred to the landfill site. This also assumes that by 2030, the treatment capacity of the current composting and recycling plants will be increased to allow for additional material recovery. The quantity of waste expected at the plant ($Q_{MSW(2030)}$) (t/d) is calculated by the following (Equation (1)):

$$Q_{MSW(2030)} = \left(P_{2030} * Q_{gen/cap} * \%W_{coll}\right) - (\%W_{rec}) \quad (1)$$

where P_{2030} is the population by 2030 using an annual population growth rate of 2.9% for the Greater Accra Region obtained from the last census data in 2021 [11]. $Q_{gen/cap}$ is the waste generated per person per day (kg/cap/day); several studies have confirmed that each resident of Accra produces an average of 0.7 kg/day [55,56]. $\%W_{col}$ represents the percentage of collected waste; in Accra, it is estimated that 91% of generated waste is collected and can be made available for waste management, which is above the national average of 56.5% for urban areas. The remaining is lost in open spaces, drains and burning. $\%W_{rec}$ is the proportion of collected waste recovered for recycling, composting or RDF by the existing composting plants and private recycling firms, which is estimated as 12% of the waste generated [44,61].

2.3.2. Quantification of Waste Fractions

The major components of the input waste expected to be received at the plant were estimated from a previous study in similar MRF plants in Accra and Kumasi (ACARP, IRECOP and KCARP) [23]. The expected fractions are presented in Table 1. Of these, the recovered portion from the MRF is 52–70%, while the remaining input waste exits the segregation system as the reject/residual fraction (RF) and inerts. The majority of the plastics are recovered as large materials through manual sorting. For the purposes of this study, the organics and plastics recovered from the MRF are referred to as the primary fraction (PF), which is considered to have an average value of 60% of the input waste. This implies that the same fraction of $Q_{MSW(2030)}$ is available for the WTE system (AD and pyrolysis). On average, RF contains 24% organics and 34.7% plastics, equivalent to 9.6% and 13.9% of the input waste.

Table 1. Estimated waste composition for the proposed WTE plant based on previous studies [23,55,62].

Waste component	Unit	Composition
Organic	%	45-65
Plastic	%	10-20
Paper	%	5-10
Inert	%	3-8
Leather	%	1-1.5
Textile	%	1-4
Metals	%	1.2-2
Glass	%	1-3
E-waste	%	0.6
Wood	%	0.3
Sanitary waste	%	4.8-5
Miscellaneous	%	5-5.3

Thus, the total quantity of the PF is calculated using the equation below, where n is the ratio of PF (%), which is taken to be 60% in this study:

$$Q_{PF} = Q_{MSW(2030)} * n \tag{2}$$

The quantities of organics and plastics from the PF after manual and mechanical sorting are calculated using the ratios in Table 2 and Equation (3):

$$Q_X = \%X_{PF} * Q_{PF} \tag{3}$$

where Q_X is the quantity of each waste fraction (organics and plastics) (tons/yr), and $\%X_{PF}$ is the fraction of each waste in the PF.

Table 2. The ratios for computation of the waste fractions from onsite material recovery, based on [60] and Table 1.

Input waste fractions (%)		Primary Fraction		Residual Fraction	
		% of PF	% of input	% of RF	% of input
Organics	48.60	65.0	39	24.0	9.6
Plastics	20	10.2	6	34.7	13.9
Metals	1.2	2.0	1	1.3	0.5
Others	24.60	18.7	10	36.5	14.4
Inerts	5.60	6.1	4	4.8	1.9
% of input waste	100		60%		40

2.3.3. Material Flow Model for GAMA

The data on resource assessment from the previous section were transferred into STAN software 2.7.101 to model the material flows through the system. The STAN software provides a comprehensive platform for assessing the material flows from a system and computing the mass balance [63]. A material flow projection for the GAMA by 2030 was developed using the current data for material flows for the GAMA, sourced from previous studies published between 2015 and 2021 [13,15,44,55,62]. The ratio of the various material flows in these studies was used to project the flows from waste generation in 2030. This assumed that the components of the waste management system in the GAMA will expand at the same rate as in 2021.

2.3.4. Incident Solar Radiation

The incident solar radiation at the Ayidan landfill site was obtained from the software-integrated NASA database in the RETSCREEN Expert® Software version 8.0.1.31. The software automatically generated the average annual incident solar radiation at the selected site at longitude −0.4 and latitude 5.8.

2.4. System Capacity and Expected Outputs

The plant is expected to produce six marketable products as outputs. Each of the products requires a specific methodology, as outlined below. The plant is expected to operate for 335 days/yr, with 30 days allocated for scheduled maintenance and unplanned breakdowns.

2.4.1. Electricity (Energy)

The electrical energy transferred to the grid is expected to come from three sources, i.e., anaerobic digestion (EAD), pyrolysis ($Epyr$) and solar PV (Epv). The net energy transferred to the grid is minus the internal energy consumption, which is estimated to be 50% of the energy from the solar PV.

Anaerobic Digestion (AD)

The AD system produces biogas for electricity generation. Biogas contains about 65% methane, along with other compounds that are often unwanted and thus must undergo purification. Pure methane is obtained, which powers a combined heat and power engine (CHP) to produce electrical energy. Table 3 details the step-by-step process for estimating the energy output for the AD system.

Table 3. Methodology for estimating the energy output from the AD system.

Step	Equation	Details
Annual methane yield (m3/yr)	$y_{CH4} = Q_{OF} * C_{TS} * BMP_{MSW} * C_{CH4}$ (modified from Kemausuor et al., 2014) (4)	y_{CH4} - methane yield (m3/yr) Q_{OF} - Organic Fraction in PF after manual and mechanical sorting (tons/yr) C_{TS} - concentration of total solids in the organic fraction which is 31.40% which also contains 85.45% Volatile organic compounds [64] BMP_{MSW} - bio-methane potential of MSW which is 320m^3 CH4/ tonTS based on continuous mesophilic digestion [65] C_{CH4} - 65.6% which is the methane content of biogas [66]
Conversion of y_{CH4} to mass (tons/year)	$m_{CH4} = ŋ_{CH4} * y_{CH4}$ (5)	m_{CH4} - mass of methane (t/yr) $ŋ_{CH4}$ - density of methane which is 0.000717t/m^3 [67]
Energy output from AD - E_{AD} (kWh/yr)	$E_{AD} = y_{CH4} * LCV * n$ (6)	LCV_{CH4} - Lower Calorific Value of methane which is assumed to be 9.94 (kWh/m^3) [68] n - efficiency of the CHP which is taken as 35% from the pilot plant
Power capacity of AD (MW)	$Cap_{AD} = \frac{E_{AD}}{T}$ (7)	T is the Operational hours (h/yr)

Pyrolysis

The pyrolysis system used in this study is expected to follow a similar setup to the pilot plant. Similar process are also described by [25,69]. The pyrolysis process is expected to be carried out through catalytic polymerization at a temperature of 500 °C using natural zeolite as the catalyst. The system contains an energy source, plastic chopper, fluidized bed reactor, condenser, acidity remover and fractional distillation chamber. The gas produced is directed into a CHP to produce electricity to power the process. A closed-loop system is formed where the mass balance within the reactor evens out the input and output masses [18]. The internal energy demand, which is estimated at 844 W/kg, is supplied by a CHP utilizing the gas recovered at the reactor. This key assumption is represented by Equation (8). Table 4 details the energy output through pyrolysis. The power capacity of the pyrolysis system is calculated using Equation (7).

Table 4. Methodology for estimating the energy output through pyrolysis.

Name of step	Equation	Details
Balance of materials (tons)	$m_{pw} = m_f + m_c + m_g + m_w$ (8)	m_{pw} - mass of plastic waste m_f - mass of oil m_c - mass of char m_g - mass of gas m_w - mass of water
Bio-oil yield (tons/yr)	$y_{oil} = Q_{Pw,PF}$ * X% (9)	$Q_{Pw,PF}$ - quantity of plastic waste in the Primary Fraction (Equation 3) X% - bio-oil yield per ton of input mixed plastic waste which is estimated to be 48wt% ±2 [70]

Energy in output (MWh/yr)	$E_{pyr} = \frac{y_{oil} * LHV_{oil} * n}{\eta}$ (10)	LHV_{oil} - Lower Heating Value of bio-oil estimated as 43,175MJ/ton [25] ŋ - 3.6 which is the conversion factor of 1 kWh = 3.6 MJ [70] n - efficiency of the CHP which is taken as 35%
Power capacity of pyrolysis system (MW)	$Cap_{AD} = \frac{E_{AD}}{T}$ (7)	T - operational hours (hr/yr)

Solar PV

For the solar PV system, the specifications are assumed to be the same as those already installed for the pilot plant. Thus, using the same module characteristics and site-specific irradiance data, the RETSCREEN Expert software version 8.0.1.31 estimates the energy output from the PV system. The Talesun TP6L72M Mono-Si module was used with the technical specifications indicated in Table 1. The Sinexcel PWG2 inverter was also applied, which has an efficiency of 95.5%. The capacity of the solar PV system (Cap_{pv}) (kW) was taken to be the same as that of the AD system. The key technical specifications for the PV module are given in Table 5.

Table 5. *Technical specifications of the selected PV module.*

Parameter	Specification
Maximum Power (Pmax)	440 W
Operating Voltage (Vmp)	40.5 W
Operating Current (Imp)	10.87 A
Open-Circuit Voltage (Voc)	49.2 V
Short-Circuit Current (Isc)	11.4 A
Module Efficiency (ηm)	20.1%
Operating temperature	-40C - +85C
Temperature Coefficient (Pmax)	-0.36%/°C
Temperature Coefficient (Voc)	-0.26%/°C
Temperature Coefficient (Isc)	+0.043%/°C
Nominal operating cell Temperature	43±2C

2.4.2. Alt Fuels

Bio-CNG and Hydrogen

From the methane yield obtained above, bio-CNG or hydrogen can be produced. First, H_2 is produced, after which Bio-CNG is produced from H_2. Hydrogen is expected to be produced from stem methane reformation (SMR), which consists of a reformer reactor and a shift reactor with nickel as the catalyst. The final quantity of compressed H_2 in m^3 is calculated using Equations (10) and (11) [33]

$$Q_{H2} = V_{CH4} \, X \, \rho_{CH_4} \, X \, Eff_{(boiler)} \, X \, Eff_{(reformer)} \, X \, 0.5 \quad (11)$$

$$Q_{H2\ compressed} = \left(Q_{H2} \, X \, Eff_{compression}\right) \quad (12)$$

where Q_{H2} is the total hydrogen produced (kg), ρCH_4 is the density of methane (kg/m^3), which is considered to be 0.717 kg/m^3, V_{CH4} (m^3) is the volume of purified methane at 95% purity and $Eff_{(boiler)}$ and $Eff_{(reformer)}$ are the efficiencies of the steam boiler and reactor for the dry and steam-reforming reactions. It is assumed that 1 m^3 of steam-reformed methane is equivalent to $(0.5 \times \rho_{CH4})$ kg of H_2 gas, and that H_2 requires compression and storage of the final product under pressure to be transported to the customer. $Eff_{compression}$ is the compression efficiency, which is assumed to be 95%.

Bio-CNG is estimated through the Sabatier reaction, where H_2 reacts with carbon dioxide to produce pure methane and water in the presence of a methane catalyst [71]. The methane gas is compressed to facilitate storage and transportation using Equation (12) above.

The two fuels can be adopted depending on the availability of the markets and the cost–benefit assessment. Bio-CNG may be preferred due to potential local markets, while hydrogen currently needs to be exported to international markets.

Refuse Derived Fuels (RDF)

RDF is produced from the quantity of the RF received after segregation and other treatment options have been exhausted. RDF studies in Ghana have shown that the RF makes up an average of 40 wt% of the initial waste and may contain up to 95% RDF components, which are made up of 70% combustible materials (CF). The RF is estimated to contain 24% organics, 9.2% paper, 34.7% plastics, 9.7% textiles, 1.3% metals, 0.4% glass, 1.2% wood, 6.7% sanitary waste, 2.2% leather, 0.8% e-waste, 4.4% others and 4.8% inert substances such as glass, ceramics and sand. The proportions in the input waste are given in Table 1. However, the presence of organics in RDF reduces the lower heating value by 26% on average [23]. Thus, in order to improve the quality of the final product, the combustibles are considered RDF components. The organic fraction of the RF (ORF) is, therefore, transferred to the production of compost. Hence, the quantity of RDF is estimated by the following equation:

$$Q_{RDF} = Q_{MSW(2030)} * RF * CF \quad (13)$$

2.4.3. Compost

One of the key outputs of the AD system is the digestate, which is a slurry that can be separated into solid digestate (SD) and liquid digestate (LD). The SD is the main component for compost production. A bulking agent is required to improve the physical and chemical properties of the final compost product [72]. The pilot plant is sited in a rural area with intensive agriculture. However, the plant being considered in this study is anticipated to be sited in an urban environment. Thus, farm waste may not be available in large quantities. Other potential sources of bulking agents include wood chippings or other industrial waste of a biogenic nature [73]. Another raw material for compost production is the organic component of residual waste from the material recovery system. It is estimated that the RF (as described in the previous section) may contain about 24% organics. This is referred to as the organic fraction of the residual waste (ORF). The quantity of compost expected to be produced through the windrow method is calculated using the following equation:

$$Q_{comp} = Q_{SD} + Q_{ORF} + Q_{Bulk} * \%loss \quad (14)$$

where Q_{comp} is the quantity of compost produced (tons/yr), Q_{SD} is the quantity of solid digestate, Q_{ORF} is the quantity of organics in the residual waste and Q_{Bulk} is the quantity of bulking materials.

2.4.4. Recyclables

The recyclables expected at the plant were estimated using previous studies from the Kpone landfill site, where the waste pickers mainly collect plastics, metals scraps, e-waste and cartons (if not contaminated). Based on the plant design and material flow, only metal scraps are expected to be transferred to recycling outside the plant. Depending on the market value and quantity, this may provide additional sources of revenue to the plant. We found that 1.2% metals are expected. The quantity by 2030 was estimated from the increase in waste generation based on the population growth rate and the input waste fractions (Equation (1)). Assuming 1 ton of steel has a volume of 0.127, and the metals are transported once every week (53 times each year), the space required to store the scrap metals is estimated using

$$\frac{Q_{metals} * V_{steel}}{53} \quad (15)$$

where Q_{metals} is the quantity of metal recyclables (tons/yr) and V_{steel} is the volume occupied per ton of steel.

2.5. Economic Feasibility Assessment

In order to assess the feasibility of the plant, a financial model was developed based on the assumptions in Table 3. The target for the new plant is to start operations in 2030 with a lifespan of 20 years, with decommissioning to begin in 2050. It is also assumed that the construction will follow the same 3-year timeline as the pilot plant. The feasibility was assessed using the net present value, the internal rate of return (IRR), the LCOE and the simple payback period (PBP). The Euro was the main currency used for this study. In cases where data were sourced in Ghanaian Cedis (GHC) (the local currency), the conversion to EUR was performed with the official European Commission exchange rate in March 2024 [74] of GHC 1 to EUR 0.073 (Table 6).

The revenues from the plant were calculated as a product of revenues and market prices. This study considered that the plant becomes an independent power producer (IPP) and transfers its net electricity production to the grid through supply to the power distribution company (Electricity Company of Ghana). From the published tariffs of the PURC in the first quarter of 2024 to take effect in April 2024, the electricity tariff for this study was 0.0726 EUR/kWh. However, the tariffs are expected to be reviewed each quarter. Based on the PURC published tariffs from 2008 to 2023, the annual escalation rate of revenue was calculated as 25% [50,76,77]. Beyond electricity, the revenues for all other products were escalated at the average rate of inflation. The inflation rate used in this study was computed as the average national inflation from 2014 to 2023 (15.14%) [78].

Table 6. *Input data for financial analysis.*

Parameter	Units	Value
Operating days	days/yr	335
Economic lifespan	Years	20
Depreciation rate	%	10
Debt to equity	-	70:30
Interest rate on debt	%	3.05
Inflation rate	%	15.14
Cooperate Income Tax (CIT)	%	1 - 25[1]
Electricity tariff for bulk generation	EUR/kWh	0.0726
Annual revenue escalation rate (electricity)	%	25

3. Results

3.1. Waste Resources by 2030

The quantity of waste is the most crucial consideration for this system. Based on the population of the 25 MMDAs within the GAMA and the regional average annual inter-censual population growth rate of 2.9% in the GAMA in 2021, it is forecast that the population will hit 6,457,913 in 2030. Figure 4 shows the estimated population increases in the metropolis and municipalities. The population will have doubled over the 20-year period from 2010 to 2030. Key hotspots are municipalities such as Kpone Katamanso and the Ga Districts, which will have populations above 400,000.

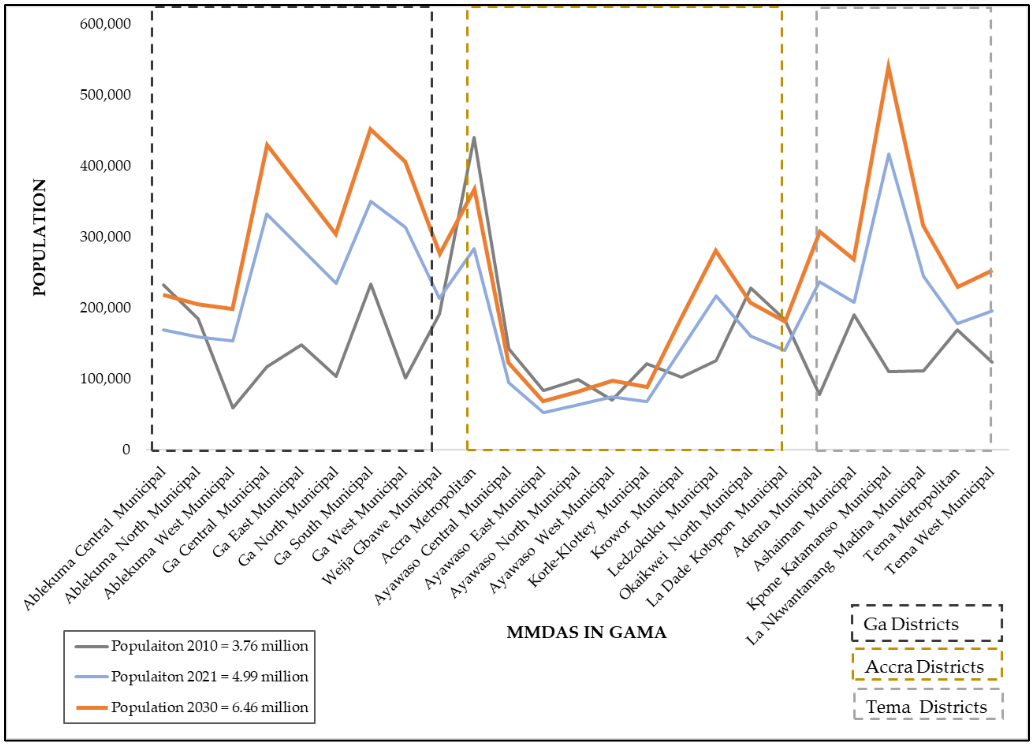

Figure 4. *Population increase in the study area between 2010 and 2021 and projected population in 2030.*

The total annual MSW generation is estimated at 1.34 million tons (Mt). Figure 5 represents the estimated waste recovery by 2030 assuming that the system expands at the same rate as in 2020. However, by 2030, it is estimated that citizen compliance with waste collection will improve in the metropolitan area, and that city authorities will improve the collection efficiency to achieve 91% of all generated MSW. Out of this, 11% will be treated in the current recycling and composting facilities across the GAMA [44]. Our estimation assumes that no new large-scale projects will be started within this period, leaving all other waste available for further treatment. Currently, all collected and untreated waste is directed to the landfill sites and open dumps across the city, and 15% of all collected waste will pass through intermediary transfer stations before its final treatment.

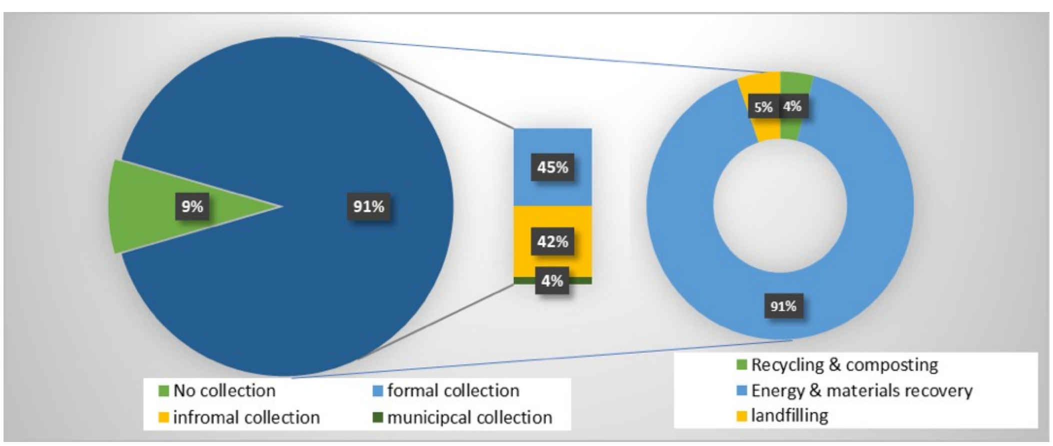

Figure 5. *The waste collection characteristics and waste recovery fractions in GAMA by 2030.*

3.2. Estimated Material Recovery at the Hybrid Waste-to-Energy Plant

The material flows once the waste arrives at the plant depend on the characteristics of the input waste and the sorting efficiency of the manual and mechanical separation. Figure 6 shows the material flows and the conversion of materials into products using various technologies. According to Table 1, 802,135 t/yr is separated as the primary fraction, which contains 64% organics and 10% plastics. The magnetic separators are expected to remove 16,042 t/yr of metals for recycling. The remaining fine components are mainly made up of a mixture of plastics and paper, directed to the RDF section of the plant. Fine inerts such as glass, stones and ceramics must be eliminated from the primary waste and directed to landfill.

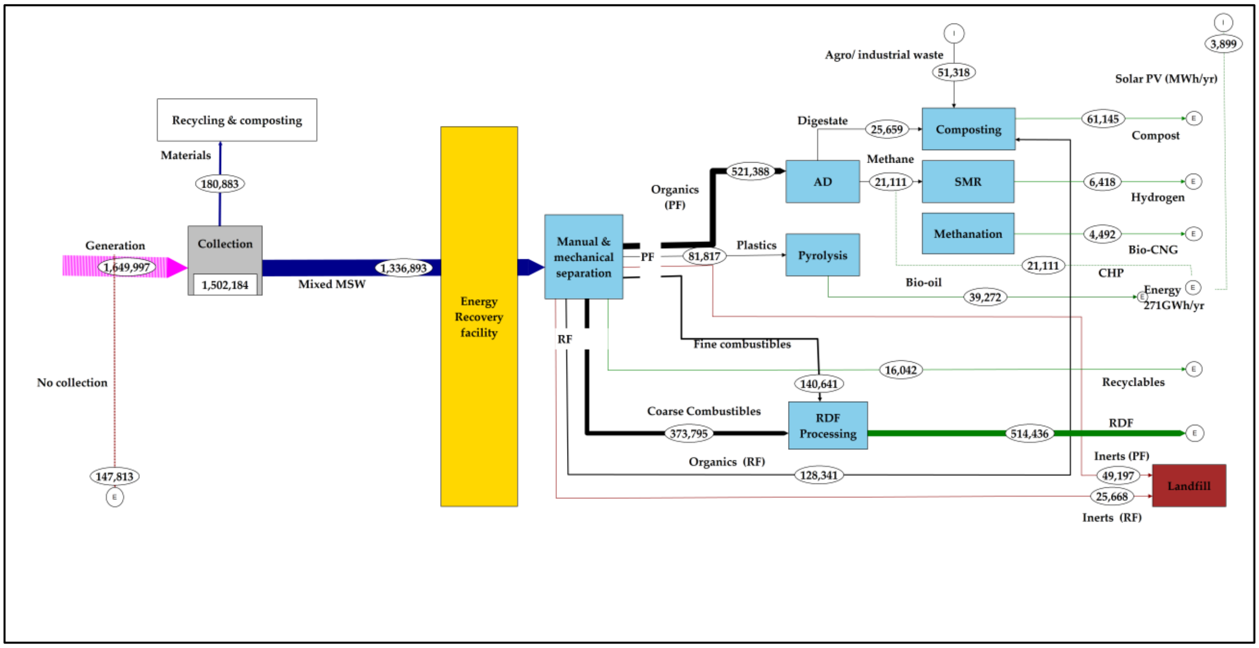

Figure 6. Mass flow of materials within the plant. Color codes for flows: Waste generation source (pink), Collected waste to energy recovery (blue), products (green), intermediary flows (black), landfill (brown).

The residual fraction represents the rejected portion from the manual and mechanical separation. It is expected to contain 24% organics, which can be separated through a secondary separation process to be added to the digestate for composting. This will potentially improve the quality of the RDF produced, with a higher calorific value as compared to that containing organics. Overall, about 0.5 Mt/yr of combustible materials can be directed to RDF production. The RF also will contain about 25,668 t/yr of inert substances, which must be directed to landfill. It must be noted, however, that the waste fractions may only represent cumulative averages over a period, and daily variations in waste fraction are likely to occur based on original consumer patterns.

For the hybrid WTE plant being considered in this study, the annual input waste is expected to be 1.34 Mt. Only 74,000/yr of inert substances are expected to be sent to landfill, representing 6% of the input MSW into the energy recovery facility and 5% of all generated waste.

3.3. Product Outputs

The technical design of the plant considers seven independent systems. However, in order to assess the potential for various products for the market, this study considered three alternatives.

- Case 1—All biogas and bio-oil for pyrolysis is converted to electricity for grid transfer and internal consumption.
- Case 2—All biogas is converted to hydrogen. In this case, bio-oil is purified and sold as an industrial fuel. Solar PV provides energy for internal consumption.

- Case 3—All hydrogen is converted to bio-CNG, while bio-oil is sold as an industrial fuel. Solar PV provides energy for internal consumption.

In total, 283 GWh of electricity is expected per year to be produced from a cumulative capacity of 107 MW. The AD system will produce 21,110 tons of methane per year. This can potentially be converted to three products (hydrogen, bio-CNG or electricity). For case 1, 27% of the revenue is expected from electricity alone. Out of this, the internal energy demand is expected to be satisfied with 3899 MWh/yr of the gross energy produced (self-consumption). This brings the total energy available for grid transfer to 229 GWh/yr. Internal energy is needed to power the various systems as well as laboratories and offices.

Cases 2 and 3 both present a scenario where alternative fuels are prioritized for industrial or transportation purposes. About 6417 tons of hydrogen is expected to be produced through steam methane reformation in Case 2, and 4492 of bio-CNG in Case 3. An additional 39,272 of crude bio-oil will be available in each case, together with RDF and compost.

The digestate from the AD system is directed to the composting shed to produce organic fertilizer for the local market. It is estimated that 25,659 tons of solid digestate will be produced from the digester. In order to improve the physical and chemical characteristics of the compost, a bulking agent is required, which must be of a lignocellulosic nature. In such an urban environment, farm waste may be difficult to acquire. Industrial waste such as wood chippings can be added at a ratio of 1:2. This is estimated to produce 61,146 tons of compost per year. When the organic component of the RF is added, this can potentially increase to 160,000 tons/yr.

The estimated recyclable metal scraps weigh 17,167 tons per annum. These will not receive any treatment on-site but will require a storage space of 45 m3 to allow for a dislodging rate of once per week. Overall, the 39,000 tons of inert substances are to be transferred to the landfill, which represents 6% of the input waste and 5% of the generated waste. This excludes all other waste that is directed for other treatment or recycling or waste that is not collected at the point of generation.

3.4. Business Case

The project-related costs are categorized as capital costs (CAPEXs) and operation and maintenance costs (O&Ms). The O&M costs are further distinguished as fixed costs and variable costs. The fixed costs for this study include labor, interest on debt, insurance, equipment replacement costs and scheduled maintenance. The variable costs depend on the revenues, and they include marketing and transportation, taxes, energy costs, maintenance and miscellaneous expenditure.

The financial parameters are presented in Table 7 below. All cases are viable, although Case 1 considering the conversion of all biogas and bio-oil to electricity is the most viable option. The NPV is positive in all cases and higher than the CAPEX. This is also reflected in the IRR, which is higher than the discount rate of 10%. The LCOE is expressed as 0.18 EUR/kWh for Case 1, while the others, which focus on internal use of solar PV energy, have a lower LCOE. The investment cost for solar PV is lower than that for the AD and pyrolysis plants, thus contributing to a lower LCOE. In all cases, compost and electricity, hydrogen or bio-CNG make up 75% of revenues. In Cases 2 and 3, RFO and RDF contributes an additional 14.6% and 9.6%, respectively, while recyclables provide less than 1%.

Table 7. Cost breakdown and resulting financial indicators of the cases from the proposed plant.

	Case 1	Case 2	Case 3
Cost breakdown			
CAPEX (EUR)	367 million	490 million	489million
Fixed O&M (% of CAPEX)	13	13	13
Variable O&M (% of Gross Revenue)	14	15	11
Financial Indicator			
Net Present value (EUR)	1030 Million	397 Million	470 Million

Profitability index	4.8	2.8	3.0
Payback period (years)	10	11	10
Levelised Cost of Electricity (EUR/kWh)	0.18	0.11	0.11
Internal Rate of Return (%)	22.03	14.0	15
Return on investment (%)	40.4	14	19.5

4.Discussion

4.1. Quantity of Waste Generated and Treated

Waste management is dependent on the population increase and other social patterns, along with the policy direction of the government, such as for waste segregation.

Recyclables can potentially be recovered by waste collectors at the site. In a 2018 study, it was estimated that about 3 tons of waste is recovered daily from a total landfill waste of 931 tons/day [19,58]. Thus, the current model reduces the current landfill waste from 85% to 6%. There are then space savings from the landfill since each ton of waste occupies 2 m3. Thus, about 1.1 million m2/year will be saved from the landfills across the city [58].

This study considered RDF from the RF, which contains various fractions of waste including organics, combustibles and inerts. The combustibles form 38% of the input waste, which is comparable to the 30% in other studies [79]. The presence of organics in RDF results in a final RDF product with a lower energy content (19.7–23.7 MJ/kg) due to its higher moisture content [80]. It is recommended that a further mechanical sorting step be incorporated to remove organic components of RDF, to improve the energy properties. Results from a previous study in Ghana showed that RDF containing only combustible materials, making up 70% of the RF, has a higher heating value (28.6–30.3 MJ/kg), which is comparable to that of coal (18–36 MJ/kg) [23]. The organics removed at this point may be directed to the compost. It has also been discovered that bio-drying can improve RDF quality by reducing the moisture content by 24% and the mass of RDF by 33% [81,82].

The combustibles can become a potential resource for the production of additional electricity for the plant. The plant can be designed with a gasification system to convert RDF to electricity, whereby 1242 GWh of energy can potentially be produced per annum per ton of RDF. This is based on the assumption that 1 ton of RDF contains 23,000 MJ of energy, with each MJ also containing 0.3 GWh at a 35% conversion efficiency [79]. This is about five times the energy produced from the other renewables. However, this will involve additional CAPEX for gasification, which may affect the LCOE and NPV. RDF is also an important source of energy for the local industry, especially the cement industry. With technical modifications such as preprocessing, RDF can potentially offer cost savings of 7.18 EUR/GJ [83].

The inerts are the only component of waste expected to be sent to landfill, representing only 5.6% of the initial waste. This is lower than in some studies involving waste from households, markets and other open areas, where the inert component of waste was found to be relatively higher at 8% [62].

Although compost contributes the most to the revenue mix, its marketing and promotion can potentially be challenging. With production in an urban area, the product must be transported to rural agricultural areas to be used for farming. Thus, 80% of the cost of marketing, promotion and transportation was allocated to the compost product. In the event that this increases above the 28% allowable margin, other product costs must be reduced to cross-subsidize the transportation cost for composting. Cross-subsidization may become an important opportunity for this plant, where various products support one another through the shared cost of operations and maintenance (Table 8).

Table 8. Comparison of daily generation and collection characteristics between previous studies and this study (tons/day).

Flow characteristics (tons/day)	2017 [15]	2020 [44]	2030 (This study)
Waste generation	1730	3293	4521
Waste collection			
Formal Collection	718	1486	2040
Informal Collection	495	1370	1880
Municipal Collection	68	142	194
No Collection	449	295	405
Material flows for collected waste			
Recycling	118	127	174
Materials Recovery and composting (current plants)	121	234	321
Materials and energy recovery (New Plant)	-	-	3719
Landfill	1170	2856	225

4.2. Energy Potential to Supplement National Energy Demand

Ghana has faced major challenges in power generation in recent years due to the overdependence on fossil-based generation sources, which has had a gross impact on the cost of energy. This study found that electricity tariffs increased by an average of 25% per annum between 2008 and 2023. A tariff review typically considers the hydro-thermal generation mix, the currency exchange rate, inflation rate and fuel prices [50]. Renewables can potentially stabilize the price adjustments and reduce the economic implications of purchasing fossil fuels from external sources. As compared to similar developing countries such as Kenya, the tariff increments caused by fluctuating fossil fuel costs and economic indicators provide a substantial risk for potential businesses and consumers who depend on electricity [84].

The total energy output from the AD system is comparable to the results obtained in a study of the energy potential of waste from the Kumasi metropolis [47]. Assuming that 100% of biogas produced is directed to electricity generation, the plant has the potential to supplement national generation by 110 GWh/yr. However, under the current plant design, only 33% is directed to electricity, with the remaining producing hydrogen and bio-CNG. According to the national energy statistics, the national dependable capacity is 4975 MW, with 95 MW renewable capacity apart from hydropower [85]. The proposed plant can potentially generate an additional 88 MW to the renewable capacity. This could potentially increase the current capacity by 92% and almost double the current contribution of renewables to the national energy mix, to 3.7%. This may make a significant contribution to the target of attaining 10% renewables in the national energy mix by 2030 if this model is replicated at a national scale [86]. One of the important policy objectives of Ghana within the energy sector is the diversification of the national energy mix in terms of energy sources by implementing programs to support the development of renewables [87].

Adopting this model at the national level also supports the objective of generation diversification based on geographic location. This can gradually be implemented by identifying the hotspots in the country for waste generation, which is also linked to the population. Various studies have identified metropolitan areas as the most important hotspots for waste generation, with a high potential for renewable energy through waste [46,48,55]. More importantly, urban areas have a higher waste generation rate due to their consumption patterns, and the collection rate was reported as 51.4% for urban areas, as compared to 5.8% for rural areas [88].

4.3. Sensitivity Analysis

The fixed costs, variable costs and tax combine to make up the total OPEX, which is escalated at the rate of inflation per annum. The O&M cost is calculated as 12% of the CAPEX, which includes the cost of capital, debt repayment, equipment replacement cost and scheduled maintenance. The variable costs, meanwhile, consist of energy costs, materials, marketing and miscellaneous expenditure. NPV and ROI approach zero when the fixed and variable costs (before tax) increase by 28.9%. This indicates that the operational and maintenance cost of the plant can be increased within this range while maintaining the economic feasibility determined by the NPV, whereas revenues must not be reduced.

The sensitivity analysis of LCOE is presented in Figure 7, which suggests that the plant expanding the capacity to 500 GWh/yr can potentially improve the LCOE. This can be expected as global RE prices continue to plummet. It also indicates that the O&M cost for electricity production will not meet the minimum point, considering the electricity export rate used for the analysis (0.076 EUR/kWh). The average residential EUT published in January 2024 was EUR 0.12 [74,89]. This indicates that the cost of the production of energy within the plant is too high when compared with the current tariff of power for the grid. Hence, the escalation rate for costs, which is the rate of inflation (15.14%), is too high to ensure a sustainable LCOE. Inflation is an external factor beyond the internal control of the plant. Due to the large capacity of the system in this study, the LCOE is lower than that of the pilot plant although higher than the tariff. The average LCOE for the pilot plant with a capacity of 400 KW was 0.53 EUR/kWh [33].

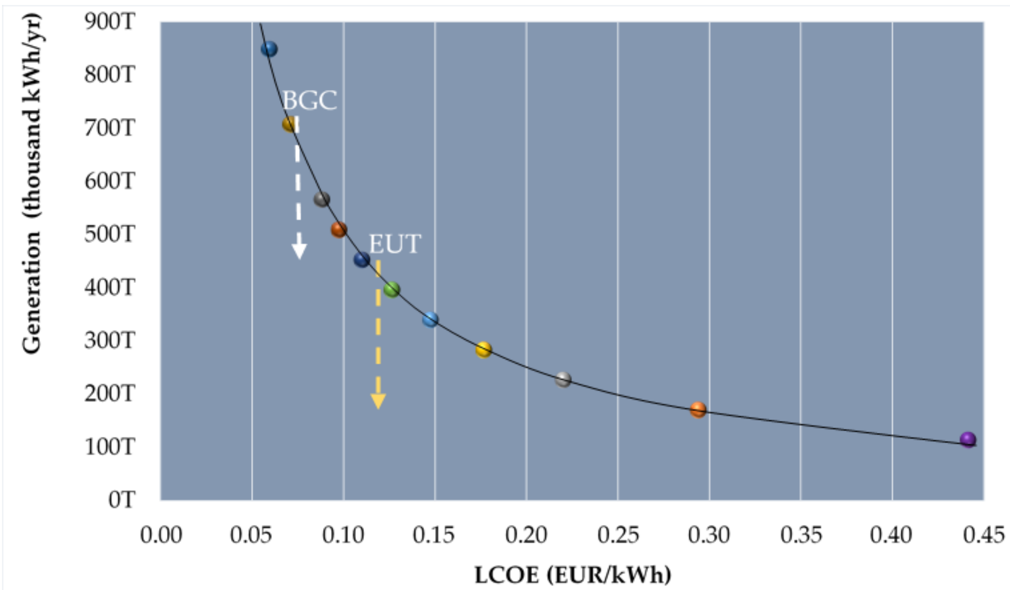

Figure 7. Sensitivity assessment of the generation against the LCOE for Case 1 indicating the end-user tariff (white) and bulk generation charge (yellow).

Other studies recorded similar high LCOE results for hybrid renewable systems in Ghana. However, such hybrid systems differ in the combination of technologies. In a 2022 study involving a hybrid solar PV and biogas system with an energy output of 396 kWh/day, it was found that it had an LCOE of 0.23 [39]. In a 2016 study, a hybrid solar PV and biodiesel generator system producing 104 kWh/day had an LCOE of 0.63 [90]. However, a 2023 study on a 400 MW floating solar system showed a very low LCOE of 0.091. This could be attributed to the lower cost per kW of solar PV (EUR1050/kW) as compared to AD or pyrolysis (3730/kW) in this study. A comparative study of solar PV, waste gasification and a hybrid of the two technologies revealed that NPV and IIR for the standalone solar PV performed better than the hybrid, with the gasification showing unattractive results. The cost difference between the technologies also has implications for future technical designs of the model proposed in this study. Moreover, it is implied that expansion of the capacity of such hybrid technologies can be implemented in regions with low waste generation and with a higher capacity of solar PV, to provide a lower overall project cost both in terms of CAPEX and O&M. In such instances, a lower LCOE can be obtained.

Since the none of these technologies are locally produced but are imported into the country, the influence of currency depreciation and fluctuations of the local currency has a high tendency to increase the CAPEX, while the OPEX is strongly influenced by local inflation. This indicates the strong influence of the local economic situation on potential investments [91].

According to the IEA and IRENA, the global cost of new renewable energy plants is expected to reduce in the next decade due to increasing research into cheaper technologies and increasing interest from governments in implementing utility-scale plants. Figure 8 shows that the LCOE is influenced by a certain percentage as the CAPEX increases or decreases. The LCOE for utility-scale solar PV plants in 2022 was 0.049, which was 29% lower than that for commissioned fossil fuel projects. Biomass, on the other hand, recorded an average of 0.54 EUR/kWh [92].

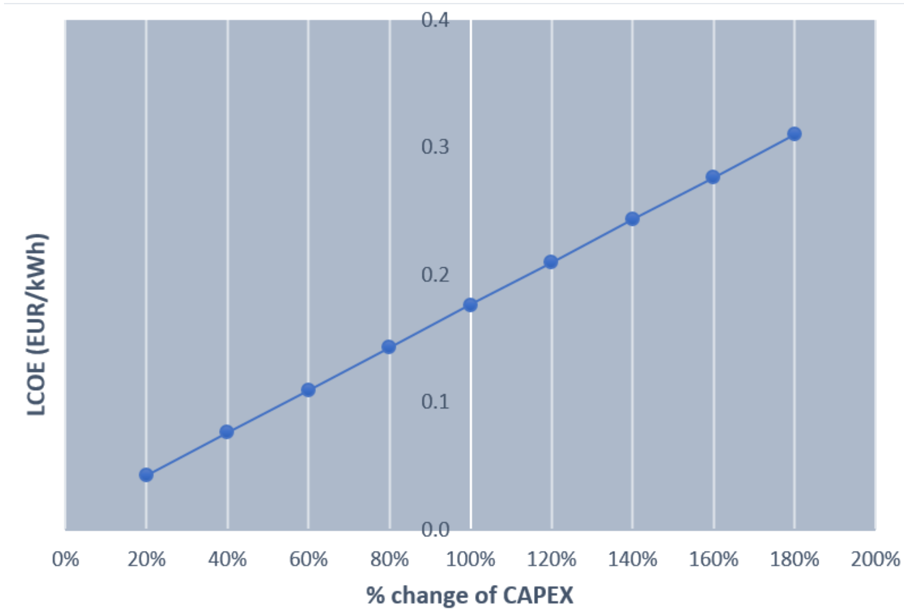

Figure 8. Impact of reducing or increasing CAPEX on the LCOE.

4.4 Broad Circular Economy Framework for GAMA

Waste governance is a major responsibility of city managers across SSA. However, this has proven to be very challenging. The circular economy created for the GAMA region includes a robust system for the collection of 96% of waste, recycling of 15% of the collected waste, with energy recovery from 45% of the input waste, 38% for alternative fuels and the remaining organics, recyclables and inerts for compost, industry and landfills, respectively. The energy, compost and recyclables present a direct source of material recycling, while the energy transferred to the grid presents energy recovery potential. Eventually, alternative fuels (hydrogen, RDF and bio-CNG) produce energy as the end use, also contributing to energy recovery from waste. This energy is typically for industrial manufacturing, also indirectly contributing to a circular economy.

In implementing this circular economy model, energy recovery must always be at the back end of material recovery. This will allow multiple players such as recycling industries within the current waste management infrastructure to be seamlessly integrated into the proposed model. Data indicate that each plastic recycling company collects about 30 tons of waste per day and has 50 direct employees on average, with an annual trade volume of EUR 14,000 by waste pickers distributed along the value chain [19,74]. This acknowledges the role of the informal sector within the waste management value chain, which incorporates over 2200 service providers and recycling entrepreneurs, who collect 1370 tons of waste per day [44].

One critical aspect of attaining a circular economy is source segregation. The social impact of this project must be carefully considered to ensure public acceptability. It has been estimated that the landfill site employs about 157 registered informal sector waste pickers who collect recyclable waste to sell to middlemen in the recycling trade. They only collect 3 tons of waste per day, with an annual average of 1000 tons [58]. This means the recyclable quantities estimated to be recovered from the plant can become a source of income for these waste pickers. However, a more sustainable approach will be to integrate them as unskilled workers at the plant. This will potentially improve their working and economic conditions since current waste collection activities are carried out with few health and safety measures. Careful public policies must be also directed toward supporting female entrepreneurs within the circular economy, such as farmers adopting the use of compost from the plant or those within the recycling industries [93].

SSA has adequate potential to implement such models to facilitate the attainment of SDGs 7,11 and 13. To do so, a multidimensional and multilevel approach is required. At the core, citizens must have a strong will to get involved in sustainable waste management. Policies focusing on source segregation, the circular economy and the trade of products are needed. To crown it all, strong institutions are required to enforce these policies [17].

This study's results indicate that the cost of energy of the system is mainly affected by external factors such as inflation and the capital cost of the technologies. However, this study did not consider different investment and financing models such as various debt-to equity scenarios, capacity financing or government concessionary loans [94]. Investment security is important within the energy sector. Under the current economic conditions within the country, government concessionary loans can provide important means to cover the cost of producing energy from the proposed plant. Furthermore, in order to support renewable energy development in developing countries, Sustainable Development Goal 7.a.1 tracks the international public financial flows to developing countries. Ghana must actively take advantage of such policies. Moreover, research has a role to play in tracking the progress of specific countries such as Ghana [95].

This study has considered a hybrid renewable energy system a city in a developing country that is currently saddled with poor waste management. Although the results of demonstrate that such a system has the potential to improve the situation, there were a few limitations to this study. For one, there were no data available from municipal authorities on the exact daily waste generated in the metropolitan area. As such, data were based on projections from previous studies within the last five years. Research is needed to develop appropriate data collection systems to support accurate waste generation data. Furthermore, the social, health and environmental impacts of proper collection were not considered. In the future, the environmental and social costs associated with waste management can be valued to improve our understanding of the overall benefits of the project [96]. Since the current energy mix is dominated by hydro and fossils, it is important to compare the environmental savings made with the renewable energy replacement.

Conclusions

This study designed and assessed the feasibility of developing a utility-scale hybrid waste-to-energy plant within the Greater Accra Metropolitan Area. Waste is considered a huge nuisance within the city, and in this way, it can contribute as much as 271 GWh per year to the national energy mix. Also, alternative fuels can be produced if a PPA cannot be secured for the national grid. The options include hydrogen, bio-CNG and bio-oil. Compost is also a very important product, which can potentially contribute about 50% of revenues if rigorous marketing and cost-effective transportation and distribution channels are established to transport compost from the city to rural areas where agriculture is prevalent. Since Ghana has few large-scale farms, extensive stakeholder engagement across the country will be required to ensure adequate distribution channels are developed. Similarly, green hydrogen requires the development of local markets or trade on the international market. Within a circular economy framework, energy recovery stands at the backend of waste reduction and material recovery. This study has estimated that by 2030, 91% of the waste within the city can be collected with improvements in collection services, and 6% will go to landfill with WTE. In sum, waste segregation, material recovery and recycling must be improved to enhance the sustainable waste management within the city. Overall, this study provides a recommended strategic direction for city authorities and policy holders in order to solve the challenges associated with waste management and sustainable development. Future research must incorporate the environmental and social impacts of the project, as well as the economic cost of improved waste management for global society. Also, national resource mapping and research into the potential of the technical model are necessary to identify the hotspots in the country for waste generation. This can provide an index of the characteristics of various geographical locations across the country. With this, investment advice can easily be provided to potential investors, as well as guidance for future public policy decisions.

Author Contributions

Conceptualization, E.A.A. and S.N.; methodology, E.A.A., F.B.A. and M.M.; validation and data curation, S.N. and M.M.; writing—original draft preparation, E.A.A. and B.B.; writing—editing and review, M.M., S.N. and E.B.; supervision, S.N. and F.K.; funding acquisition, S.N. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

Not applicable.

Data Availability Statement

Data are contained within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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ANNEX V: JOURNAL PUBLICATION 3 (PAPER V)

Environmental Assessment of Hybrid Waste-to-Energy System in Ghana

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Abstract

Waste management in most parts of Africa is characterized by the disposal of mixed waste in unengineered landfills. The aim of this study is to assess the environmental impact of mixed waste received at a waste-to-energy plant in Ghana relative to the current model of landfilling. A Life Cycle Assessment was conducted using OpenLCA software version 2.3.1 based on the ReCiPe Midpoint method. For landfilling, LandGEM software version 3.03 was used. The results indicate that waste-to-energy has the potential to provide carbon savings of 3.52 tCO_2eq/ton of waste treated compared to landfilling. Pyrolysis is observed to have high avoided burden across all impact categories, with the lowest Global Warming Potential of −2.3 $kgCO_2eq$. Anaerobic digestion shows a near neutral environmental impact with the highest value of 47.56 kg 1,4DCB for Terrestrial Ecotoxicity, while Refuse-Derived Fuel and segregation processes show low environmental burdens. The net avoided burden is highest for global warming and non-carcinogenic human toxicity potential. Overall, the hybrid waste-to-energy model is concluded to be an environmentally preferred waste management option compared to conventional landfilling methods, and we recommend that decision-makers facilitate investments into it. It is also recommended for the development of local inventories and databases to encourage more country-specific environmental impact studies and to reduce uncertainty.

Keywords:

life cycle analysis; waste to energy; anaerobic digestion; pyrolysis; refuse derived fuels; environmental impacts; global warming potential; openLCA; LandGEM; Ghana

1. Introduction

Developing countries continue to lag behind as the 2030 target of the Sustainable Development Goals (SDGs) draws nearer [1,2]. Waste management and energy are crosscutting sectors with high environmental footprints mainly linked to SDGs 3, 6, 11 and 13. With a record high of 37.4 Gt energy related CO_2 emissions in 2023, greenhouse gas (GHG) emissions from these sectors are a key concern to the global agenda. Renewable energy is, in particular, crucial for reducing emissions [3,4]. The recently ended United Nations Climate Conference 2024 (COP 29) was strongly dominated by discussions of climate finance and carbon markets with stronger commitments to supporting developing countries [5]. Ironically, a study in South Africa, Nigeria, Cameroun and Ghana identified a lack of strong policy implementation as a challenge to renewable energy uptake and particularly waste-to-energy (WtE) projects in Ghana [6,7].

Waste is a resource material for energy generation with the potential to substitute fossil fuels and consequently reduce the environmental burden of poor waste management [8]. CEWEP estimates that in 2021 alone, the conversion of waste to energy (WtE) supplied 35,000 GWh of electricity to 21 million Europeans, together with 87,000 GWh of heat to 17 miilion residents, which translates into 22–44 million tons of CO_2 savings [9]. The end products of WtE include electricity, hydrogen, biodiesel, RDF and heat, although electricity and heat are the most common. They can generally be categorized into either energy or fuels [10].

Comparative environmental studies support key decision-making on WtE technology selection. Decisions can be made between WtE technologies and conventional/existing treatment options such as landfilling. For instance, WtE shows methane emissions reductions of about 52% for biomethane production compared to landfilling [11]. A decision can also be made on the selection of the most environmentally friendly technology or process. For instance, electricity/heat cogeneration was found to be the most environmentally friendly scenario, releasing 1.95 $kgCO_2eq/m^3_{biogas}$ compared to the combined end-products of electricity/biomethane [12]. In another city-scale scenario analysis, it was concluded that a thermal WtE option (incineration) provided the best GHG savings of (652,626 tCO_2eq/yr), which was more than twice that of two other scenarios: recycling/landfill gas to energy and recycling/composting [13].

Following the Paris agreement, countries like Ghana have set up a National Greenhouse Gas Inventory. Data from the directory indicate that the three major contributing sectors are energy, agriculture, forestry and other land uses (AFOLU) and waste. Between 1990 and 2019, the total national GHG emissions increased by 853.1% and 265.1% in the energy and waste sectors, respectively, with the energy sector alone contributing 45.7% in 2019. Strategies to reduce emissions as the population and economy continue to expand are critical [14]. The energy sector has been reported to be financially unsustainable due to its high dependence on externally sourced fossil fuels for power generation [15]. On the other hand, the country aims to achieve 10% renewable energy penetration by 2030 through the Intended National Determined Contribution (INDC), which is unlikely to be achieved due to low incentives [16]. Meanwhile, solar, wind and biomass (including waste) have been identified as attractive alternatives to achieve this target, considering the local abundance of these resources [17,18,19]. It is estimated that WtE technologies such as anaerobic digestion (AD), incineration and landfill gas to energy (LFGTE) have the potential to supplement 59% of the country's renewable energy target in 2030 [20]. Ironically, the waste management sector in Ghana is plagued by the poor implementation of sustainable waste treatment options, with an estimated 931 tons of waste sent to landfilling daily from the capital and adjoining towns alone [21].

Several WtE studies have been carried out in Ghana, mostly incorporating techno-economic assessments. Existing and operational WtE plants include the Safi Sana and HPW plants, which incorporate AD and solar PV technologies [22]. It is clear that such projects require the strict assessment of impacts, including environmental impacts and the incorporation of risk mitigation measures, to avoid adverse impacts [23]. Published studies have considered the potential for establishing WtE plants under various settings in Ghana such as rural electrification [24], university sewage treatment [25], urban municipalities [26,27,28], incineration at the national scale [29] and landfill sites [30]. All the studies focused on one key product, electricity to grid, and concluded on technical feasibility, considering varied conditions.

The German government has recently supported the establishment of a pilot WtE plant in Ghana in Gyankobaa in the Ashanti Region. It has been projected to generate 810 MWh of electricity per annum with other associated fuels such as RDF, plastic pellets and compost. The technical model of the plant, which involves a hybrid of solar PV, AD and plastic pyrolysis, has been proven to have the potential to be replicable in other parts of the country [31]. A detailed techno-economic assessment of this case study plant has been previously conducted and published. The results indicate that a standalone WtE plant relying only on grid connected electricity is not feasible. A business case, which involves the strong integration of solar PV at a larger capacity than the current plant, is presented [32]. In an assessment of product models, it was concluded that the conversion of generated energy into fuels and materials such as green hydrogen, biomethane, RDF and compost will potentially make the plant more feasible [33]. These studies are intended to strategically direct the business model when the plant becomes fully operational. One important element of business models is the environmental impact. Also, at the national level, WtE is generally expected to generate negative environmental burdens compared to energy generation from fossil fuels or the landfilling of waste. A research gap is therefore identified for the environmental assessment of WtE using the hybrid WtE plant as a case study.

The aim of this study is therefore to investigate the potential avoided environmental burden from the pilot plant compared to the current landfilling alternative. Also, this study will conduct a comparative assessment of the environmental performance of the subsystems at the plant. It is expected that the results will enhance investment from both the private and public sectors to support decision-making in waste management projects.

The most standardized environmental assessment technique for WtE systems is the Life Cycle Assessment (LCA) [34]. LCA is a well-developed environmental management technique used to assess the environmental impacts of technologies, scenarios or systems. The ISO 14040 and 14044:2006 provides principles and detailed guidelines for conducting an LCA [35,36]. For WtE systems, the most commonly used LCA methods are the CML impact assessment series, IPCC, ReCiPe and Eco-indicator. Global Warming Potential (GWP) is the most analyzed impact/damage category. Generally, landfilling has the highest GHG emissions compared to WtE technologies [37]. The CML method is one of the earliest and most established LCA methods and focuses on individual impact categories. IPCC is primarily considered in assessing climate change impacts such as GWP. ReCiPe, on the other hand, covers a wide range of impact categories, which is relevant for such a study [38].

2. Materials and Methods

2.1. Study Scope and System Boundaries

The study focuses on the environmental assessment of multiple technologies at a pilot WtE plant located at Atwima Nwabiagya Municipality in Ghana. The Business-as-Usual (BAU) is the current waste management model where municipal waste is collected, transported and disposed at the Kyereso landfill, which is basically an unengineered landfill/dumpsite [39]. This study uses the LCA methodology, which follows four major stages, as recommended by ISO 14040 (1997): definition of scope, inventory development, impact assessment and interpretation of results [35]. Figure 1 shows the system boundary and the process flow within the plant beginning from the gate of the treatment facility/dumpsite to the end of the treatment. Although the plant also has the capacity to treat other forms of waste through recycling and composting, this study focuses on the environmental aspects of energy/fuel production [33].

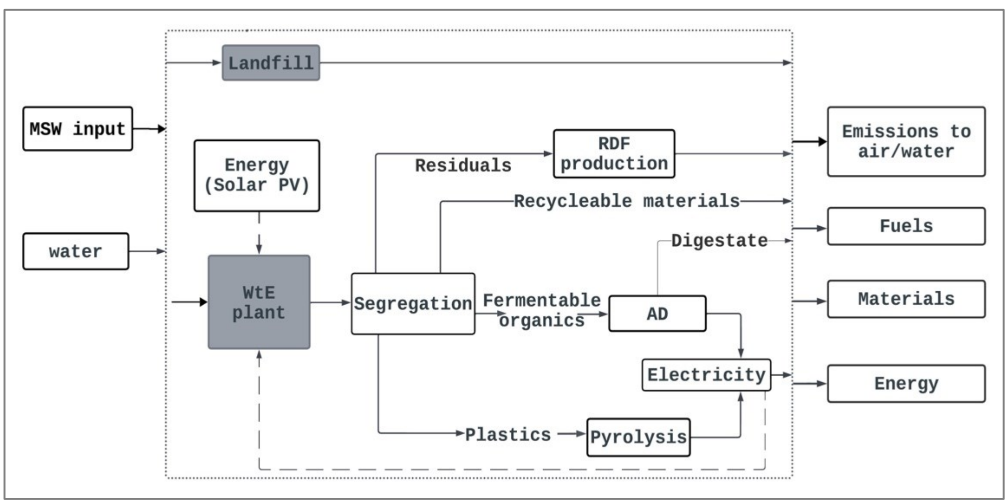

Figure 1. System boundary, technical framework and the flows for each product system for the WtE plant.

2.2. Functional Unit

Based on the goal of the study, the functional unit (FU) considered is one ton of mixed MSW waste received at the treatment facility. Since the capacity of the WtE plant is 50 t/day, it is compared with the same quantity at the landfill site over an active lifespan of 20 years.

2.3. Waste Composition and Segregation

Mixed MSW arriving at the plant or landfill is estimated to have the following characteristics according to a related study within the same municipality [39]: fermentables (37.8%), plastics (17.1%), paper (1.2%), wood (1.5%), cardboards (3.2%), metals (1.2%), glass (1.3%), textiles (4.4%), special wastes (4.2%), inerts/fine ores (16.8%) and miscellaneous materials including e-waste, sanitary materials and household repair debris (11.3%). The first stage of treatment is the four-stage manual and mechanical sorting system, similar to what is used in other Material Recovery Facilities (MRF) in Ghana, such as the Kumasi Compost and Recycling Plant (KCARP) [40,41]. After this, the various fractions are transferred to the respective processes, as shown in Figure 1.

2.4. Life Cycle Inventory Analysis (LCIA)

LCIA involves stock-taking of the inputs and outputs of materials, emissions and energy from each process within the boundaries of the product system [37]. Sources of data are primary data obtained from the plant, other related studies and calculated values based on literature. Elementary flows for emissions were estimated using emission factors from sources such as [42,43]. Pollutant emissions focus on greenhouse gases (CH_4, CO_2, N_2O) and acidic pollutants (SO_2, NO_x) [44]. The inputs and outputs of materials and energy for each process within the WtE plant were summarized in the following sections.

2.4.1. Business-As-Usual (BAU)

In BAU, mixed waste is disposed of at the dumpsite without any treatment. Landfill Gas Emissions Model (LandGEM) version 3.03 was used to estimate the emissions from 50 t/day MSW deposited at the Kyereso dumpsite [45]. The LandGEM software employs a first-order decomposition rate equation, as described in [43]. Localized values were calculated for the methane generation rate and the potential methane generation capacity to replace the default values (Table 1).

Table 1. Key input variables for landfill gas modelling in LandGEM.

Input Variable	Value	Units	Details	Reference
Precipitation	1318.34	mm/yr	Regional annual average for Ashanti Region (1990–2021)	[46]
Methane correction factor	0.8	-	Default for deep, unmanaged landfills	[47]
Temperature	26.98	°C	Regional annual average for Ashanti Region (1990–2021)	[46]
Methane fraction in landfill gas	50	%	Default	[47]

Landfill gas is generally a mixture of two major components (CH_4 and CO_2) and several trace gases. LandGEM generates default outputs for Total LFG, CH_4, CO_2 and NMOC [45]. The GWP of landfill gas for 100-year horizon (GWP_{100}) in $kgCO_2eq/yr$ is computed as the sum of GWP of GHGs. According to IPCC, GWP_{100} for CO_2 (GWP_{100}) and non-fossil methane (GWP_{CH4}) are 1 and 27, respectively [48]. Not all methane generated in a landfill is directly emitted into the atmosphere. Losses occur through the surface cover, methane oxidation in cover soils and lateral migration or losses during storage, which is assumed to be 10% of the generated methane. Thus, mass uncontrolled methane emissions (UMP_{CH4}) from landfills without Gas Collection and Control Systems (GCCS) and subsequently (GWP_{100}) is estimated by [49]

$$UM_{CH4} = M_{CH4} \times 0.9 \quad (1)$$

$$GWP_{100} = (UM_{CH4} \times GWP_{CH4}) + (M_{CO2} \times GWP_{CO2}) \quad (2)$$

2.4.2. Anaerobic Digestion (AD)

The inventory for this study follows a similar assessment in a related publication [50]. Electricity generated is computed based on [51,52]. The source of energy for the engines is the solar PV system, while the AD receives recycled heat energy from the CHP. Sources of emission from the AD system are mainly from digester and the CHP engine. Methane losses from the digester are estimated to be 5%, and CO_2 is ignored because it is of biogenic origin, which has insignificant environmental impact [44]. Emissions from the CHP engine are estimated using the emission factor for GHG, acidifying pollutants are computed [53] and the inventory is presented in Table 2.

Table 2. *Inventory for the AD process.*

Flow Direction	Parameter	Units	Value
1. Bio-digestion			
Inputs	Organic waste	tons	1.00
	Electricity (solar PV)	kWh	38.45
	Heat (CHP)	kWh	237.80
	Water (groundwater)	m^3	0.37
Outputs	Methane	m^3	62.14
	Digestate	tons	0.88
	Methane (emissions)	kg	1.34
2. Cogeneration			
Input	Methane	m^3	62.14
Outputs	Electricity	kWh	216.20
	Avoided heat	kWh	237.80
	Carbon monoxide	kg	5.16E-09
	N_2O	kg	0.0012
	NO_x	kg	0.16
	SO_2	kg	0.02

2.4.3. Pyrolysis

The pyrolysis system has the capacity to process 30–50 kg/h of mixed single-use plastics (SUPs). The process is described in a recent related publication [54]. It begins with the pretreatment stage involving shredding, washing and drying, which results in a 5% loss of weight due to the elimination of impurities and moisture. The feedstock is then introduced into the reactor. The main process outputs (wt%) are bio-oil (79.38%), gas (15.22%) and char (5.4%). The bio-oil and gas are combusted in separate CHP engines to generate electricity. Electricity from bio-oil is directed for grid supply, while electricity from the gas is internally recycled to provide the process energy for the reactor. The energy output (kWh/ton) of input waste from bio-oil estimation is based on [55]. Other outputs from the system are the wastewater from washing and emissions from the CHP engine. The main source of emissions is the CHP since the reactor is specifically designed to operate under airtight conditions. Emission factors from [55] are used. The inventory analysis is summarized in Table 3 below.

Table 3. *Inventory for plastic pyrolysis process.*

Flow Direction	Parameter	Units	Value
1. Pretreatment			
Inputs	Waste–plastic mixture	tons	1.00
	Water (well)	m^3	0.15
	Electricity	kWh	1.00×10^{-5}
Outputs	Waste–plastic mixture	tons	0.95
	Wastewater	m^3	0.165
2. Pyrolysis			
Inputs	Waste–plastic mixture	tons	0.95
	Electricity (solar PV)	kWh	0.009

Outputs	Bio-oil	tons	0.75
	Char	tons	0.05
	Syngas	m^3	0.13
3. Cogeneration			
Inputs	Bio-oil	tons	0.75
Outputs	Electricity	kWh	0.0033
	Heat	kWh	0.0093
	Carbon dioxide (non-fossil)	kg	2.15
	N_2O	kg	0.0003
	Methane (non-fossil)	kg	0.0001
	NO_2	kg	0.0039
	SO_2	kg	0.0209

2.4.4. RDF Production

The conversion of residuals to RDF involves three main stages: separation to remove complex waste and recyclables such as glass, metals or e-waste, cutting/shredding to homogenize waste into required particle sizes and finally compacting to reduce volume for easier transportation [56]. Energy demand for these processes has been computed using the power ratings of the equipment onsite and the 8 h of daily operating. Energy is sourced from internal solar PV system; thus, pollutant emissions are negligible. The inventory for the RDF process is specified below in Table 4.

Table 4. *Inventory for RDF production.*

Flow Direction	Parameter	Units	Value
Inputs	Residual materials	tons	1.00
	Electricity (solar PV)	kWh	51.58
Outputs	RDF pellets	tons	0.95
	Heat (loss)	kWh	33.0
	Trace particles	kg	0.05

2.5. Life Cycle Impact Assessment (LCA)

The OpenLCA 2.3.1 software was used to model each process following the guidelines of the ISO 14040/14044:2006 [35,36]. According to ISO 14042 [57], LCA process follows three mandatory steps: selection of characterization methods, classification and characterization. Additional optional steps are also recommended: normalization, grouping, weighing and data quality analysis [57].

The following steps were therefore followed with the aid of the OpenLCA software. Firstly, the impact categories, indicators and characterization models were selected. ReCiPe2016 midpoint (H) impact assessment method was used, which identifies 17 midpoint characterization factors that are linked to three endpoint protection areas [58,59]. This study focuses on ten midpoint impact categories due to their relevance to the scope, as is done in similar studies and this is represented in Table 5 [60].

Table 5. Selected impact categories and their relevance to the study.

Impact Categories	Relevance to the Study	Link to Endpoint Impact	Unit
GWP	Risk to human health and ecosystem	Human health	kg CO_2 eq
PMFP	Increase in respiratory diseases		kg $PM_{2.5}$ eq
HTP/C	Increased risk of carcinogenic diseases		kg 1,4-DCB
HTP/NC	Increase in other diseases		kg 1,4-DCB

WCP	Reduced access for consumptive uses		m^3
TETP	Risk to terrestrial spp.	Ecosystems	kg 1,4-DCB
FETP	Risk to freshwater spp.		kg 1,4-DCB
AP	Risk to terrestrial spp.		kg SO_2 eq
METP	Risk to marine life		kg 1,4-DCB
FFP	Increased scarcity and cost of extraction	Resource availability	kg oil eq

The second stage involves assignment of LCIA results (classification). In OpenLCA, the inventory results were input for each process within the system boundary. The Ecoinvent Database v3.5 provided secondary data in the calculation of impacts. The category indicator results were then calculated by the software. Normalization is recommended in LCIA to assess the magnitude of the category indicator results relative to a reference value. This was carried out based on the World 2010 normalization method [61].

2.6. Interpretation of Environmental Impacts

The interpretation of results of LCIA was conducted according to ISO 14044:2006 [35]. This involves evaluation of results through checks for consistency, completeness and analysis of results. Results were then assessed through an iterative process where significant issues were searched, checked and analyzed. When significant issues were detected, corrections were made, and the simulation was re-run [57]. The characterization and normalization results were then imported from OpenLCA to be analyzed with Microsoft Excel. The characterization results were adjusted to percentage to assess the relative contribution of various impact categories. However, uncertainty results were exported from the OpenLCA software and analyzed using Python (Jupyter Notebook).

Interpretation of results includes sensitivity analysis and uncertainty analysis. This is done to check for the robustness, consistency and completeness of the data used in the analysis. A Monte Carlo simulation was conducted using 1000 iterations to perform the uncertainty analysis of the results. The data quality pedigree matrix was used to assign uncertainty values to the dataset used during the life cycle inventory stage [62].

3. Results and Discussion

3.1. Impact Assessment of Subsystems

This study focuses on an assessment of four subsystems at the WtE plant. Figure 2 shows the relative environmental impact of the various subsystems compared to the impact factors. Generally, pyrolysis shows a high negative impact across all impact categories, representing a high avoided environmental burden. The other subsystems show a positive impact, but one that is not so high. Segregation and RDF have positive values showing environmental burdens. AD, on the other hand, shows a generally neutral environmental impact. A neutral GWP was also recorded in a similar study, which assessed an AD system using different energy consumption scenarios [50]. In another study comparing AD with incineration, which is also a thermal conversion technology, AD showed near-neutral impacts, while incineration showed a high negative impact.

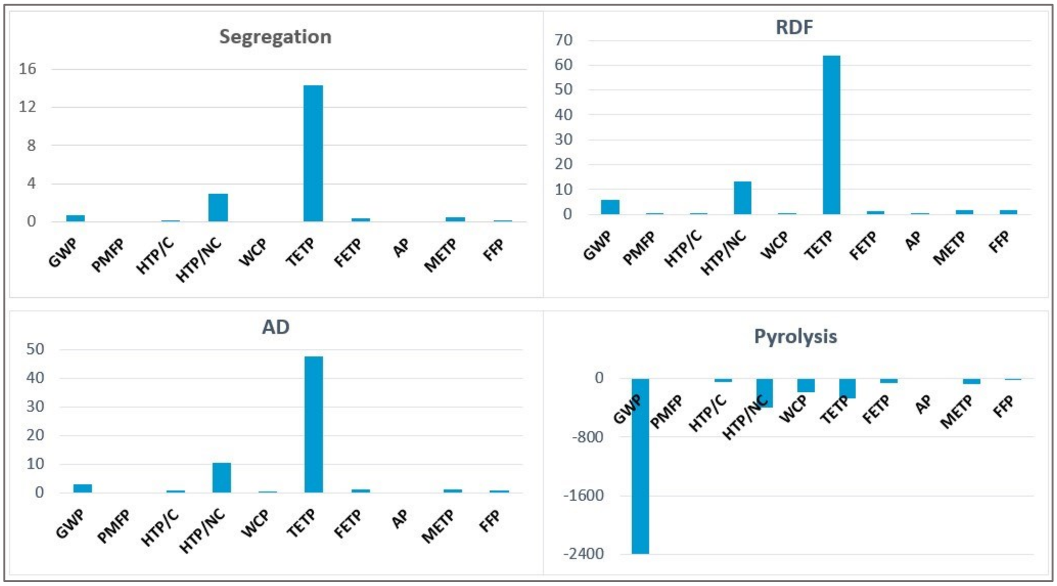

__Figure 2.__ The impact of subsystems according to impact categories.

Figure 3, on the other hand, shows the percentage comparison of impact categories to the various subsystems. Pyrolysis for instance shows better environmental impact due to the production of new products such as char and digestate in the AD process compared to the negative impact the processes themselves generate [63]. Pyrolysis oil can also be considered a fuel similar to diesel [64]. Sources of environmental impact for the AD system include methane leakages from the biodigesters and the combustion of methane in the internal combustion engine. The highest environmental impact on soil and water in terms of toxicity may potentially originate from the digestate [65]. Overall, the magnitude of environmental burdens of the processes can be summarized as follows: RDF > segregation >AD > pyrolysis. RDF production and segregation, on the other hand, release process emissions, especially particulates [66].

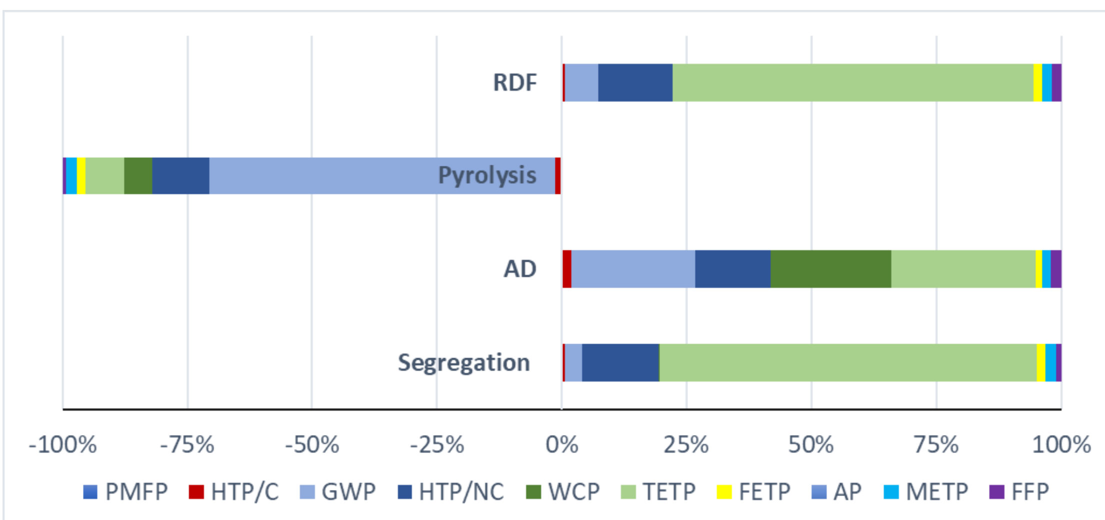

__Figure 3.__ Percentage contribution of the relative environmental impact of subsystems at the WtE plant.

3.2. Impact Assessment According to Impact Categories

Figure 4 shows the net contribution of all processes to the impact categories. The net emissions represent a balance of positive (burdens) and negative (offsets). This highlights the actual burden after accounting for reductions. The total net GWP for the WtE plant is estimated at −2.382 tCO_2eq/FU.

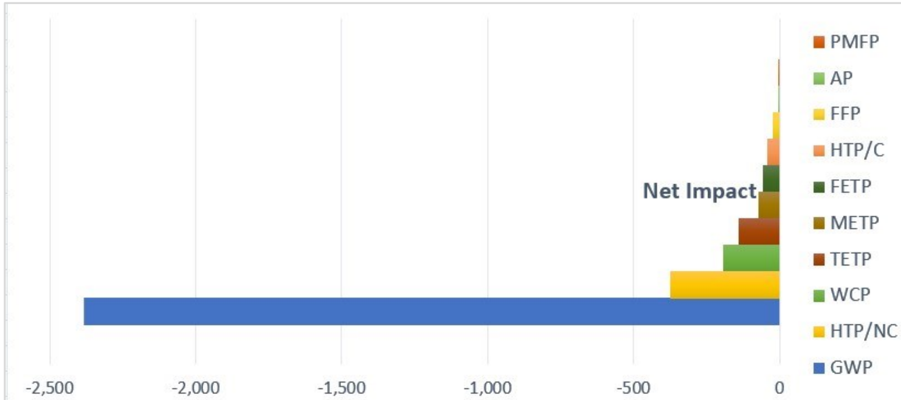

Figure 4. *Net (cumulative) impact of the four subsystems according to impact categories.*

Figure 5 shows the relative contribution of impact categories based on normalized results. It corroborates the results of Figure 3, where the dominant subsystems are pyrolysis and AD.

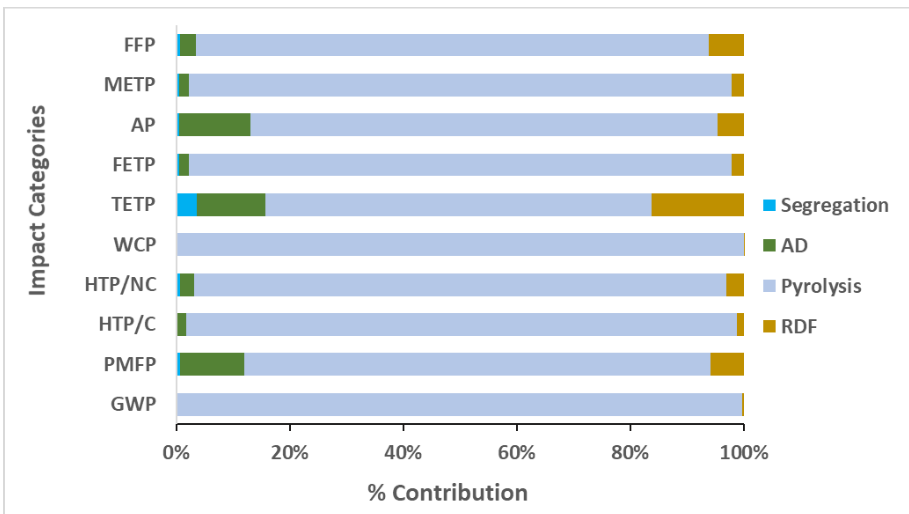

Figure 5. *Percentage contribution of impact categories and processes based on the normalized values.*

3.2.1. GWP

The GWP is strikingly the highest impact category with the highest avoided burden compared to the other impact categories. GWP is an important metric for environmental emissions and climate change. Pyrolysis had the lowest negative GWP value of −2.3 tCO_2eq/FU, indicating high carbon savings (Figure 3). Net emissions are important in determining the burdens.

On the other hand, the GWP_{100} is presented in Figure 6 for the same 50 t/day of waste disposed of at the landfill site. This is estimated to be 1.133 tCO_2eq/ton of waste-in-place by the end of the lifespan of the landfill. By the time of closure, the landfill would have emitted 4409.56 tons of uncontrolled methane into the atmosphere, although GHG emissions would continue for another 100 years. The total GWP over the lifespan is estimated to be 413,564.21 tCO_2eq since the landfill under consideration has no gas control infrastructure. The GWP of the landfill is based on uncontrolled methane emissions and non-biogenic CO_2.

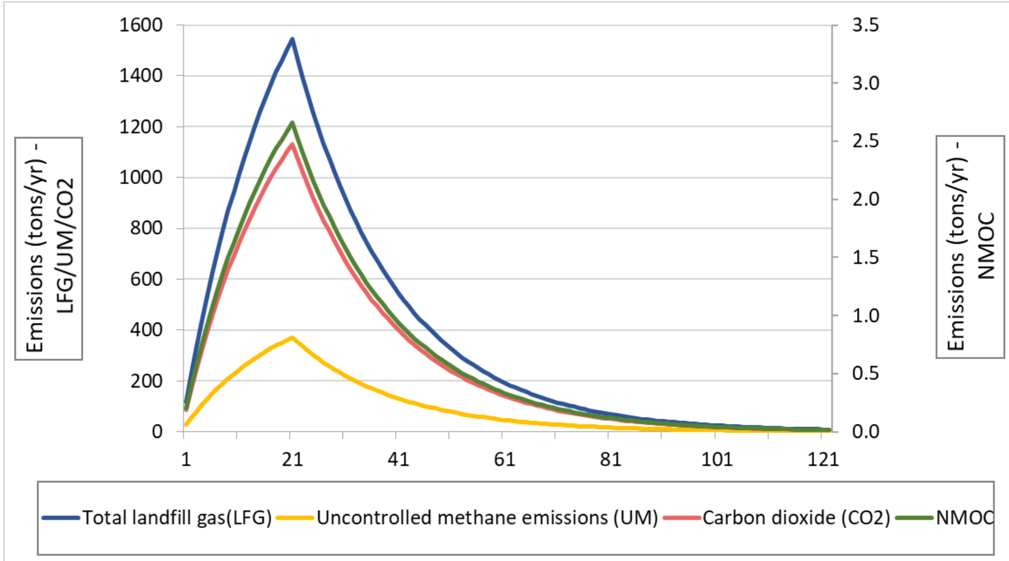

Figure 6. *Landfill gas emissions based on LandGEM representing a lifespan of 20 years.*

The WtE plant reduces emissions by 3.52 tCO_2eq/FU, representing the avoided emissions. The WtE plant is expected to treat 365,000 tons of MSW over its 20-year lifespan. With the calculated net carbon reductions, this could result in carbon savings of an estimated 1.28 million tCO_2eq. This may be associated directly or indirectly with the financial feasibility of the WtE plant if such reductions are adequately verified [67]. The net emissions show that the WtE plant reduces emissions by 310%. This may, however, be subject to differences if long-term monitoring is conducted over the entire lifespan of the WtE plant compared to the long-term considerations made for the landfill. In a comparative study in Nigeria, a hybrid AD/incineration system and an LFGTE had the potential to release 75–93% and 400% less, respectively, compared to conventional landfilling [44]. A similar result was obtained in a study in the US where landfilling released 75.24% higher GHG compared to gasification systems [68]. In another study in Australia, landfilling recorded the highest environmental burden in 9 of 10 midpoint impact factors assessed, indicating that landfilling is the least environmentally friendly option [60]. Since the source of GHG at landfill sites is the biodegradable components and non-biogenic CO_2, the biochemical process can be compared to the AD system at the WtE plant, which has a GWP of 0.0032 tCO_2eq/FU. Although recent studies in Ghana have estimated that LFGTE is a feasible option, AD is even more efficient, with a lower GWP compared to LFGTE [28]. This is attributed to higher losses due to landfill cover of 10% and gas capture efficiency of 75% compared to 5% losses from the biodigesters [43,69].

The carbon intensity of WtE technologies is linked to the source of energy [60]. Sources of emissions from the WtE plant include engines and leakages of methane from AD. Energy for the RDF and segregation equipment is sourced from internally generated electricity, solar PV systems and biogas, which has a low emission profile. Also, heat energy losses from the RDF and segregation systems add up to environmental burdens. Assuming electricity for RDF pelletizing is sourced from fossil sources (diesel), avoided emissions can be estimated using emission factors [70]. With an energy demand of 452 kWh/day at full capacity, the GWP of a diesel-fired RDF pelletizer machine is estimated at 13.84 $kgCO_2eq$/ton, which, in this study, can be considered an avoided emission. RDF produced using cleaner energy reduces the overall environmental footprint of the energy produced from it. In addition, combustibles and other non-biodegradable components of waste are more efficiently treated with thermal energy conversion technologies such as gasification and pyrolysis rather than storage in land space at a landfill.

Studies have shown that the pretreatment and dewatering of waste significantly reduce emissions [13]. The low GWP recorded for pyrolysis may be a combination of the source of energy (solar PV and syngas), incorporating pretreatment and potential carbon sequestration from char. Char produced from pyrolysis possess has the capacity to sequester carbon, leading to the negative release of carbon [63,71].

Additionally, bio-oil and syngas replace fossil fuels for the production of electricity, thus further accounting for the avoided release of stored/fossil carbon, which could potentially end up in the atmosphere.

3.2.2. Toxicity Potentials

Toxicity represents the environmental fate and accumulation of a chemical in the food chain and its associated effects [58]. The toxicity potentials analyzed in this study are Human Toxicity Potentials (HTP) and Ecotoxicity Potentials (EP) in terms of Terrestrial (TETP), Freshwater (FETP) and Marine Ecotoxicity (METP). HTP is presented in two parts by the ReCiPe method: carcinogenic (HTP/C) and non-carcinogenic (HTP/NC). Both are linked to endpoint damage to human health due to an increase in lifetime disease incidence as a result of the intake of substances such as contaminated water or food from contaminated soil [59]. Generally, AD showed a high environmental burden due to the release of digestate. Digestate is planned to be upgraded into a soil amendment product. In the case that high quantities of heavy metals and contaminants are present, digestate may potentially have an alarming disease-causing impact on humans [72].

HTP is a very important potential risk that should be further investigated due to the mixed nature of the waste. High concentrations of heavy metals such as zinc, copper, lead, chromium and nickel have been detected in waste from the same region [73]. Heavy metals and chlorines in RDF must also be avoided due to their potential risk when gasified at industrial plants [41]. HTP/NC recorded the second-highest avoided impact for pyrolysis due to the production of char. Char has the potential to adsorb such pollutants and has been effectively used in soil/wastewater remediation. This can, however, be substantial only if the char is utilized for this purpose and the sorption capacity is improved through techniques such as grinding [74].

The ecotoxicological effect measures the Potentially Affected Fraction (PAF) or the change in Potentially Disappeared Fractions (PDF) of ecological species due to exposure to unacceptable pollutant concentrations [59,75]. TETP, FETP and METP measure the impact on land-dependent, freshwater or marine organisms, respectively. EPs are notably high for AD, and the lowest avoided burdens for pyrolysis are in the order of TETP > METP > FETP. Digestate and methane losses from the AD are a major source of ET to ecological systems. Methane emissions from AD are a potent GHG, which can potentially have a greater negative impact on PAF and PDF. Marine ecosystems have been shown to be highly sensitive to changes in global climate changes from GHG. Also, the bioaccumulation of chemicals such as heavy metals in species and the food chain as a result of digestate is a source of toxicity to land, freshwater and marine environments [76]. Since this is a potential environmental burden, it is necessary to carefully monitor and control the use of digestate. In the case of pyrolysis, avoided emissions due to the substitution of internally generated energy and the avoided use of grid-powered electricity from fossil sources account for high negative impacts.

3.2.3. Water Consumption Potential

Water is an important resource for the AD and pyrolysis process that is sourced from onsite groundwater (borehole). Water consumption/depletion is assessed as a negative impact when the abstracted water evaporates or is used in a production process far from the point of abstraction, which reduces human access to the resource at the point of abstraction [61]. The pretreatment stage of pyrolysis consumes water, which is a source of environmental burden, while the RDF is insignificant. However, in this LCA model, both pyrolytic water and liquid digestate can be reused/recycled which reduces the demand for freshwater. However, the burden of AD is potentially higher if digestate is transported to another site and cannot be reused.

3.2.4. Particulate Matter Formation Potential (PMFP)

PMFP measures the endpoint impact of fine particles/aerosols with a diameter of less than 2.5 µm ($PM_{2.5}$) on human health. These particles are a complex mixture of organic and inorganic substances, which has a potential effect on the cardio-pulmonary system and mortality after long-term exposure [58,59]. This is a very important parameter because the WtE plant under study requires human operations for at least 40 h a week. Although all the PM values recorded indicated a low impact (−0.21 to 0.03 kg $PM_{2.5}$ eq), the emission factors used are only limited to the engine. Data on site-specific operational emissions are not available. Air quality measurements are highly recommended for future studies to determine the exact potential PM emissions at various waste treatment plants across Ghana and the corresponding impact on humans and the ecosystem. In a previous study to assess the concentrations of PM in the breathing zones of informal e-waste workers in Ghana, the PM 2.5, 2.5–10 concentrations were 2–3 times above a control group and also above the WHO air quality standards. The study recommended the assessment of the impact of long-term exposure [77]. In the long term, PM may also impact the ecosystem of the area, which is predominantly agricultural, thus requiring further investigation.

3.2.5. Terrestrial Acidification Potential

Acidification Potential (AP) measures the potential impact of acidifying substances such as NO_x, NH_3 and SO_2 on soils and their dependent species [58]. The values of AP were generally low, with a net avoided impact of 0.31 kg SO_2 eq, which is linked to the low emissions of these pollutants directly from the systems. The use of electricity from the solar PV system contributes to avoided emissions.

3.2.6. Fossil Resource Scarcity

Fossil resources are subject to depletion apart from their high climate footprint once combusted. The increased substitution of fossil energy for renewable energy is important. The energy mix in Ghana is composed of 68% generation from thermal combustion of fossils [78].

3.3. Uncertainty Analysis

Each box plot shows the distribution of uncertainty values for each impact category (Figure 7). Uncertainty in the LCA results highlights the variability and spread of data within each impact category. High uncertainty is recorded for HTP/NC, HTP/C and FETP, which indicates a high level of uncertainty in the input data, suggesting that the impact assessments for this category are highly variable and potentially influenced by many factors. FETP, METP and GWP, on the other hand, show moderate uncertainty with several outliers, indicating some level of variability. FFP, WCP, PMFP and TETP show relatively low levels of uncertainty, with smaller IQRs and fewer outliers. This suggests that the data for these impact categories are more consistent and reliable. Categories with low uncertainty provide more confidence in the results and can be used more reliably in environmental impact assessments and sustainability planning. In summary, the uncertainty plot provides valuable insights into the reliability and variability of LCA results across different impact categories.

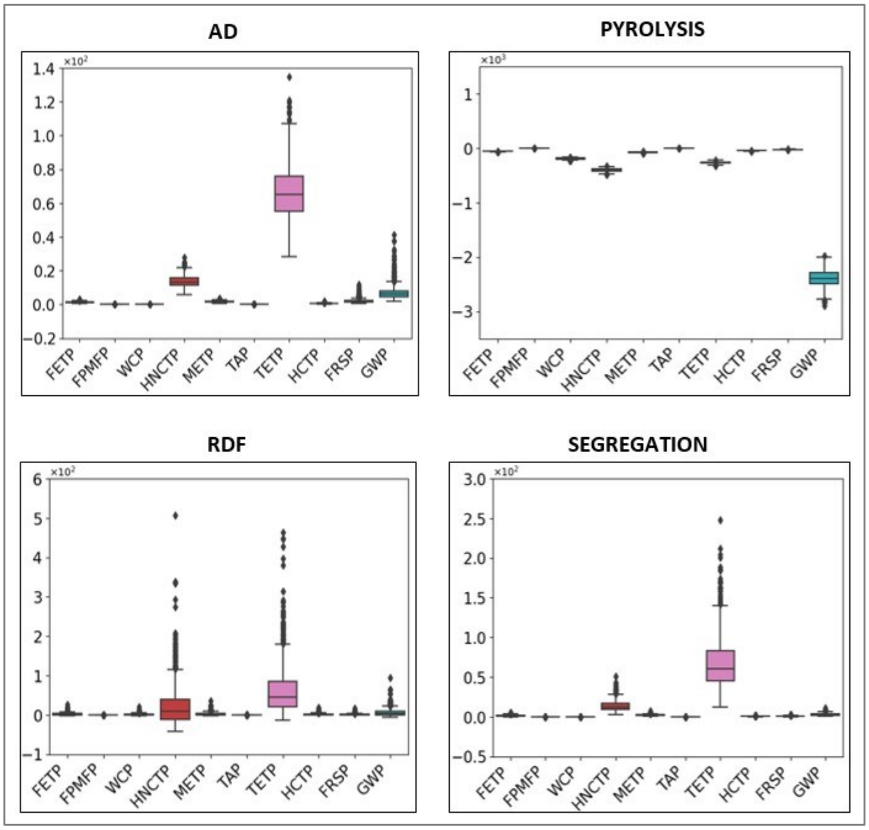

Figure 7. *Uncertainty plot for the processes.*

3.4. Other Potential Impacts

Other potential impacts include socio-economic and public health improvement in rural communities. According to the 2021 census data, 36.8% of rural households have no waste collection, while 57.3% use open dumps with potential health impacts. With the plant located within a municipality with 64.7% rural households, the proximity of a WtE plant will likely reduce the cost of waste collection services and encourage more residents to pay for WtE services. Also, the plant currently provides employment and income security to many residents, while compost may support agriculture at a lower cost since this is the most prevalent economic activity within the town [39]. Additionally, a buffer zone has been created around the plant site within a 1 km distance from the closest households for protection against fire outbreaks, odor and noise.

The promotion of WtE in such settings has climate mitigation impacts at both national and international levels. Ghana's NDCs aim to reduce GHGs by 64 $MtCO_2eq$ and create one million decent and green jobs by 2030. The expansion of WtE systems within a circular economy concept will support the attainment of such national targets with global impacts [79]. As of 2022, Ghana's national energy mix was made up of 1.9%, 70% and 28.1% renewable energy, fossil fuels and hydro, respectively. The sustained substitution of WtE with fossil fuels is important to reaching the set targets and protecting global resources.

3.5. Limitations and Recommendations

One major limitation of this comparative study is the lack of an ongoing monitoring system with a recent, detailed localized database on waste generation and treatment pathways across cities [38]. The Ecoinvent Database, for instance, does not contain some locally specific data for Ghana, especially for the plant site in Atwima Nwabiagya. Where locally specific data were not available, data from the rest of the world were used during the modeling in OpenLCA. This provides a limitation to the results, which may have a substantial deviation from the site-specific environmental impacts.

It is strongly proposed that a country-specific database be developed for Ghana by the government. Since Ghana is a signatory to the Paris Agreement, such a database becomes a technical resource that will enhance the accuracy of climate monitoring and auditing. The development of a database can be facilitated through the following:

- Dedicating funding to this;
- Dedicating human resources for national coordination, such as incorporating it into the Ghana Carbon Market Office;
- Future research focused on carrying out detailed and up-to-date studies on aspects such as national waste composition similar to that carried out in 2014 [80]. Other important areas of concern are emission factors and operation-related emissions from waste treatment activities;
- Facilitating training programs for waste management companies, research institutions, agencies and decision-makers to enhance monitoring and compliance.

The uncertainty in LCA results is crucial for decision-making and policy development. High uncertainty in certain impact categories, such as HTP, indicates that more research and data collection are needed to improve the reliability of these assessments. Another major source of concern is the potential impact of mixed waste on the HTP as well as ETP through bioaccumulation in terrestrial, freshwater or marine species. The waste segregation model for the socio-cultural setting in Ghana needs to be studied and implemented to avoid such impacts.

Life cycle costing is highly recommended in future studies to incorporate the cost of environmental impact in decision-making. Carbon trading can potentially stimulate more emission reduction developmental projects in local communities [81]. It is important for WtE plants to obtain international certifications such as ISO 14001, which may return positive financial benefits for the case study plant, although it requires adherence to strict requirements. Environmental assessment studies such as this to support carbon financing mechanisms that require international certification [82].

Conclusions

This study conducted an environmental assessment of various processes within a pilot waste-to-energy plant in Ghana. The Life Cycle Assessment was conducted using OpenLCA software version 2.3.1. Landfill emissions were considered the baseline for estimating potential emission reduction. The results indicate that the GWP has the highest potential environmental impact followed by the toxicity potentials, mainly high Human Toxicity Potentials. Pyrolysis showed high avoided impacts, while AD showed near-zero impacts. The major attributing factors are the potential sequestering of the produced char end-product and the input of renewable energy. Overall, pyrolysis technology is the most environmentally friendly. This is relevant because a comparative assessment of the GWP of landfilling showed that the WtE plant has the potential to reduce emissions by 3.52 tCO_2eq/FU, resulting in a total of 1.28 million tCO_2eq over its 20-year lifespan based on the expected capacity. This can directly or indirectly potentially improve the business case of the plant. Uncertainty assessment also points to the need for a national database with relevant localized data to improve the reliability of future studies. Also, although AD showed a near-neutral environmental impact, the release of digestate may have high human and ecotoxicity impacts when substances such as heavy metals are present. This can be a potential risk in Ghana, where the source segregation of waste is largely non-existent. As such, the implementation of AD technology must be associated with strict regulations and monitoring systems on the management of digestate. Based on these findings, it is recommended that pyrolysis of end-of-life and non-recyclable plastics be incorporated strongly into the waste-to-energy models. Decision makers have a role to play by introducing innovative approaches to encourage source segregation. It is also recommended to use strict guidelines and monitoring systems to ensure that emission control is implemented by waste-to-energy plants according to environmental compliance. With the siting of the WtE plant in a rural community, the municipal authorities are encouraged to take advantage of this to stimulate community participation in environmental protection by providing incentives such as lower waste collection costs. In the long term, this WtE plant may contribute relevant data for improving decision-making based on environmental assessments in Ghana. It may also provide a basis for carbon trading and enhance the financing profile of the WtE model studied. Future studies may be extended to include other processes such as composting and recycling.

Author Contributions

Conceptualization: E.A.A., F.B.A., F.K. and M.M.; methodology: E.A.A., F.B.A., F.K., S.N. and M.M.; Formal analysis: E.A.A., T.B. and M.M.; writing—original draft preparation: E.A.A.; Writing—review and editing: T.B. and M.M.; visualization: T.B.; supervision, S.N. and F.K. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Data are contained in the article.

Conflicts of Interest

Author Theophilus Baidoo was employed by the company Zeal Environmental Technologies and Author Satyanarayana Narra was employed by the company German Biomass Research Centre gGmbH. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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SUPPLEMENTARY MATERIALS

Table S.1: The estimated production quantities and corresponding prices of AF&M products

Product	Unit/ yr	Selling price €/unit	Production units /year
Electricity	MWh	83.49	810
Pellets	tons	720.00	318.25
Compost	tons	121.78	1537.65
Bio-CNG	tons	1,008.00	9.94351
Hydrogen	m^3	4,600.00	17,05114
RDF	tons	15.00	5025
RFO	litres	0.75	7,931
Lab	samples	3.39	3000

Table S.2: Labels, location and scores to explain map (Figure 5.3 and Figure 5.4)

Label	REGION	MMA
1	GREATER ACCRA	KPONE KATAMANSO
2		ACCRA METROPOLIS
3		GA CENTRAL
4		GA SOUTH
5		GA WEST
6		GA EAST
7		AYAWASO NORTH
8		ABLEKUMA CENTRAL
9		ASHAIMAN
10		LEDZOKUKU
11		LA-NKWANTANANG MADINA
12		GA NORTH
13		ABLEKUMA WEST
14		ABLEKUMA NORTH
15		ADENTA
16		OKAIKWEI NORTH
17		TEMA WEST
18		TEMA METROPOLITAN
19		KROWOR
20		WEIJA GBAWE
21	GREATER ACCRA	AYAWASO CENTRAL
22		AYAWASO EAST
23		LA DADE-KOTOPON
24		KORLE KLOTTEY
25		AYAWASO WEST
26	CENTRAL	AWUTU SENYA EAST
27		CAPE COAST
28		KOMENDA-EDINA EGUAFO-ABIREM
29		MFANTSEMAN
30		EFFUTU
31		AGONA WEST
32		UPPER DENKYIRA EAST
33		ASSIN CENTRAL
34		BIRIM CENTRAL
35	EASTERN	ABUAKWA NORTH
36		ABUAKWA SOUTH
37		NEW JUABEN NORTH

38		KWAEBIBIREM
39		WEST AKIM
40		AKWAPEM NORTH
41		SUHUM
42		YILO KROBO
43		KWAHU WEST
44		NEW JUABEN SOUTH
45		NSAWAM ADOAGYIRI
Label	**REGION**	**MMA**
46	EASTERN	LOWER MANYA
47		KETU SOUTH
48	VOLTA	HO
49		KETA
50		KETU NORTH
51		HOHOE
52		KPANDO
53		KRACHI EAST
54	OTI	NKWANTA SOUTH
55		NKWANTA NORTH
56	WESTERN	NZEMA EAST
57		WASSA AMENFI WEST
58		AHANTA WEST
59		JOMORO
60		WASSA EAST
61		EFFIA KWESIMINTSIM
62		TARKWA NSUAEM
63		PRESTEA/HUNI VALLEY
64		SEKONDI TAKORADI
65	WESTERN NORTH	BIBIANI ANHWIASO-BEKWAI
66		SEFWI-WIAWSO
67		AOWIN
68	ASHANTI	JUABEN
69		AHAFO ANO NORTH
70		ASANTE AKIM CENTRAL
71		ASANTE AKIM SOUTH

72		MAMPONG
73		OBUASI
74		BEKWAI
75		EJURA-SEKYEDUMASE
76		ASOKWA
77		OFFINSO
78		ATWIMA NWABIAGYA NORTH
79		KWADASO
80		EJISU
81		SUAME
82		OFORIKROM
83		ASOKORE MAMPONG
84		OLD TAFO
Label	**REGION**	**MMA**
85	ASHANTI	KUMASI METROPOLITAN
86	BONO EAST	TECHIMAN
87		KINTAMPO NORTH
88		ATEBUBU AMANTIN
89		NKORANZA SOUTH
90	BONO	DORMAA MUNICIPAL
91		JAMAN SOUTH
92		BEREKUM EAST
93		SUNYANI
94		WENCHI
95	AHAFO	ASUNAFO NORTH
96		TANO NORTH
97		TANO SOUTH
99	NORTHERN	GUSHEGU
100		SAVELUGU
101		YENDI
102		TAMALE METROPOLITAN
103		SAGNERIGU
105	NORTH EAST	WEST MAMPRUSI

106	SAVANNAH	EAST GONJA
107	UPPER WEST	WA
108		JIRAPA
109		LAWRA
110		SISSALA EAST
111	UPPER EAST	BUILSA NORTH
112		KASENA NANKANA EAST
113		BOLGATANGA
114		BAWKU

Table S.3: Raw data for Figure 5.5

Region	Organic	Paper	Plastic	Leather & Rubber	Textile	Metal	Glass	Inert	Miscellaneous
Ahafo[1]	69.0	6.0	19.0	1.0	-	2.0	3.0	-	-
Ashanti[2]	48.4	6.5	17.6	1.6	0.1	4.5	2.9	10.7	7.8
Bono East[1]	69.0	6.0	19.0	1.0	-	2.0	3.0	-	-
Bono[1]	69.0	6.0	19.0	1.0	-	2.0	3.0	-	-
Central[2]	63.2	4.1	10.6	1.2	1.1	2.1	1.9	10.2	5.6
Eastern[3]	70.0	6.0	16.0	-	0.0	3.0	5.0	-	-
Greater Accra[2]	65.8	5.3	10.4	2.1	2.0	3.1	2.8	5.2	4.1
North East[2]	58.6	3.2	10.9	1.0	0.9	2.8	4.9	4.5	3.4
Northern[2]	58.6	3.2	10.9	1.0	0.9	2.8	4.9	4.5	3.4
Oti[2]*	61.0	5.0	14.0	1.0	2.0	3.0	3.0	6.0	5.0
Savannah[2]	58.6	3.2	10.9	1.0	0.9	2.8	4.9	4.5	3.4
Upper East[4]	46.0	3.3	6.3	-	5.0	6.3	-	31.3	5.0
Upper West[4]	46.0	3.3	6.3	-	5.0	6.3	-	31.3	5.0
Volta[2]*	61.0	5.0	14.0	1.0	2.0	3.0	3.0	6.0	5.0
Western[5]	60.0	7.1	11.5	1.2	2.9	2.4	1.5	8.0	5.0
Western North[5]	60.0	7.1	11.5	1.2	2.9	2.4	1.5	8.0	5.0

- *n.d – not determined/not stated in the study results. *National average
- References: (Agyei, 2020)[1]; (Miezah et al., 2015)[2]; (Asamoah-Okyere, 2011)[3]; (Monney et al., 2013)[4]; (Seshie et al., 2020)[5]